Interaction between Beams and Vacuum System Walls.

R. Cimino,

LNF INFN, Frascati, Italy.

Interaction between Beams and Vacuum System Walls.

- Phenomenology:

What happens to the Vacuum beam pipe in presence of the beam?

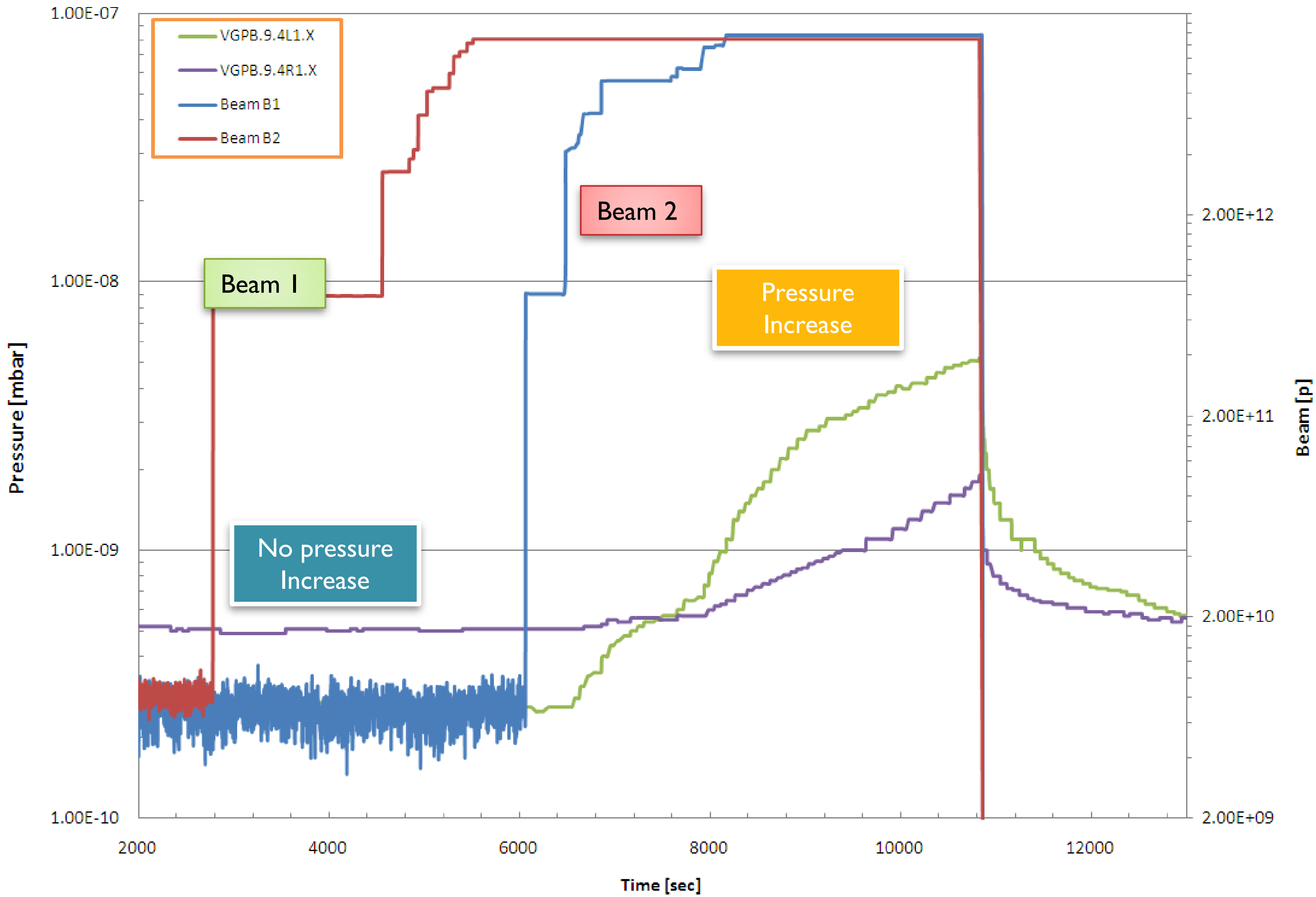
  - Synchrotron radiation: Heat Load, Photo-electrons and electron induced desorption
  - Ion induced desorption and associated instability.
  - Desorption yields and conditioning.
  - "Electron cloud" effects and associated instabilities
  - Additional materials → Addendum
- Mitigation strategies
- Conclusion

One real example to see what the beam does to Vacuum:

8-10-2010

450 GeV – 150 ns bunch spacing: Merged vacuum @ LHC

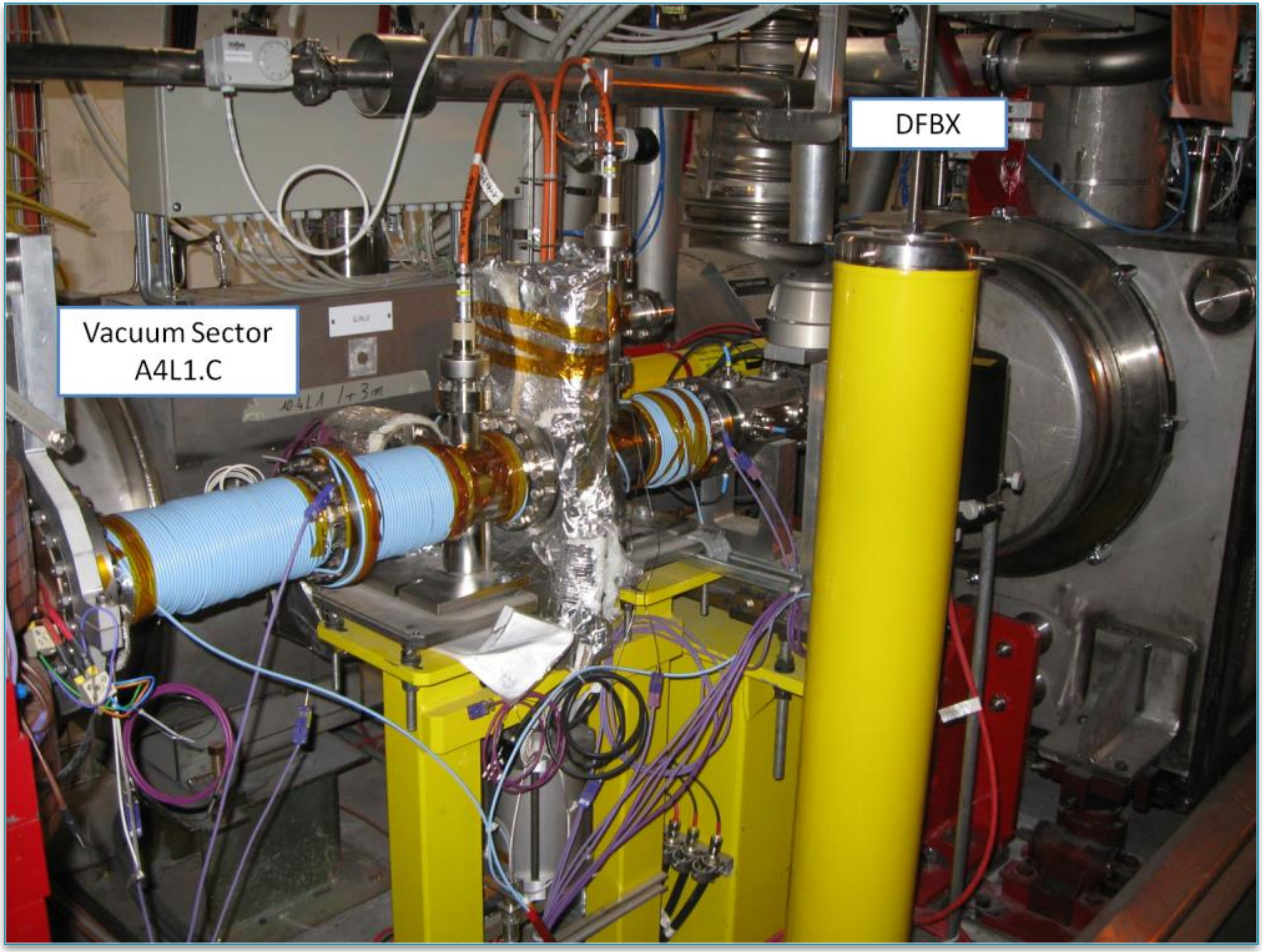
Exotic Vacuum behavior @ LHC:



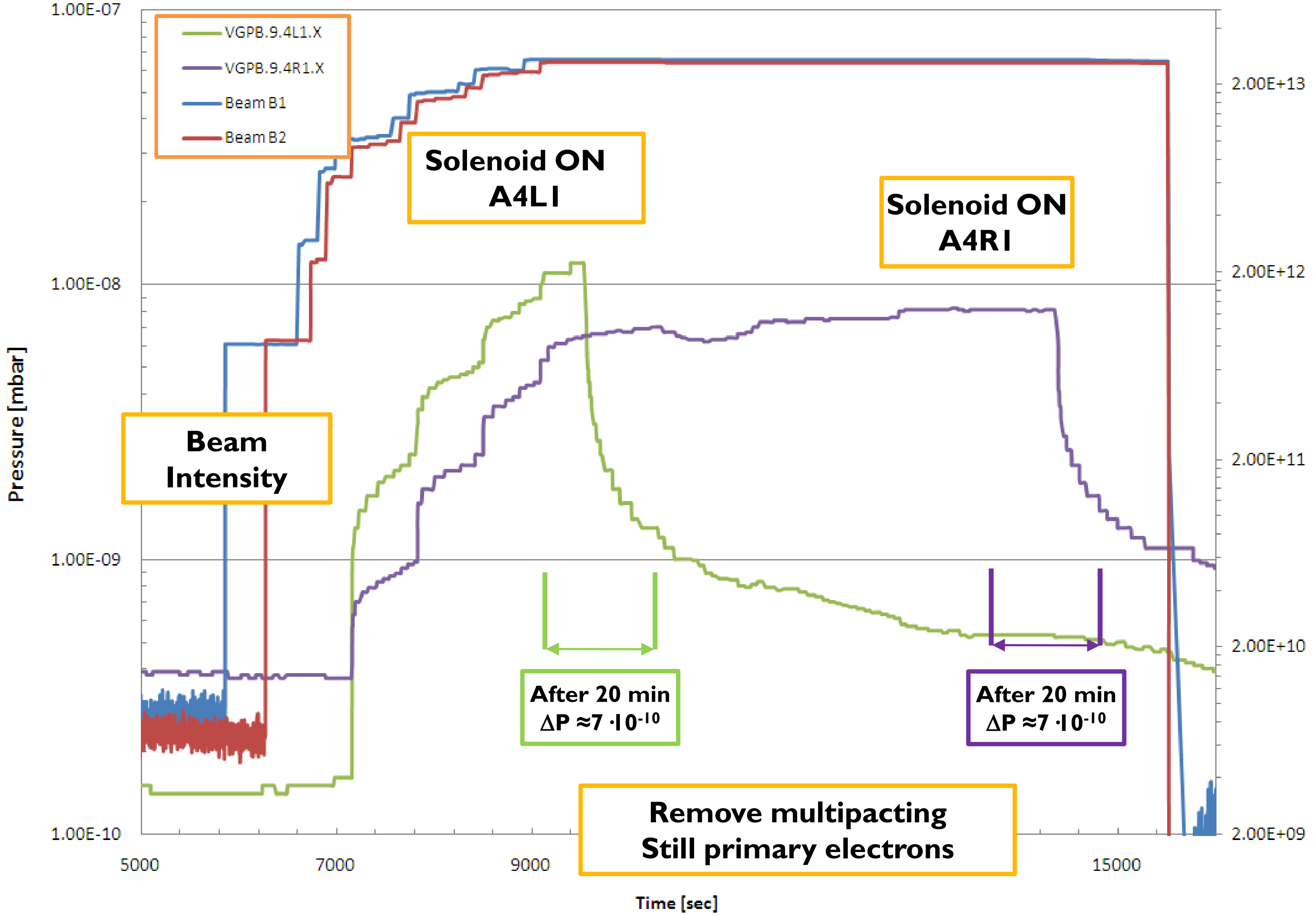
450 GeV – 150 ns bunch spacing: Merged vacuum

8-10-2010

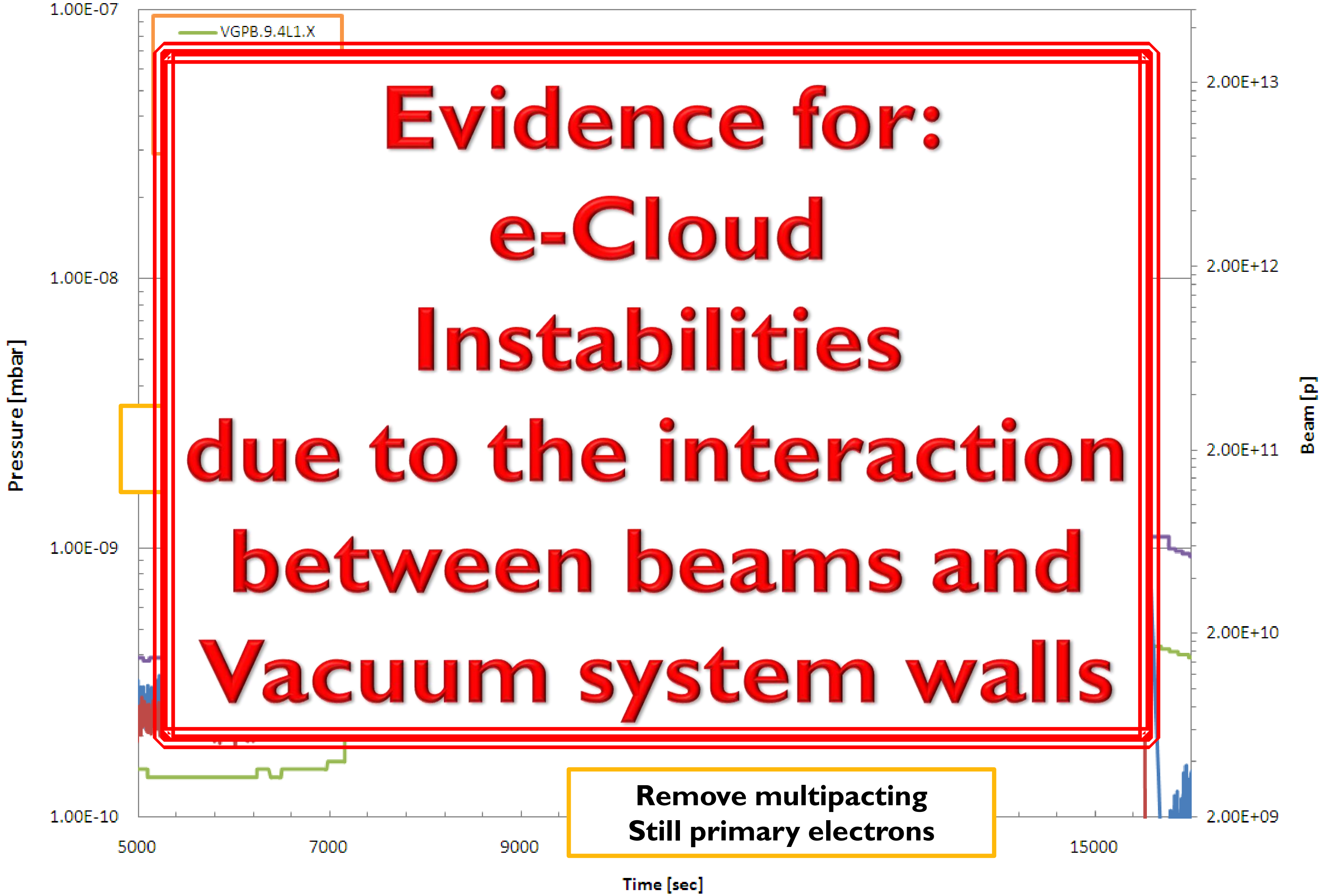
Easily solved: Installation of Solenoids



Solenoids have effect on pressure!!!



Solenoids have effect on pressure!!!



**Evidence for:
e-Cloud
Instabilities
due to the interaction
between beams and
Vacuum system walls**

**Remove multipacting
Still primary electrons**

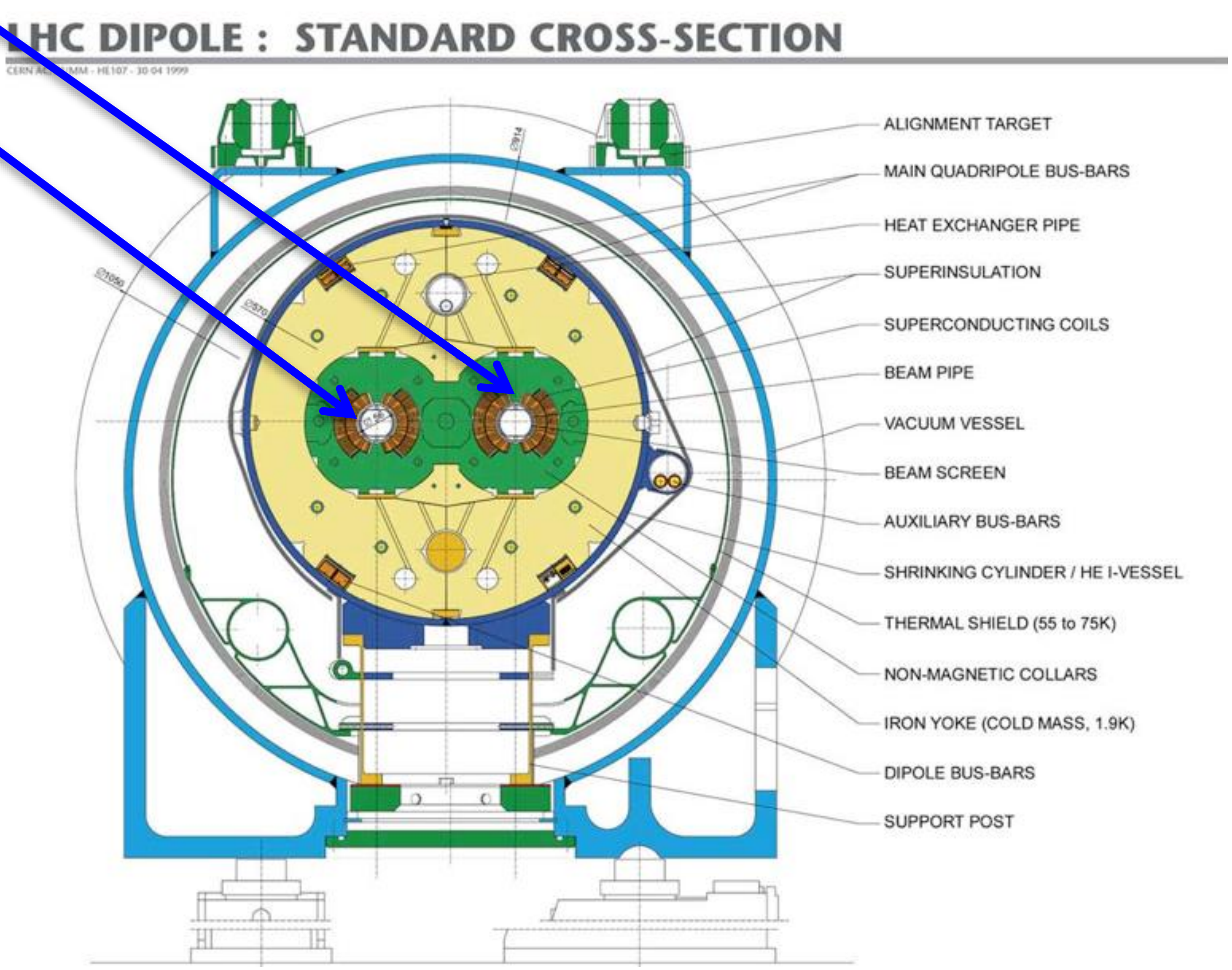
Vacuum in new generation accelerators is much "more" than a technical issue!

- Let us see what may cause such beam and/or pressure instabilities.
- The case of the:

LHC arcs

Static

Cold Bore @ 1.9 K



Extreme High Static Vacuum (<< 10^{-13} Torr)

Static

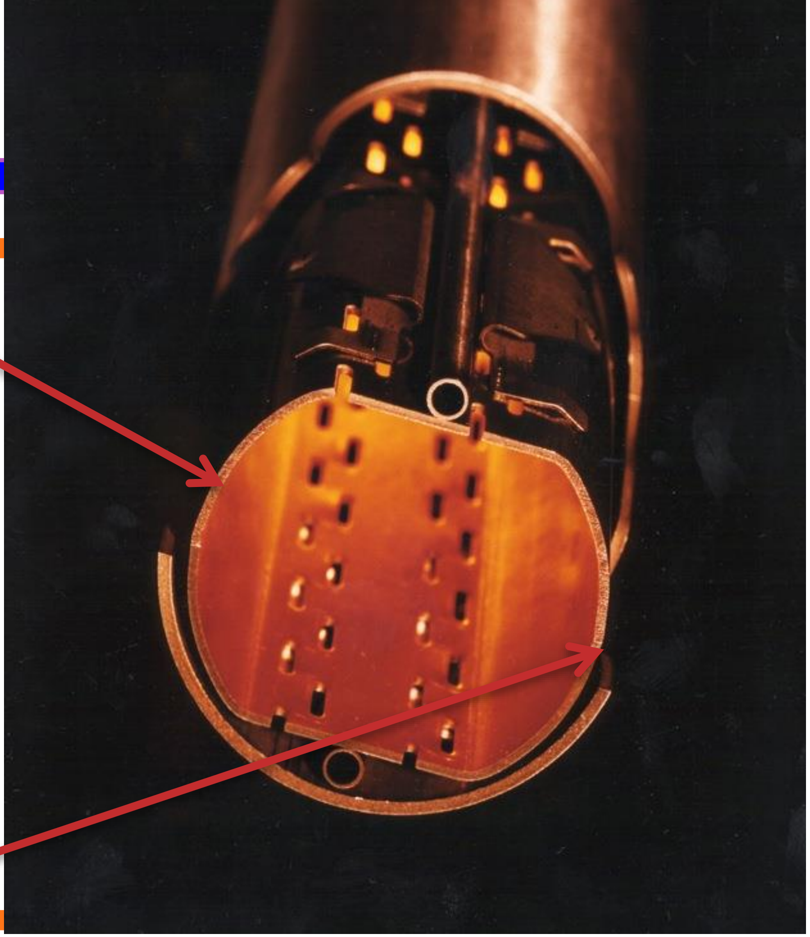
Cold Bore @ 1.9 K

Radial Distance

Need of a Beam Screen

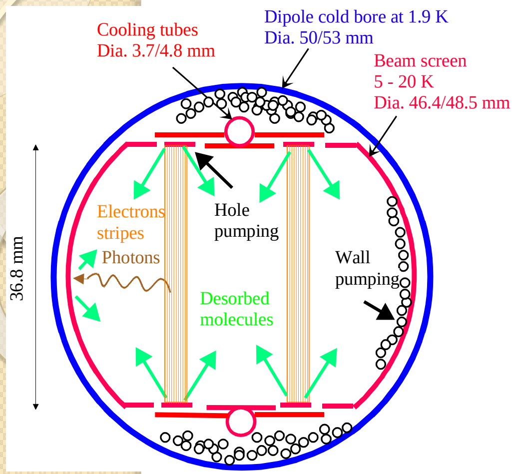
@ 5K< T <20K

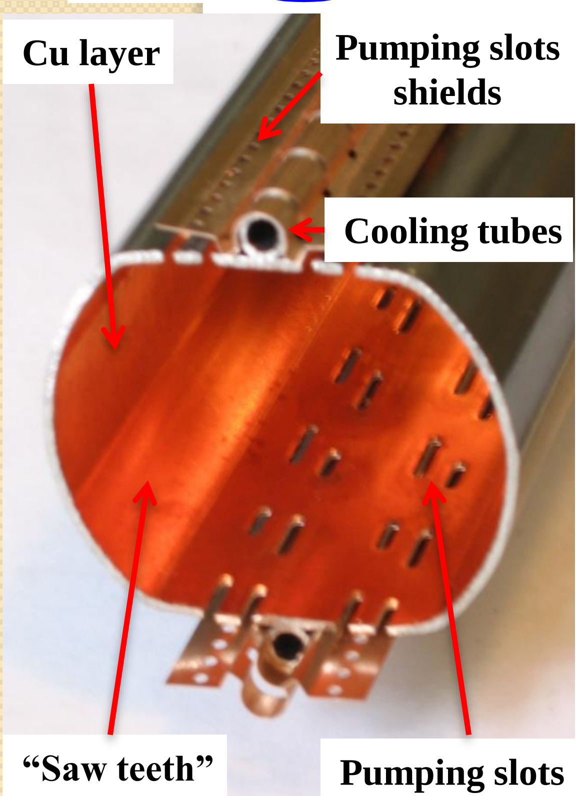
to reduce heat load (SR, Eddy current, Impedance, etc…) on Cold bore for thermal load issues

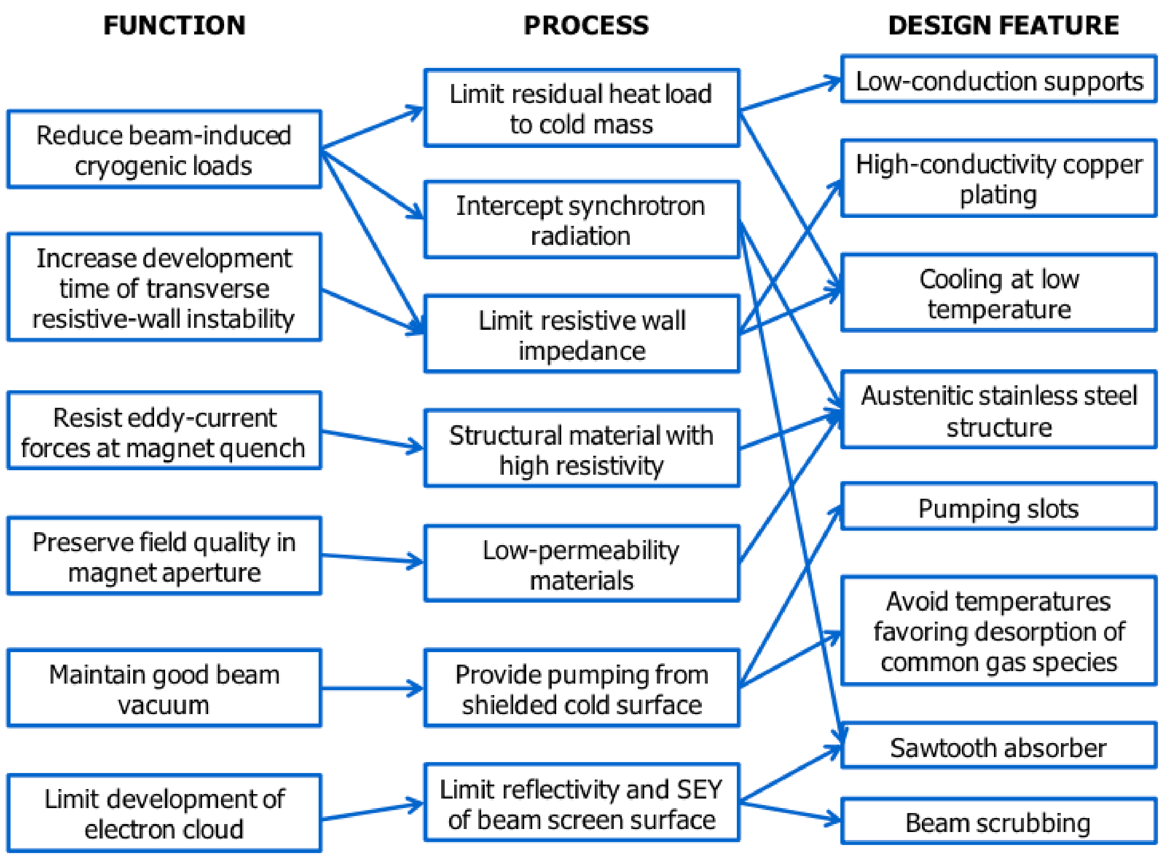


T=0, without beam

The Beam Screen is a complex technological product!





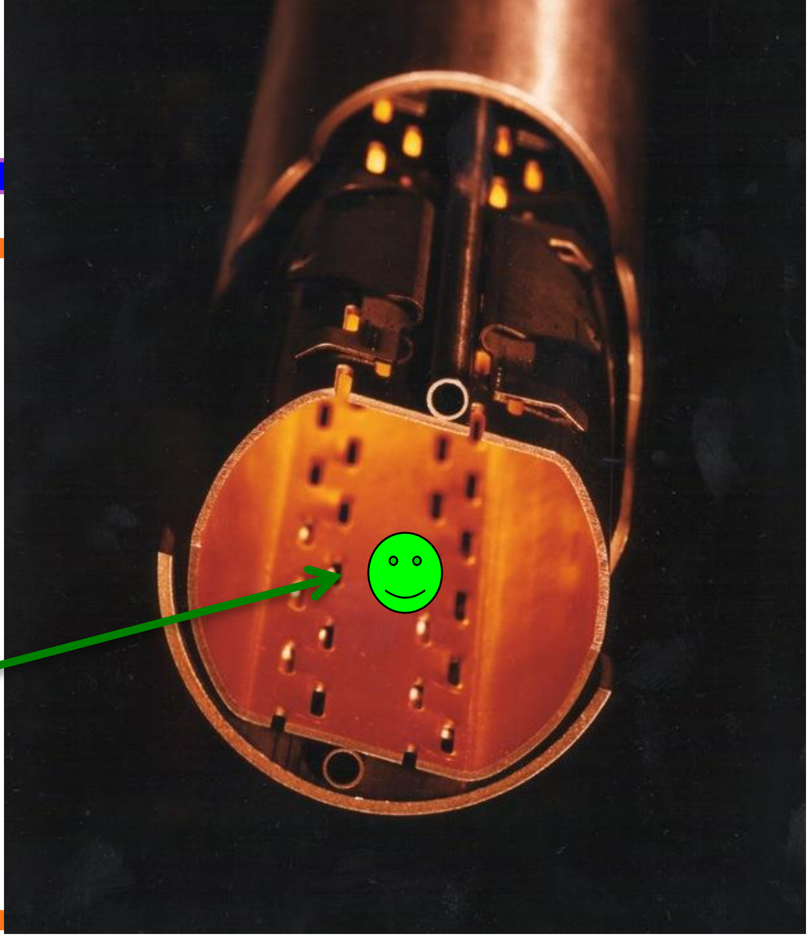


Static Cold Bore @ 1.9 K

Radial Distance

Let us see what happens during operation and beam passage to:

- The vacuum system
- the Beam screen Surface



T=0, without beam

Beam – Gas Interactions

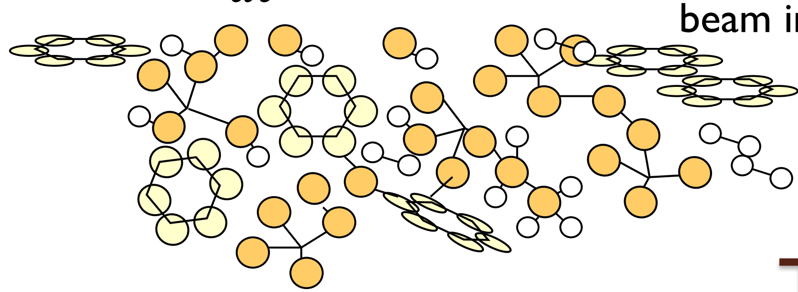
Radial Distance

CB

BS

The beam interacts with the residual gas:

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



p +

- Where:
- σ is the cross section i.e. the probability the beam interacts with the atoms of target
- I is the beam intensity
- n is the atomic density of a target of thickness dx
- v is the beam velocity

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

This define: Vacuum Beam Life time (τ)

$$\tau = \frac{1}{n\,\sigma\,v}$$

For a vacuum system: $\frac{1}{\tau} = \frac{1}{\tau_{H2}} + \frac{1}{\tau_{CH4}} + \frac{1}{\tau_{H2O}} + \frac{1}{\tau_{CO}} + \frac{1}{\tau_{CO2}}$

The vacuum life time must be much larger (*i.e.* >> 24 h) than other life times such as e.g. the particle loss due to the collisions

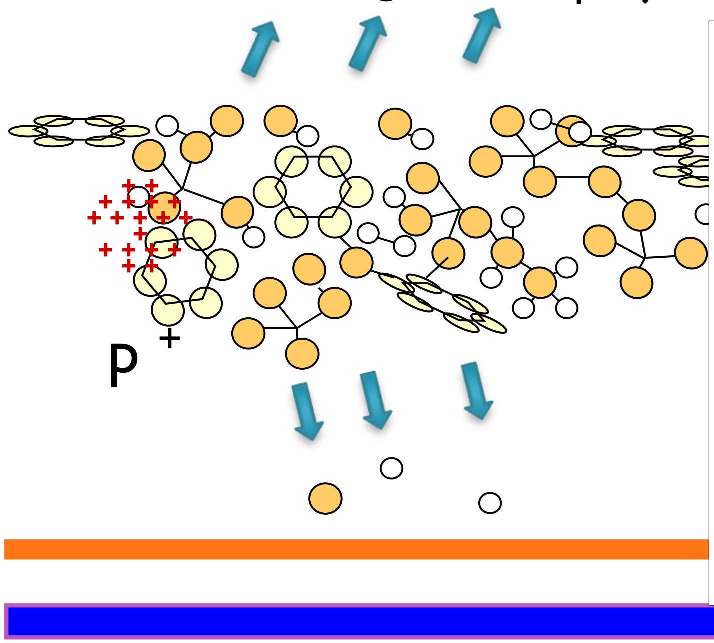
Beam – Gas Interactions: ion production

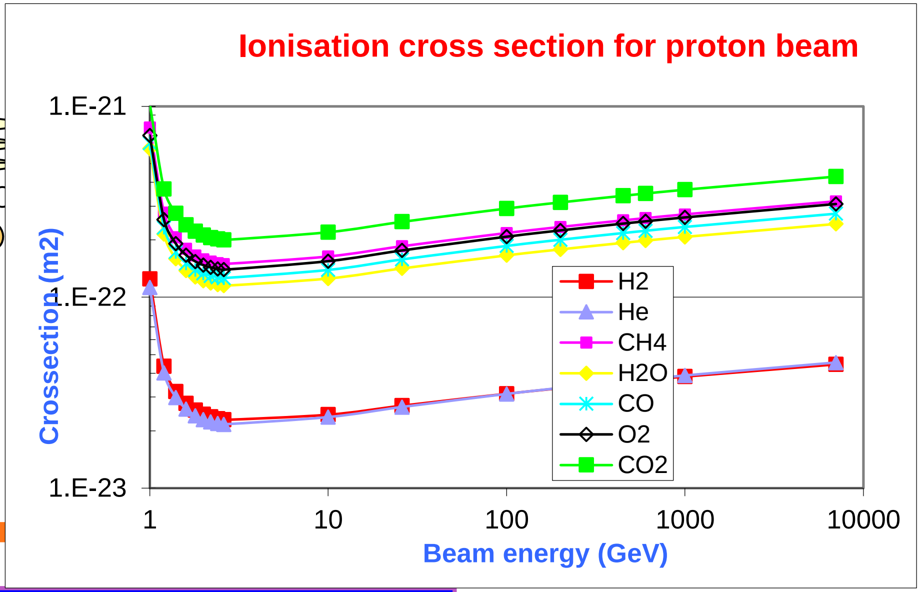
Radial Distance

CB

BS

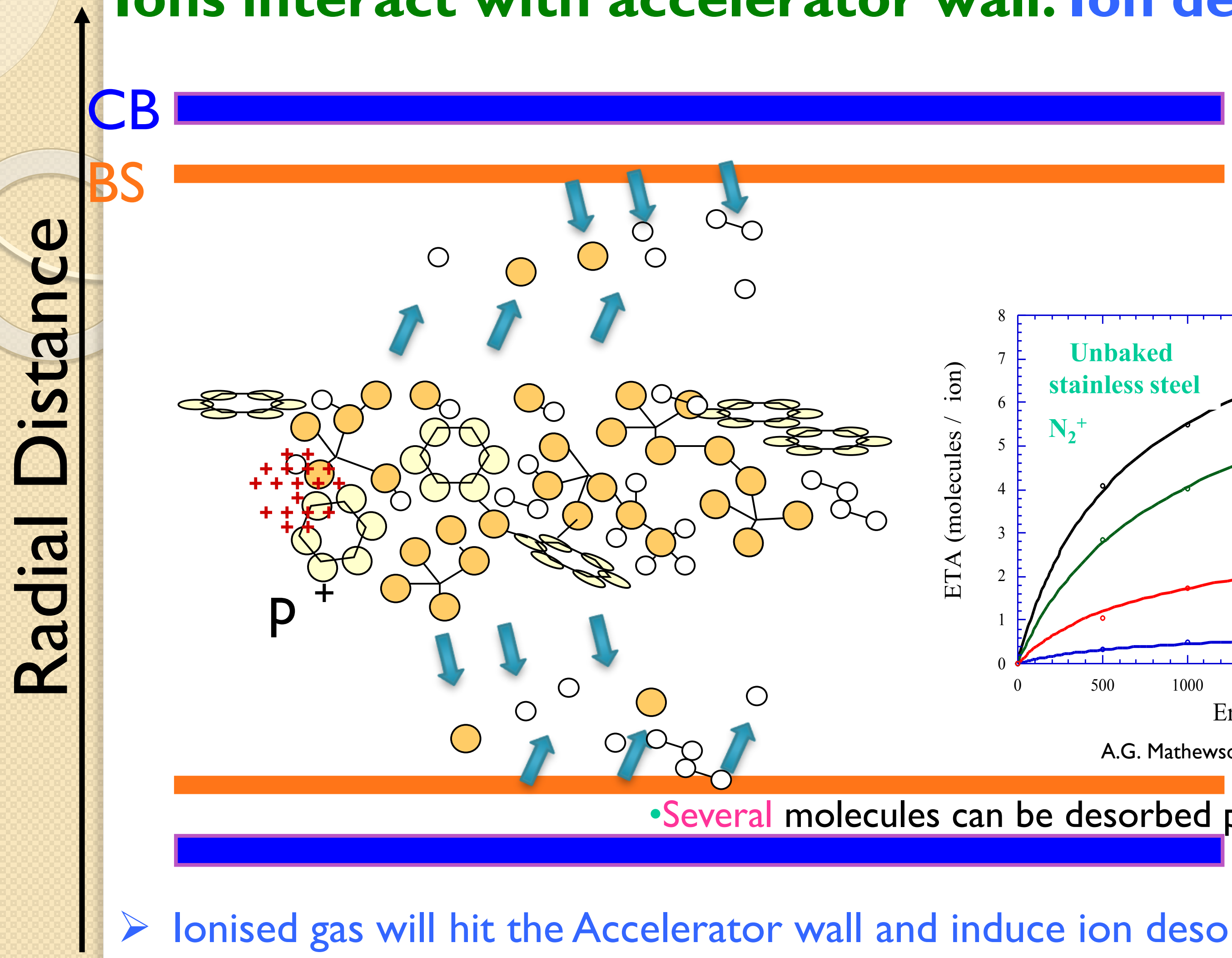
Ionisation cross section is a function of the speed & the charge of the projectile and of the nature of the residual gas





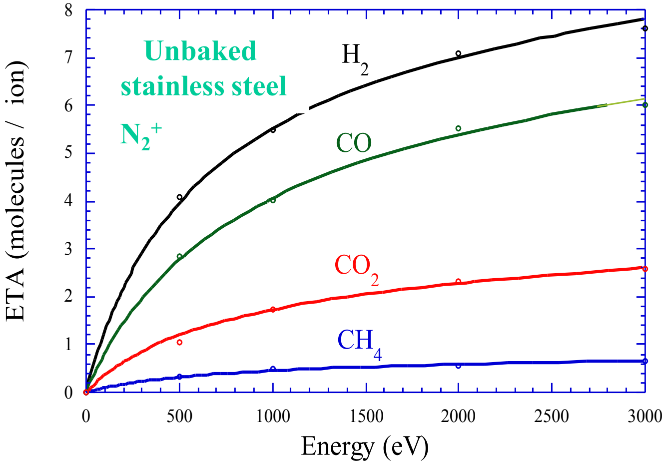
→ Heavy gas must be avoided

Ions interact with accelerator wall: Ion desorption yield



Varies with:

- the material,
- the ion energy
- and ion species

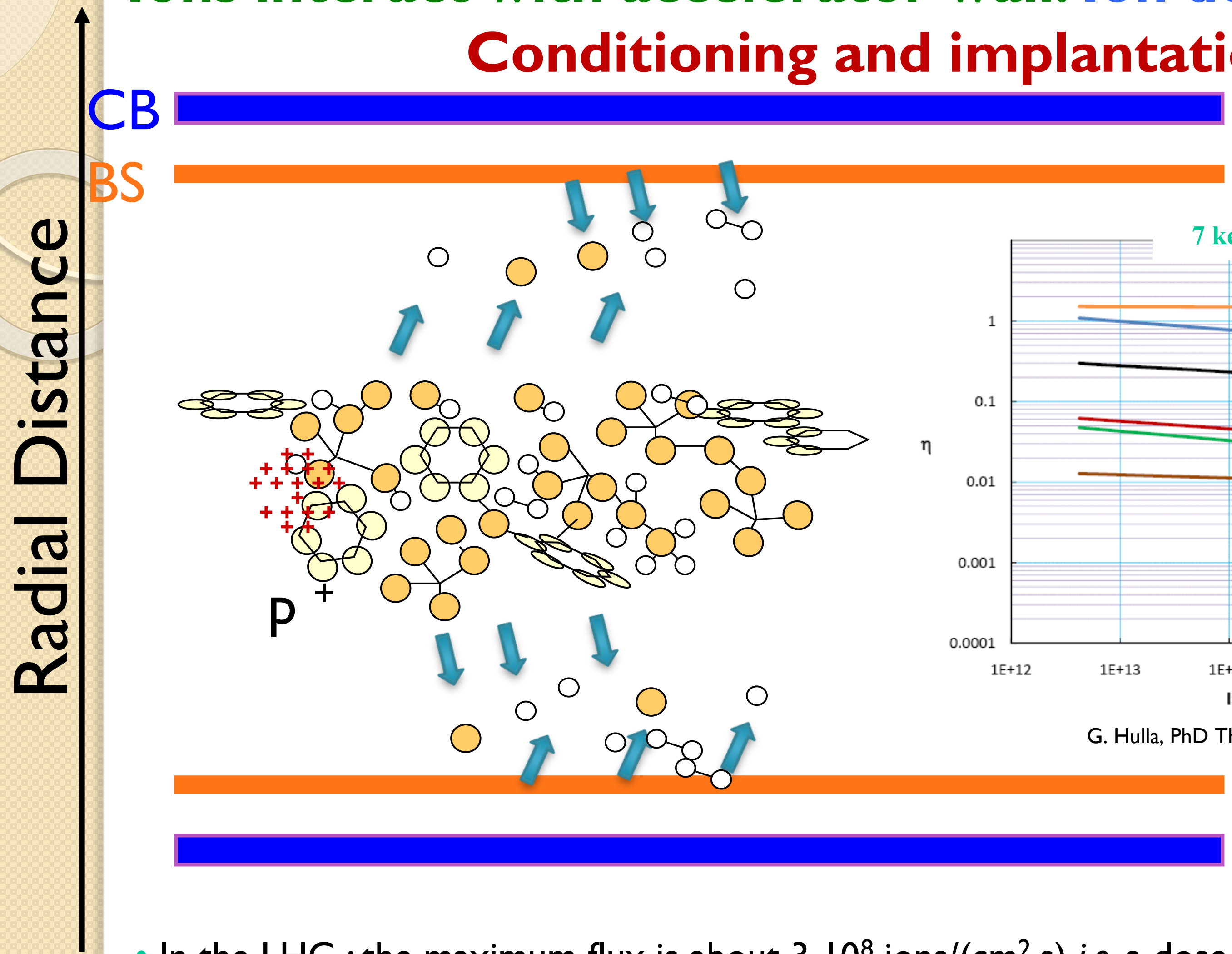


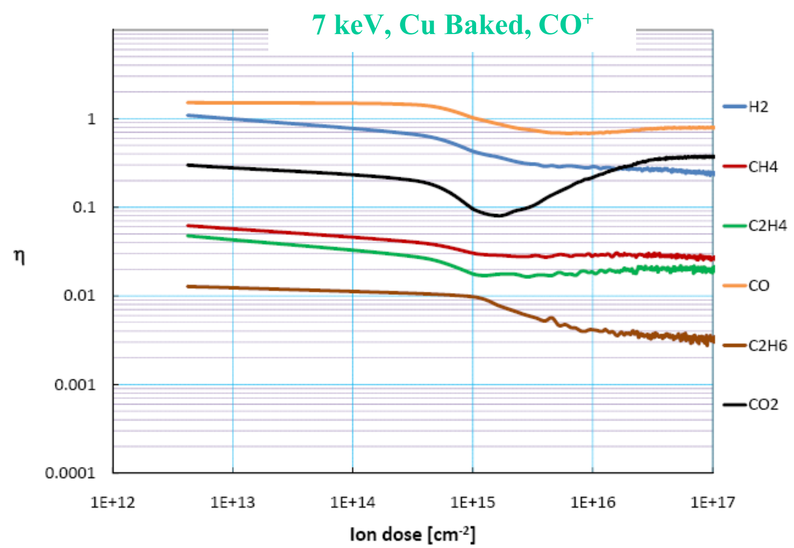
A.G. Mathewson, CERN ISR-VA/76-5

- Several molecules can be desorbed per ion ➔ Sputtering

- Ionised gas will hit the Accelerator wall and induce ion desorption.
- Pressure and beam ion interaction will increase, increasing desorption
- Such a resonant phenomenon will cause Vacuum instability and there will be a critical beam current, at which the pressure increases to infinity.

Ions interact with accelerator wall: Ion desorption yield.
Conditioning and implantation





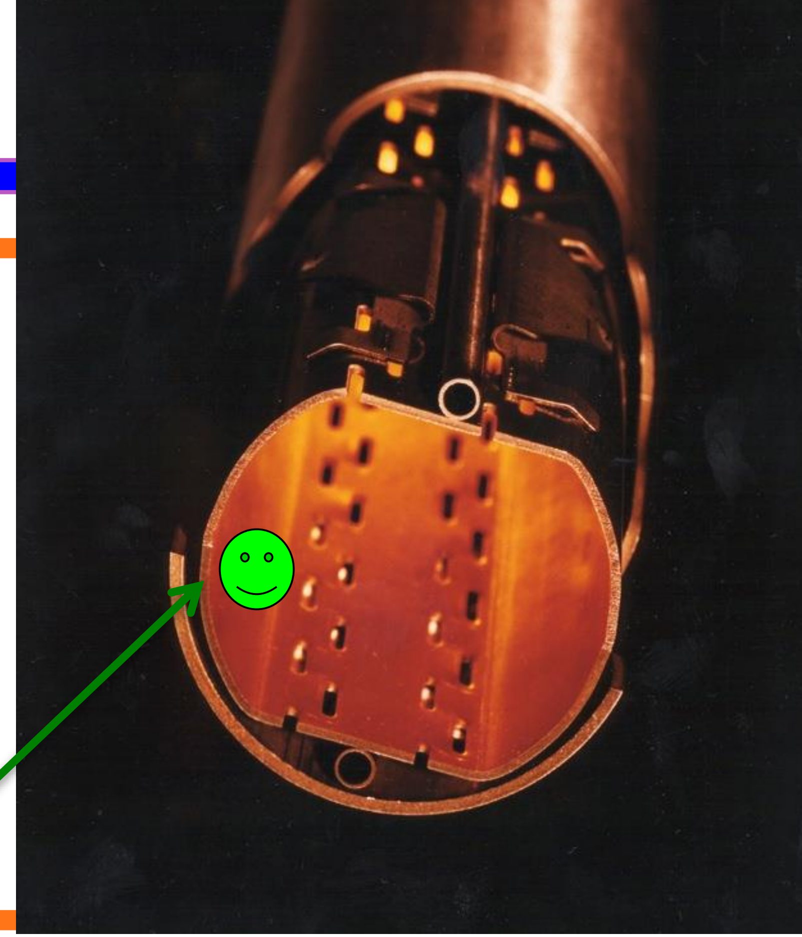
G. Hulla, PhD Thesis, Vienna Tech. U, 2009

- In the LHC : the maximum flux is about 3 10^8 ions/(cm^2.s) *i.e.* a dose of 3 10^{15} ions/(cm^2.year)
- **In the LHC, there is no conditioning due to ion bombardment**

Static Cold Bore @ 1.9 K

Let us see what happens during operation and beam passage to:

- The vacuum system
- the Beam screen Surface

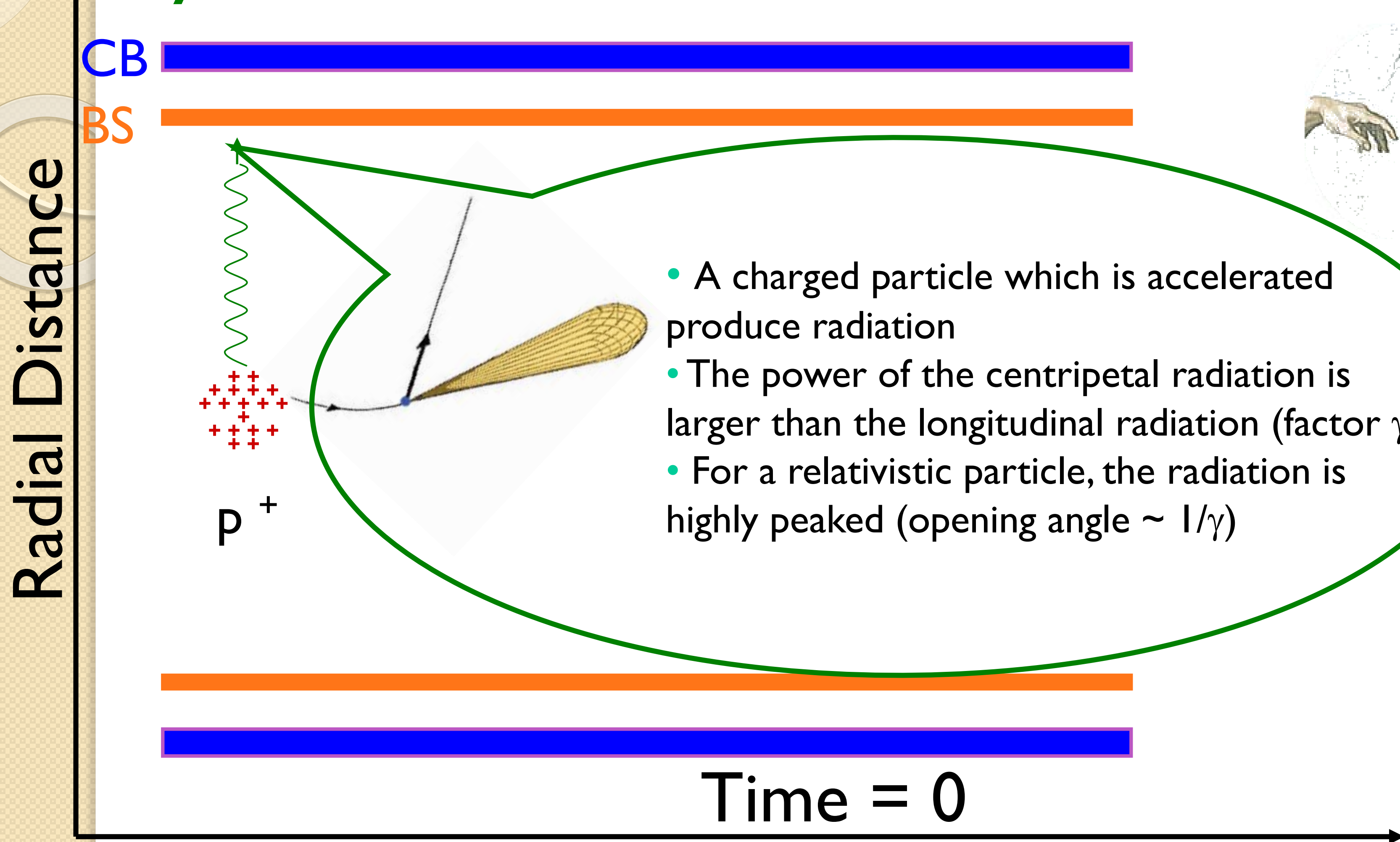


Radial Distance

T=0, without beam

Synchrotron Radiation

calculation



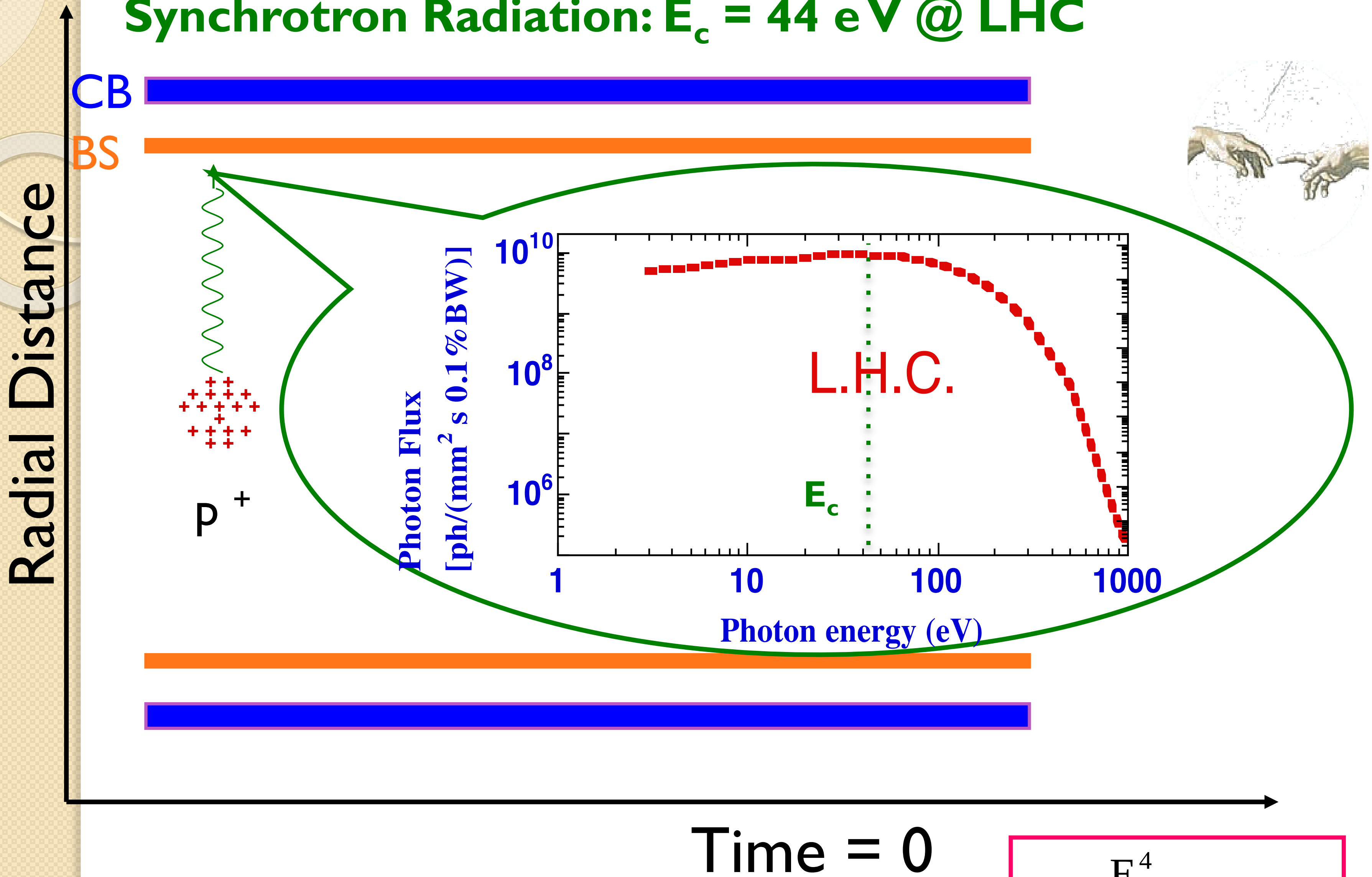
Critical energy: divide the power spectrum in two equals parts

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

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

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

Synchrotron Radiation: E_c = 44 eV @ LHC



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

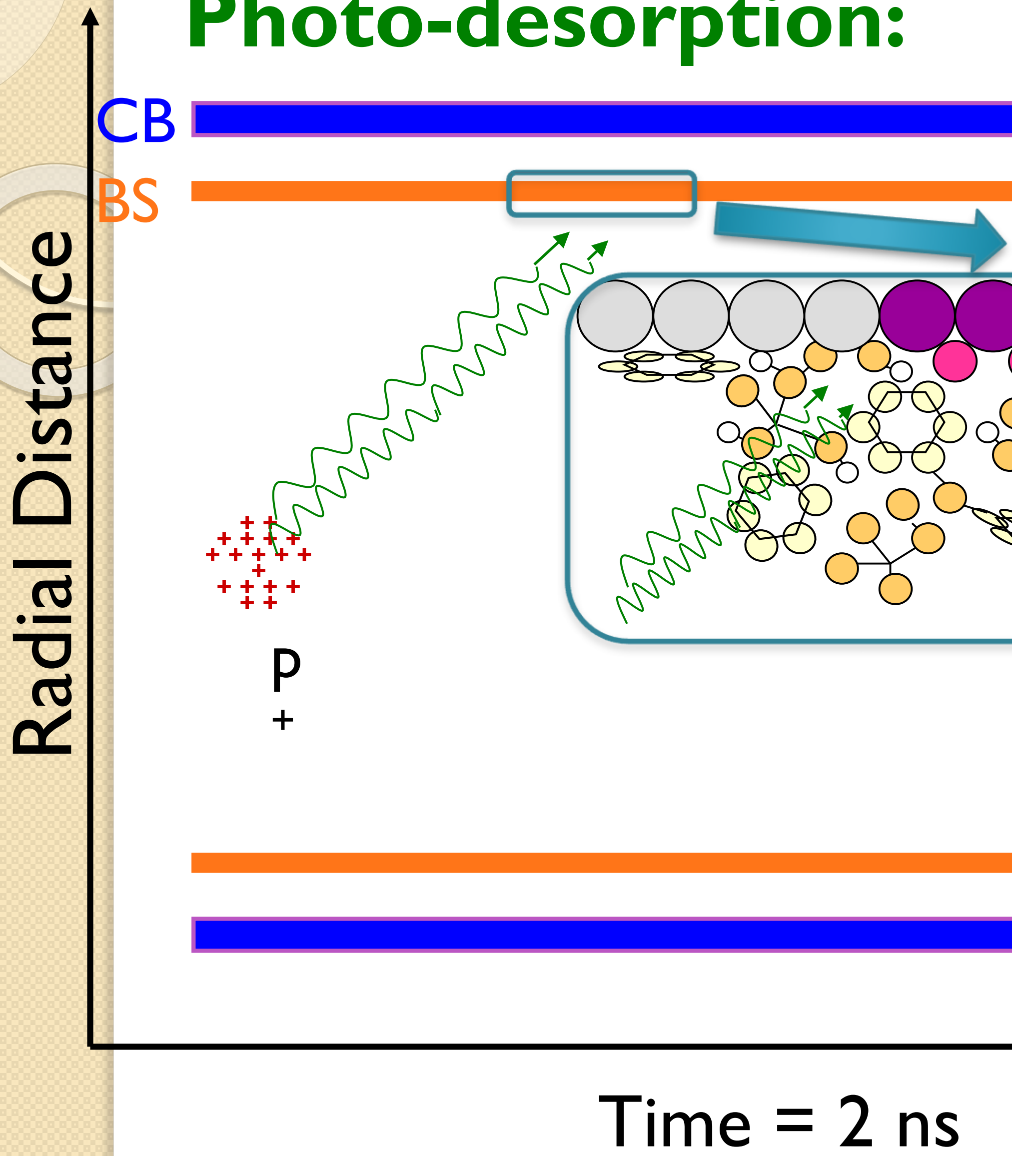
$$P_0 \propto \frac{E^4}{\rho^2} I \propto B^2 E^2 I$$

For LHC: P_{SR}= **0.17 W/m/apert.**

19

Photo-desorption:

SR & Surface Science



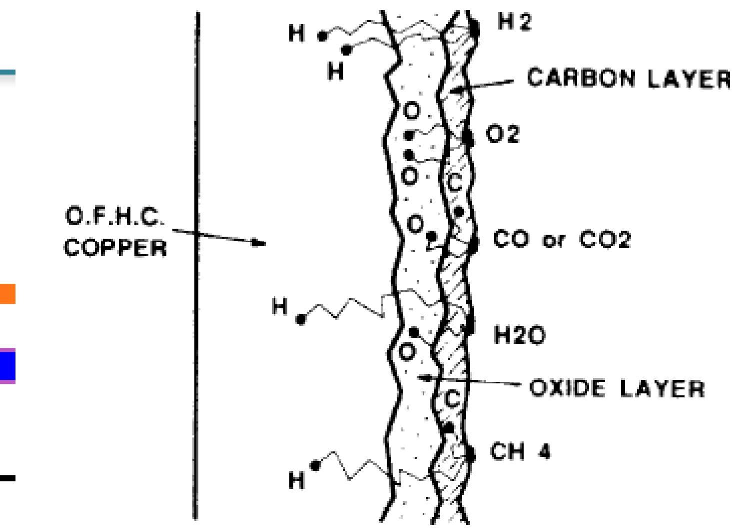


Fig. 6. Tentative Microscopic Model for PSD from OFHC Copper.

O. Gröbner *et. al.* EPAC 1992

Photo-desorption:

SR & Surface Science

CB

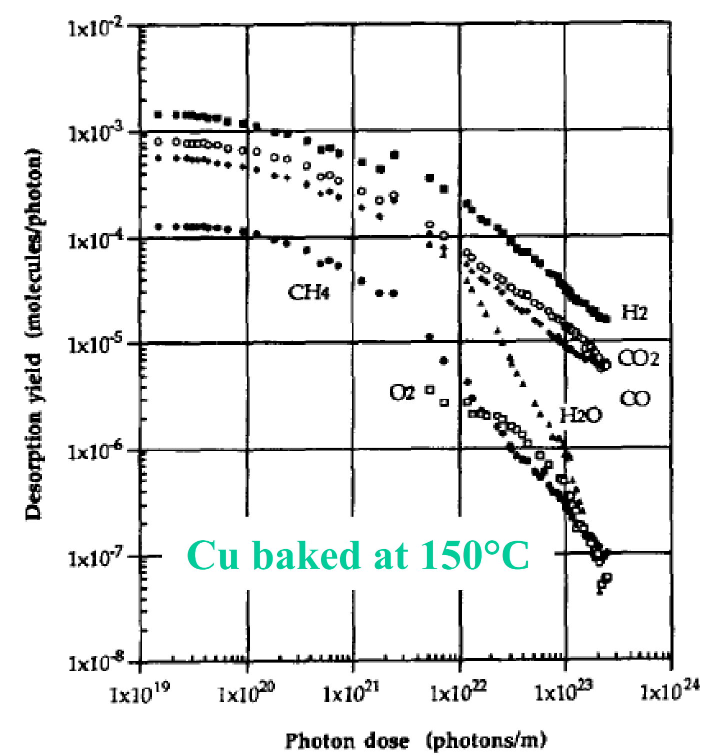
BS

Radial Distance

P+

- The dynamic pressure decrease by several orders of magnitude with photon dose: "photon conditioning"

- The photon desorption yield is characterised by η_{photon}



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

Time = 2 ns

See: talk from **O. Malyshev**

Photo-desorption at LT:

SR & Surface Science

Radial Distance

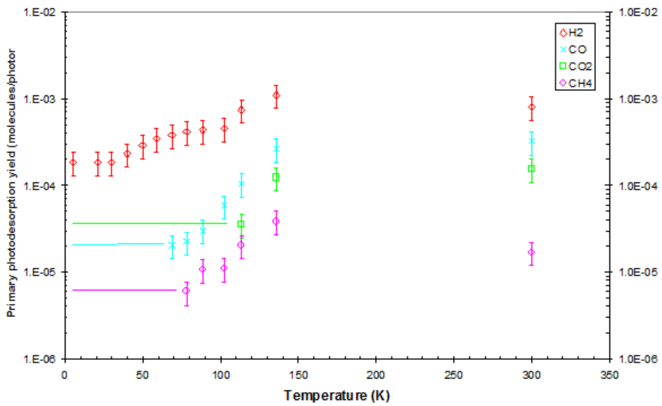
CB

BS

Initial yield, η_0, are smaller than at room temperature

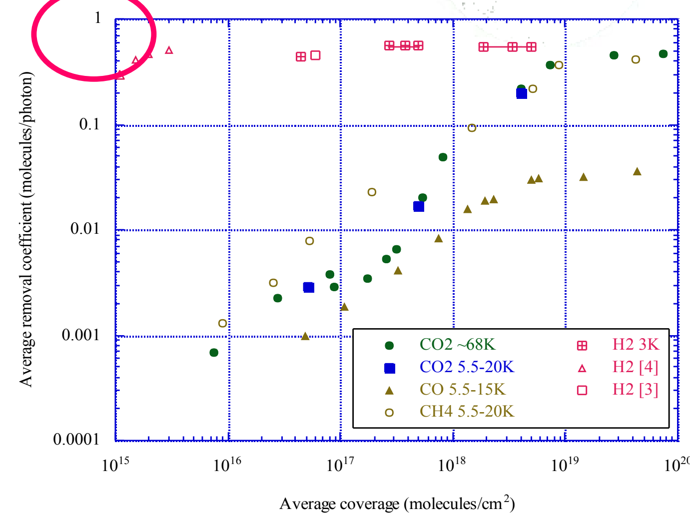
P

+



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

BUT at LT:
presence of physisorbed molecule

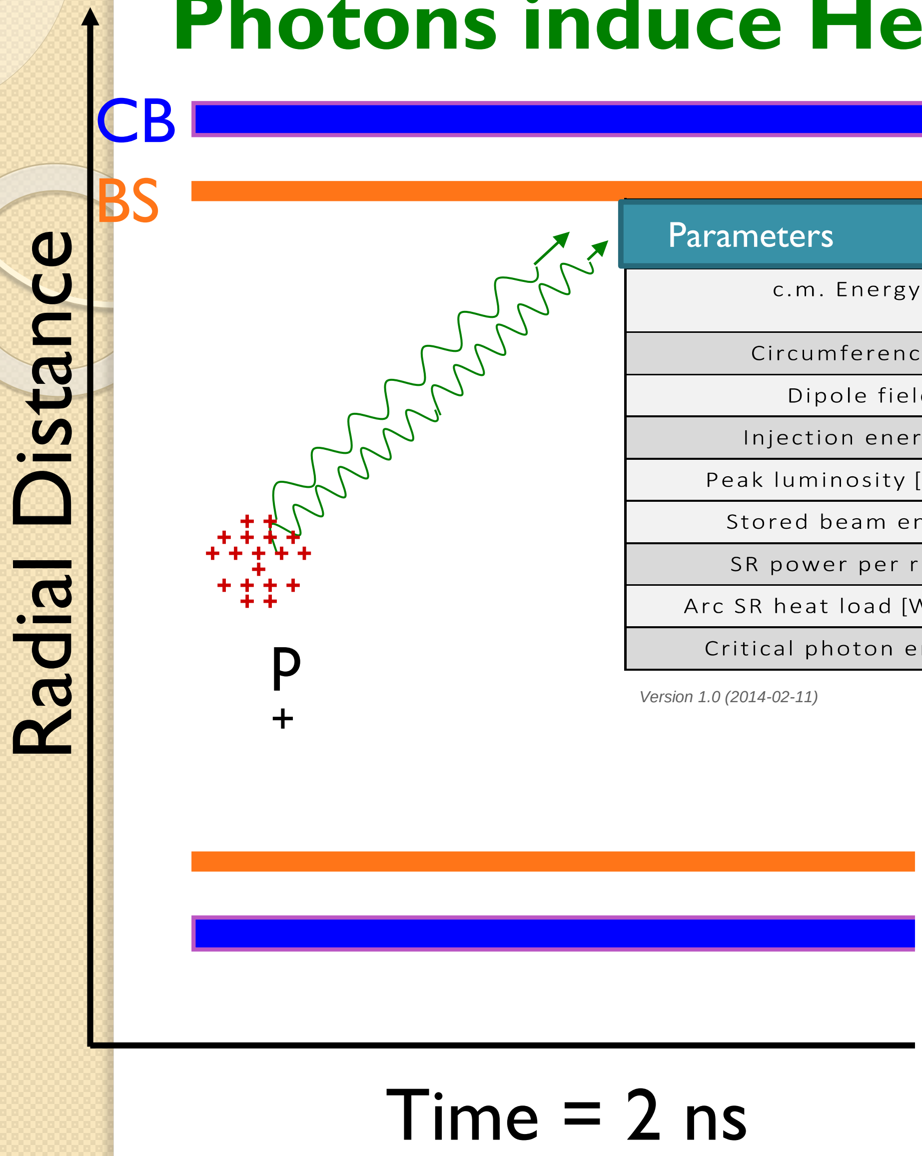


V. Anashin *et al.*, Vacuum 53 (1-2), 269, (1999)

Time = 2 ns

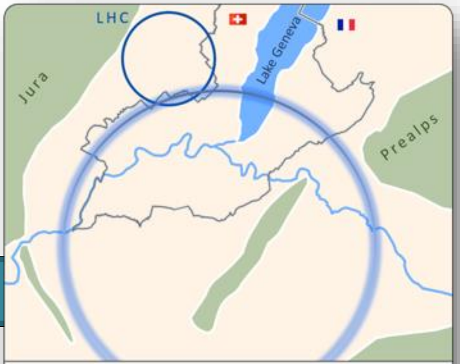
See: talk from **V. Baglin**

Photons induce Heat load:



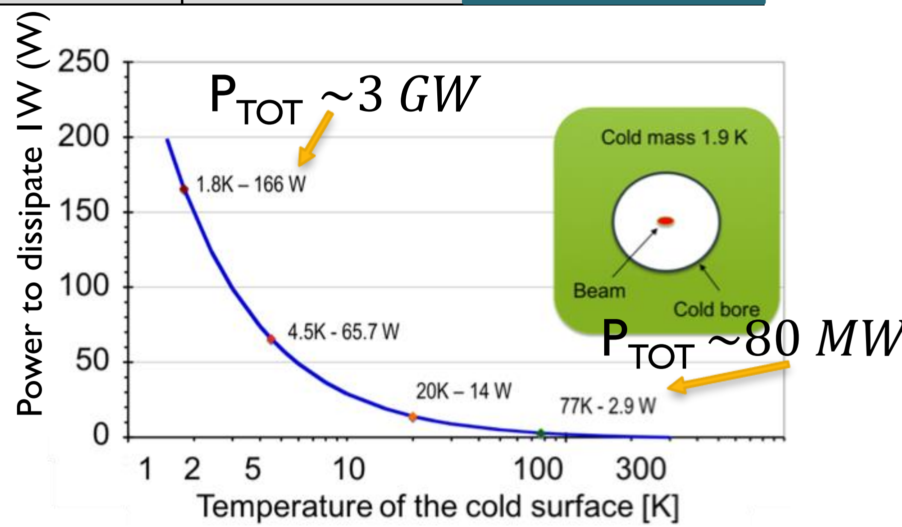
Parameters	LHC	H-L LHC	
c.m. Energy [TeV]	14		[illegible]
Circumference C [km]	26.7		[illegible]
Dipole field [T]	8.33		16 (20)
Injection energy [TeV]	0.45		[illegible]
Peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0
Stored beam energy [GJ]	0.392	0.694	8.4 (7.0)
SR power per ring [MW]	0.0036	0.0073	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	0.33	28.4 (44.3)
Critical photon energy [keV]	0.044		4.3 (5.5)

Version 1.0 (2014-02-11)



Schematic of an 80 – 100 km long tunnel

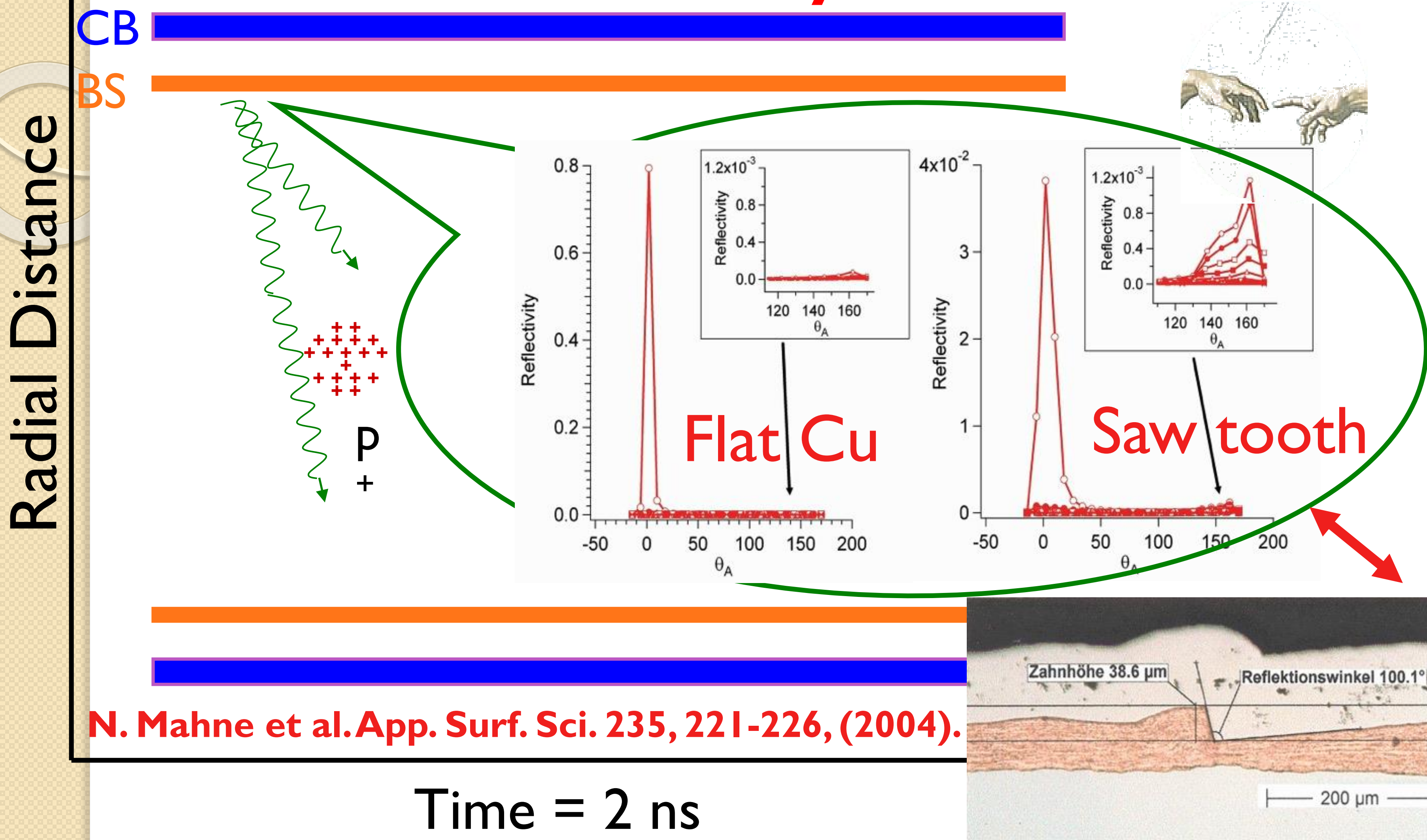
In FCC-hh



Credits: R. Kersevan -- Beam Dynamics meets Vacuum, Collimations, and Surfaces 2017

Photon reflectivity:

SR & Surface Science



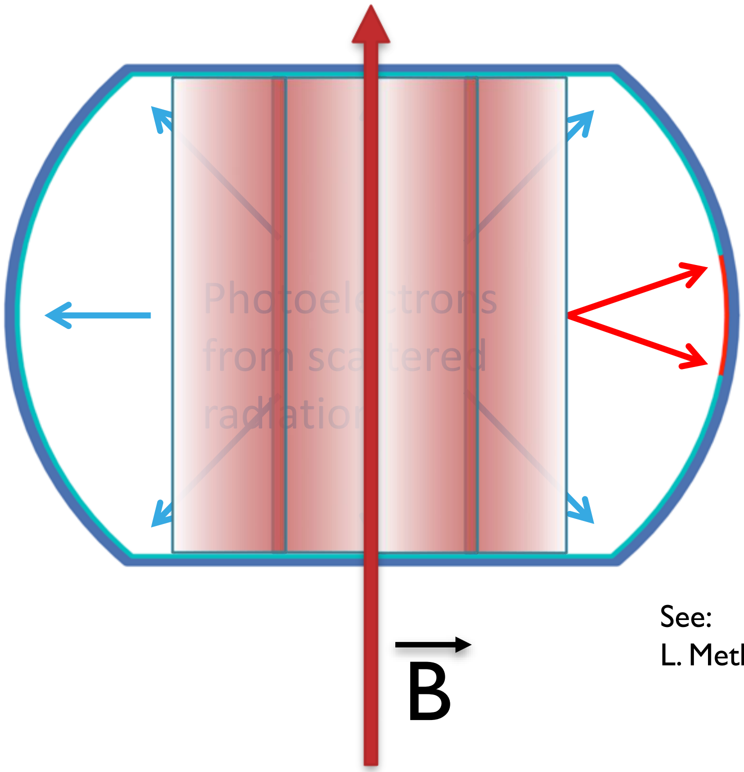
N. Mahne et al. App. Surf. Sci. 235, 221-226, (2004).

PS: reflected photons do NOT induce HL.
See: R. Cimino V. Baglin and F. Schäfers PRL 2015

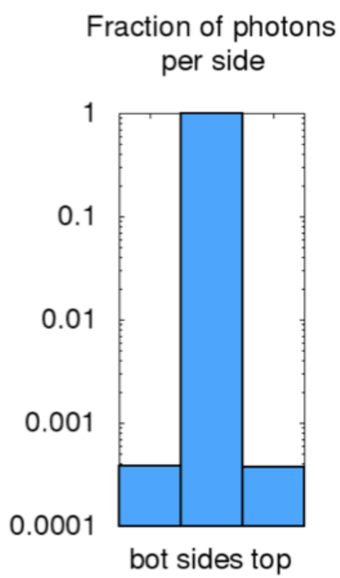
Photon reflectivity: where photons go?

In the dipoles we are in presence of a strong Magnetic field

Photoelectrons contributing to e-cloud build-up mainly from scattered photons



Photoelectrons from direct impacts



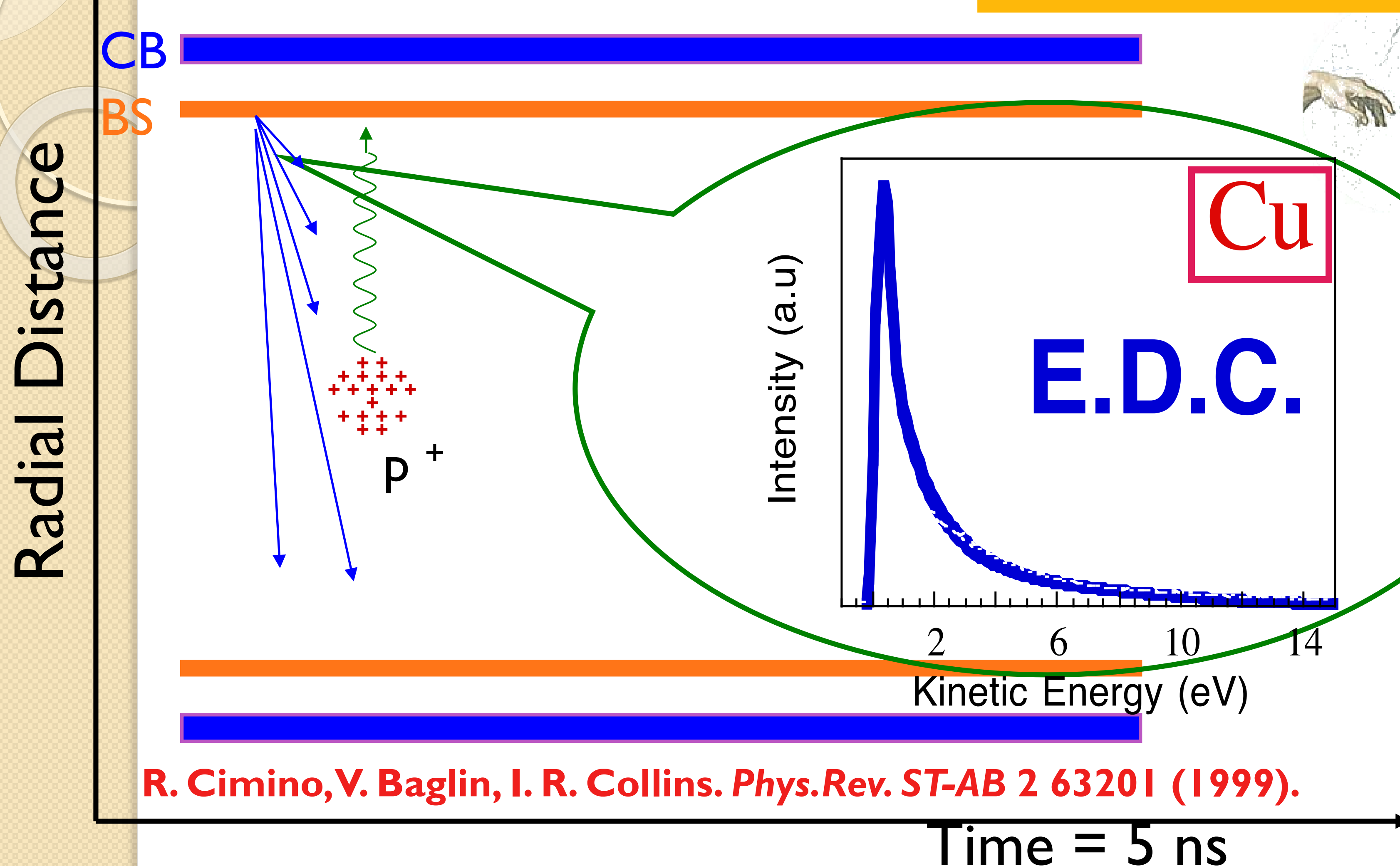
See:
L. Mether, et al. In FCC-Berlin 2017

Mainly electrons produced by photons absorbed on the top and bottom of beam screen can seed e-cloud build-up in dipoles and BS is optimized to reduce them.

PS: Reflected photons do NOT produce photoelectrons.
See: R. Cimino V. Baglin and F. Schäfers PRL 2015

Photoemission:(vs. hν, Q, E,T, B)

SR & Surface Science



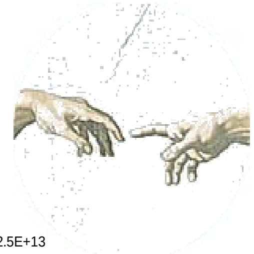
R. Cimino, V. Baglin, I. R. Collins. *Phys.Rev. ST-AB* 2 63201 (1999).

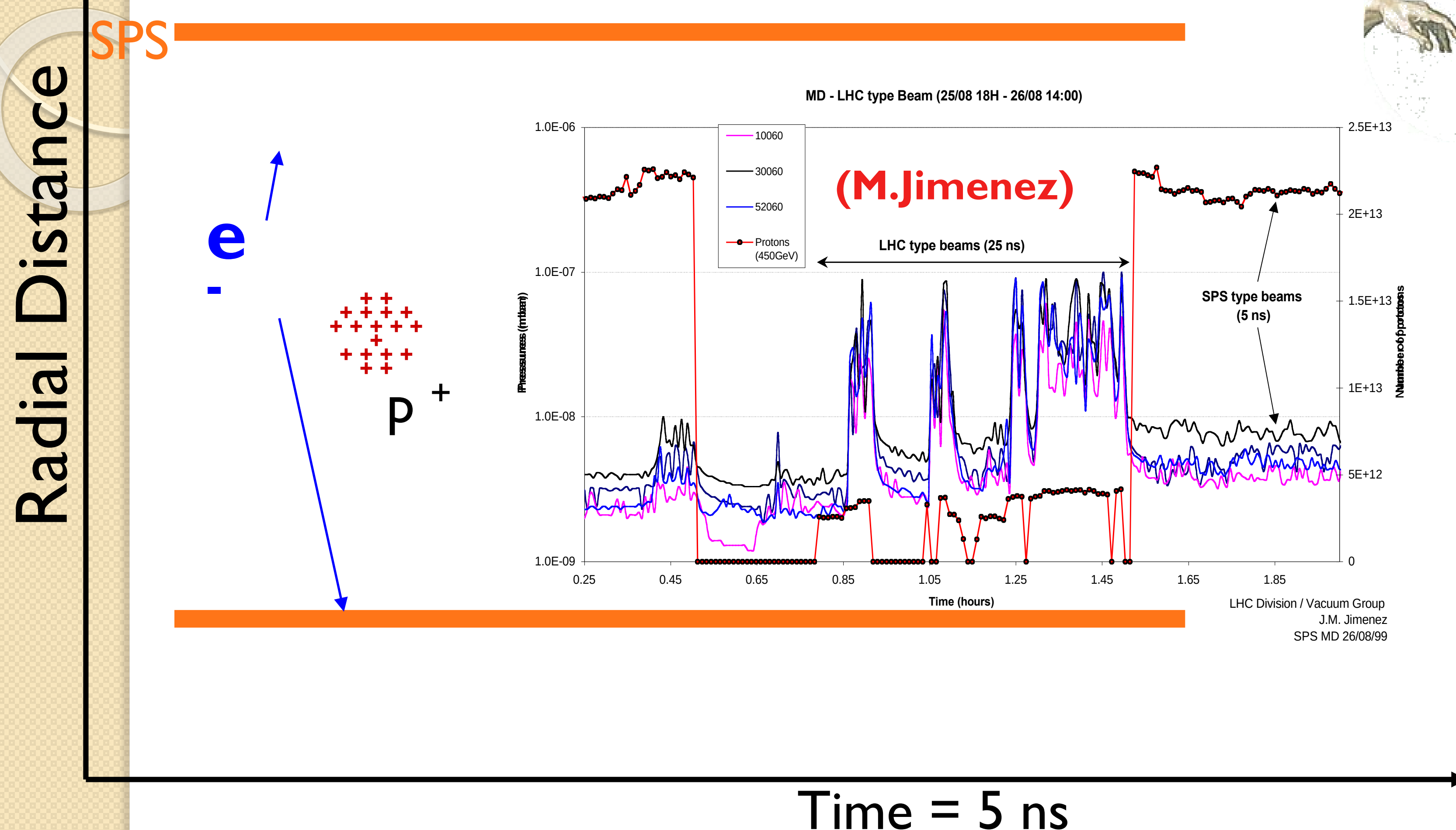
Produced e⁻ (PY): very important for single beam instabilities (K.Ohmi and F. Zimmermann PRL 2000)

Observation

Even in absence of SR:

e⁻ from ionization of residual gas… etc

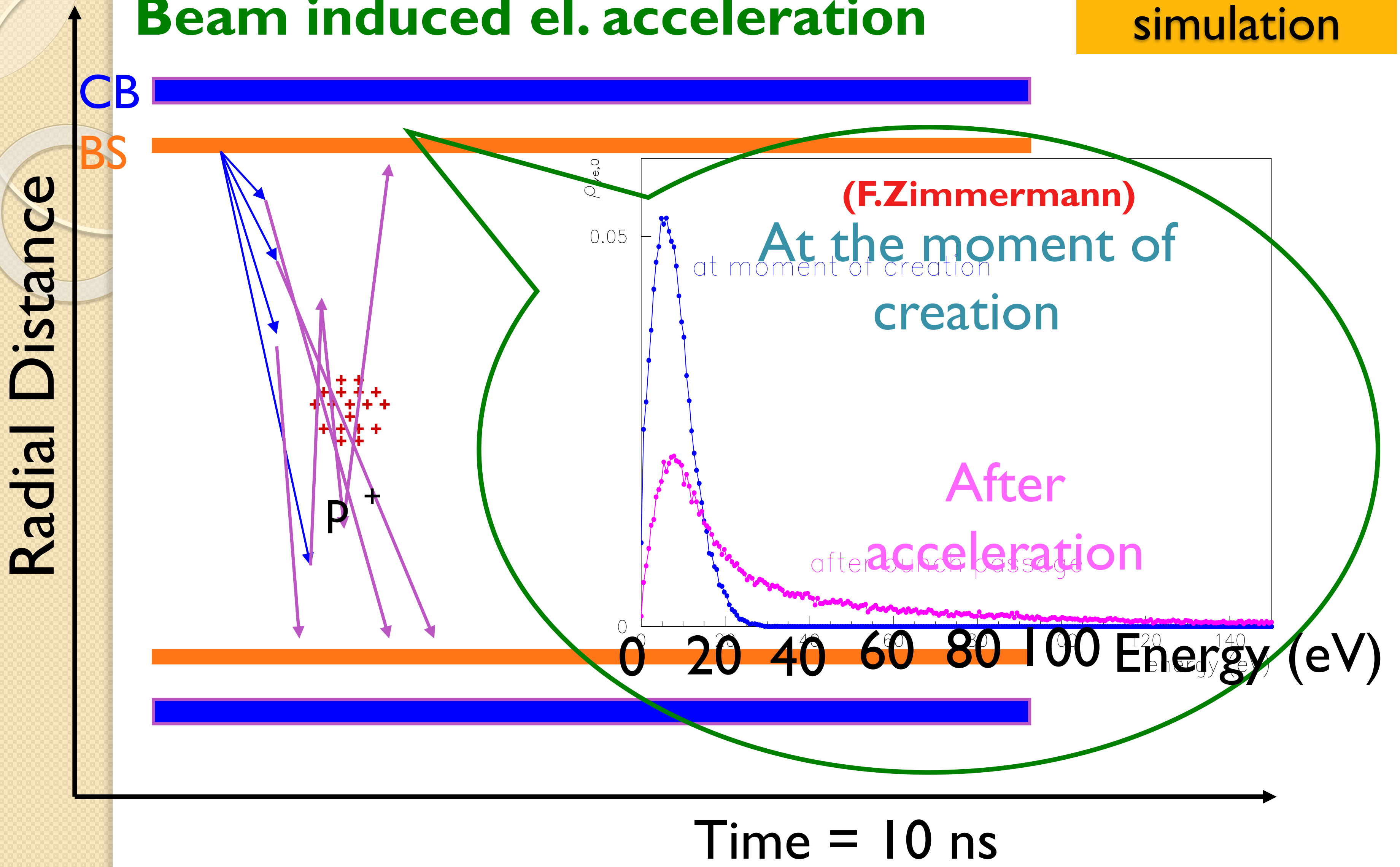




Beam induced multipacting is observed in SPS where no e⁻ are photoemitted.

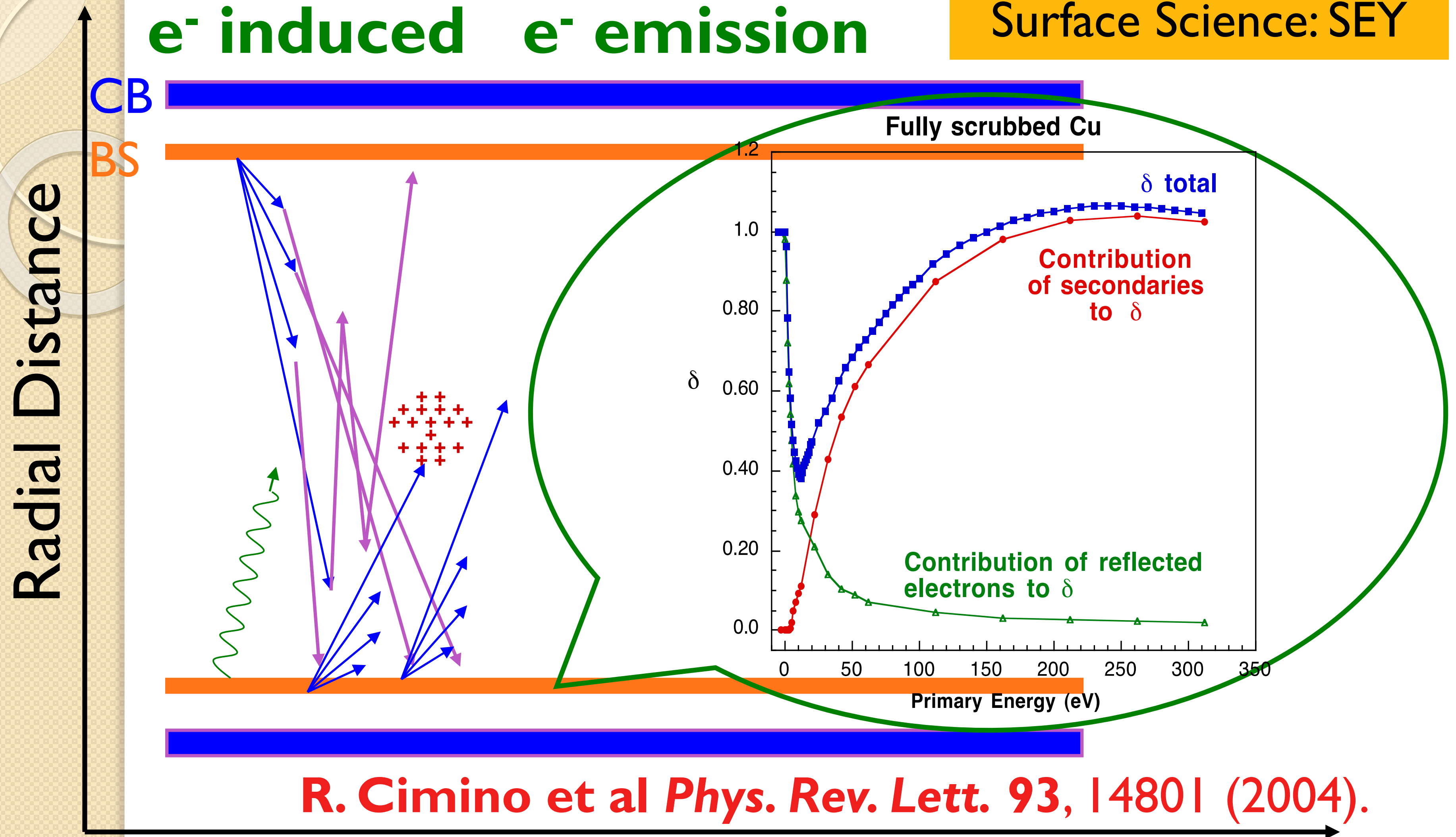
Beam induced el. acceleration

simulation



e^- induced e^- emission

Surface Science: SEY

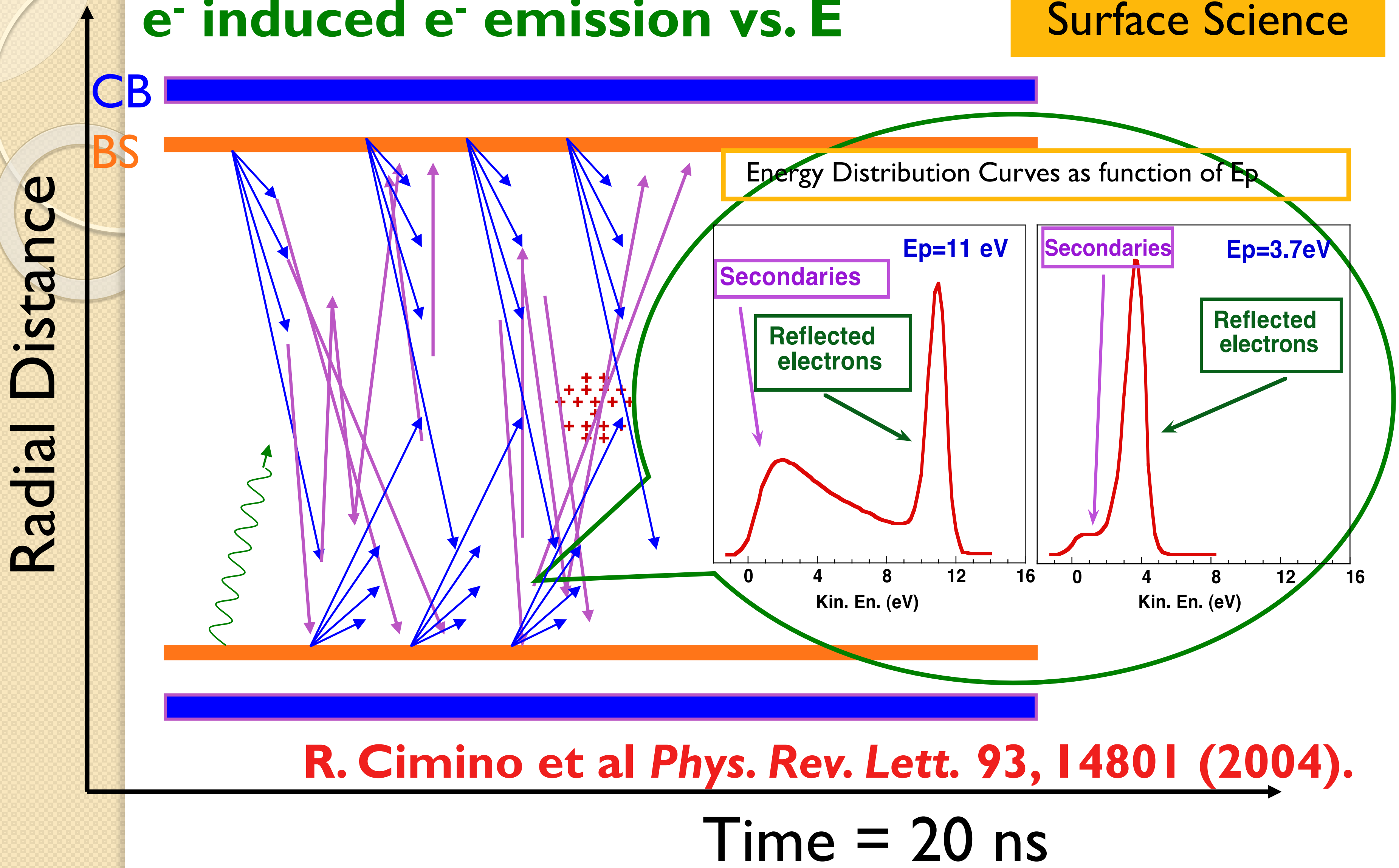


R. Cimino et al ***Phys. Rev. Lett.*** **93**, 14801 (2004).

Time = 15 ns

e⁻ induced e⁻ emission vs. E

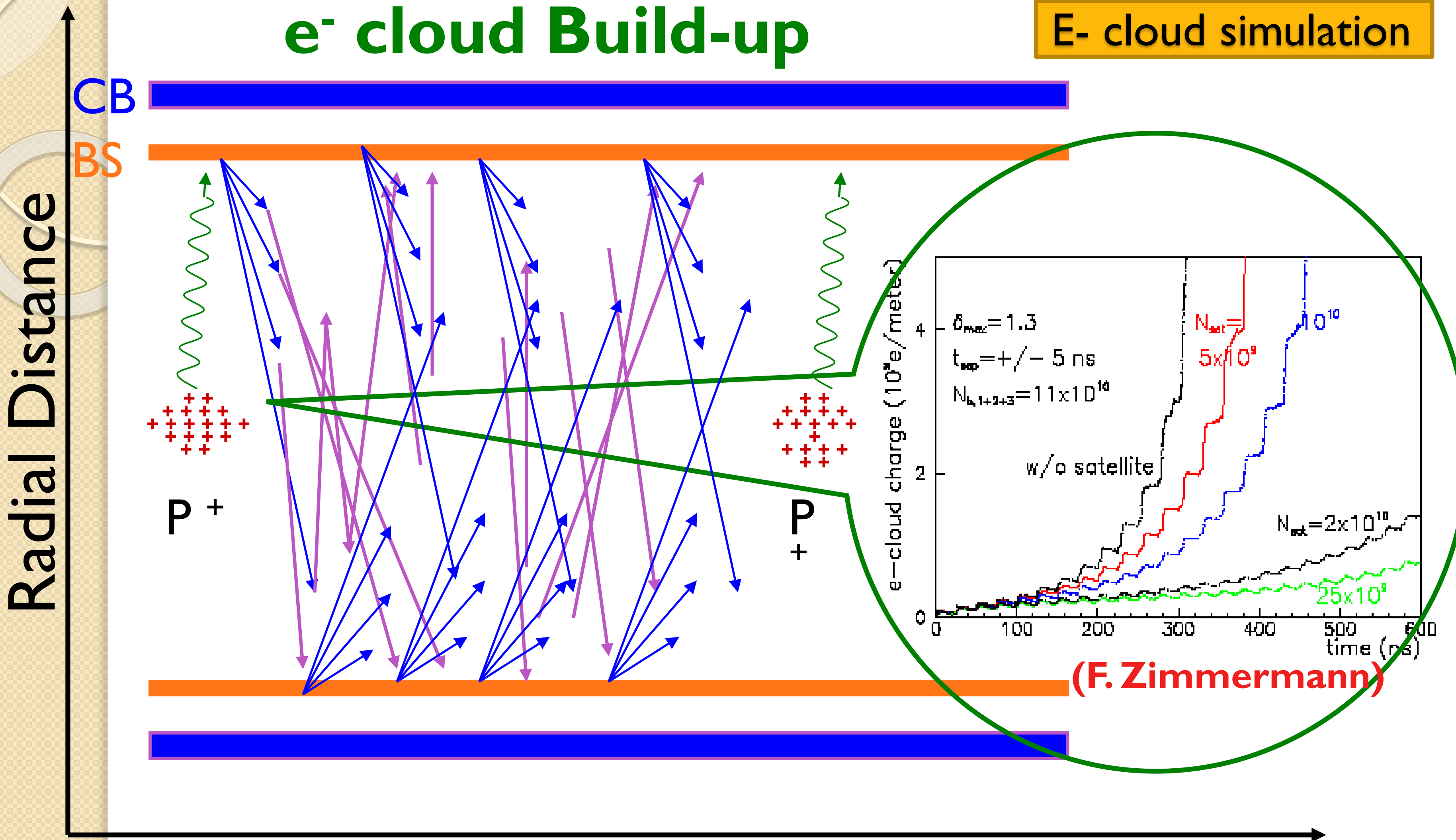
Surface Science



R. Cimino et al *Phys. Rev. Lett.* 93, 14801 (2004).

e^- cloud Build-up

E- cloud simulation

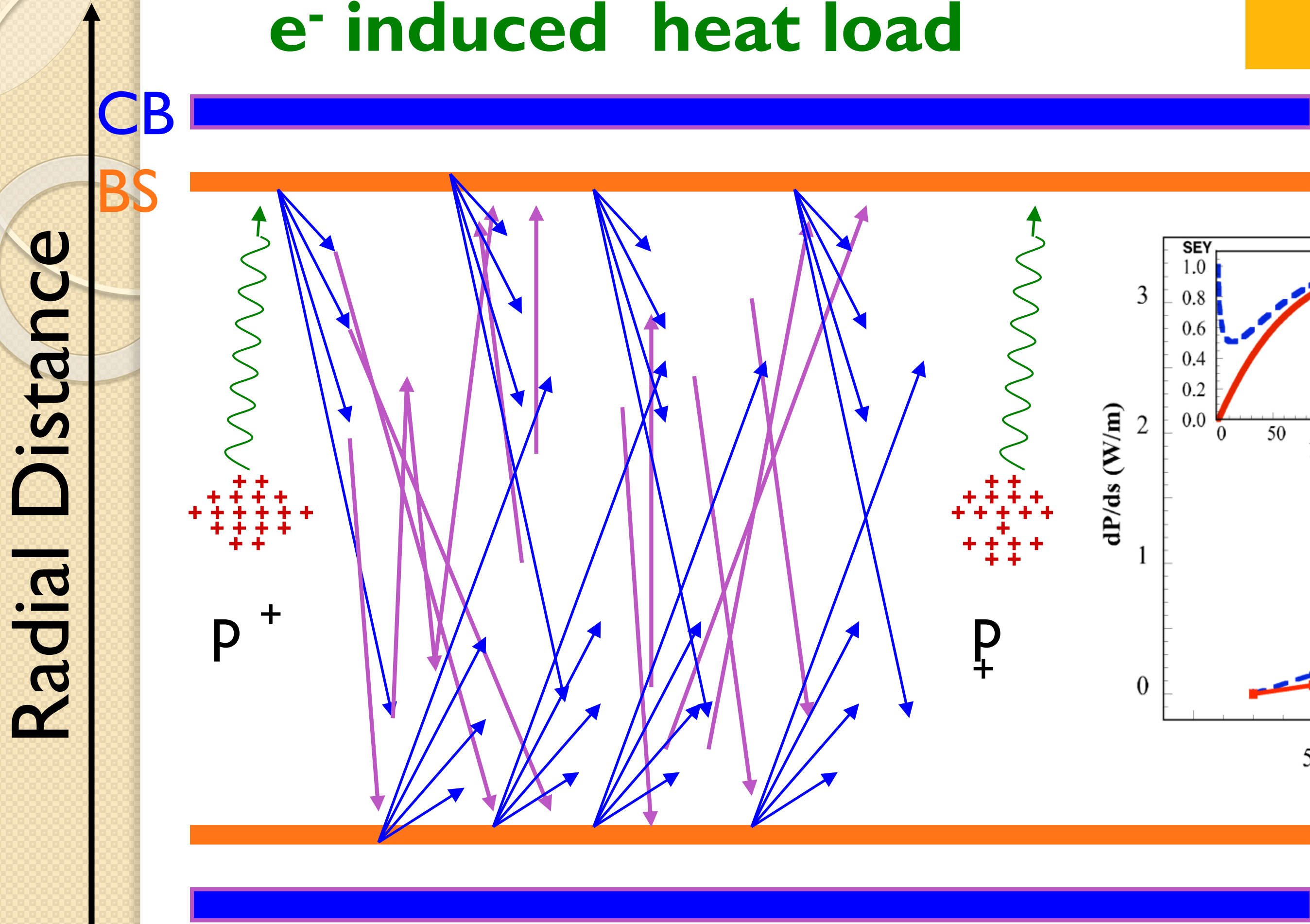


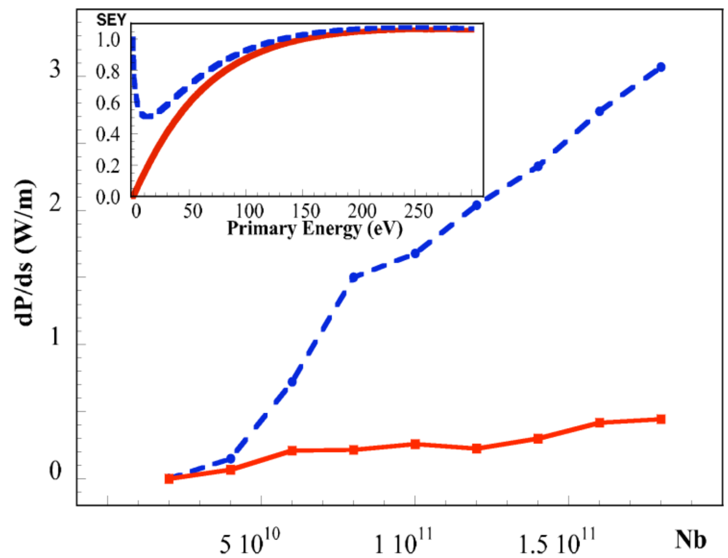
Time = 25 ns

Time structure vs. Simulations.

e^- induced heat load

Simulation





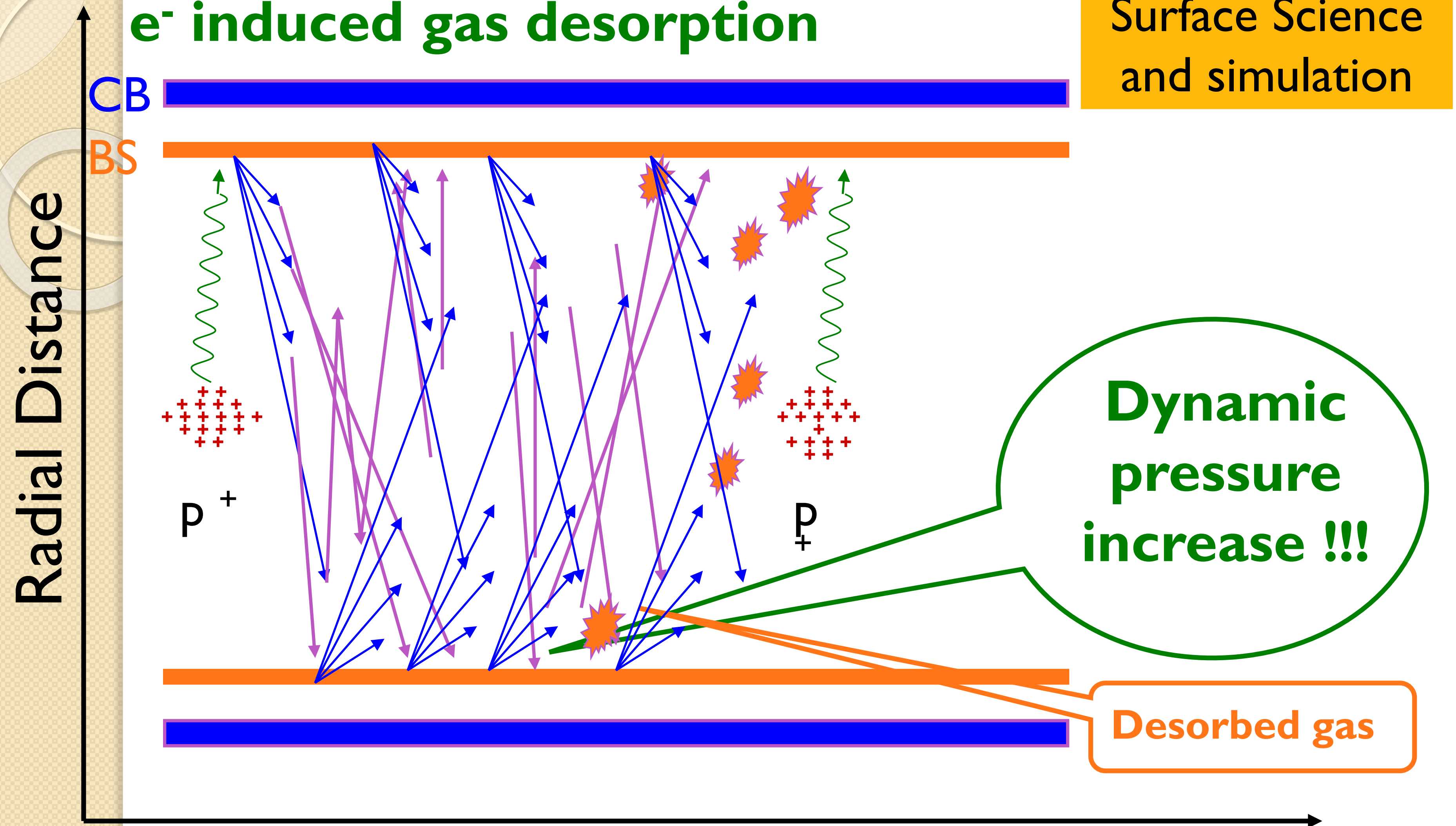
R. Cimino et al *Phys. Rev. Lett.* 93, 14801 (2004).

Time = 25 ns

e^-cloud build up causes Heat load!

e^- induced gas desorption

Surface Science and simulation

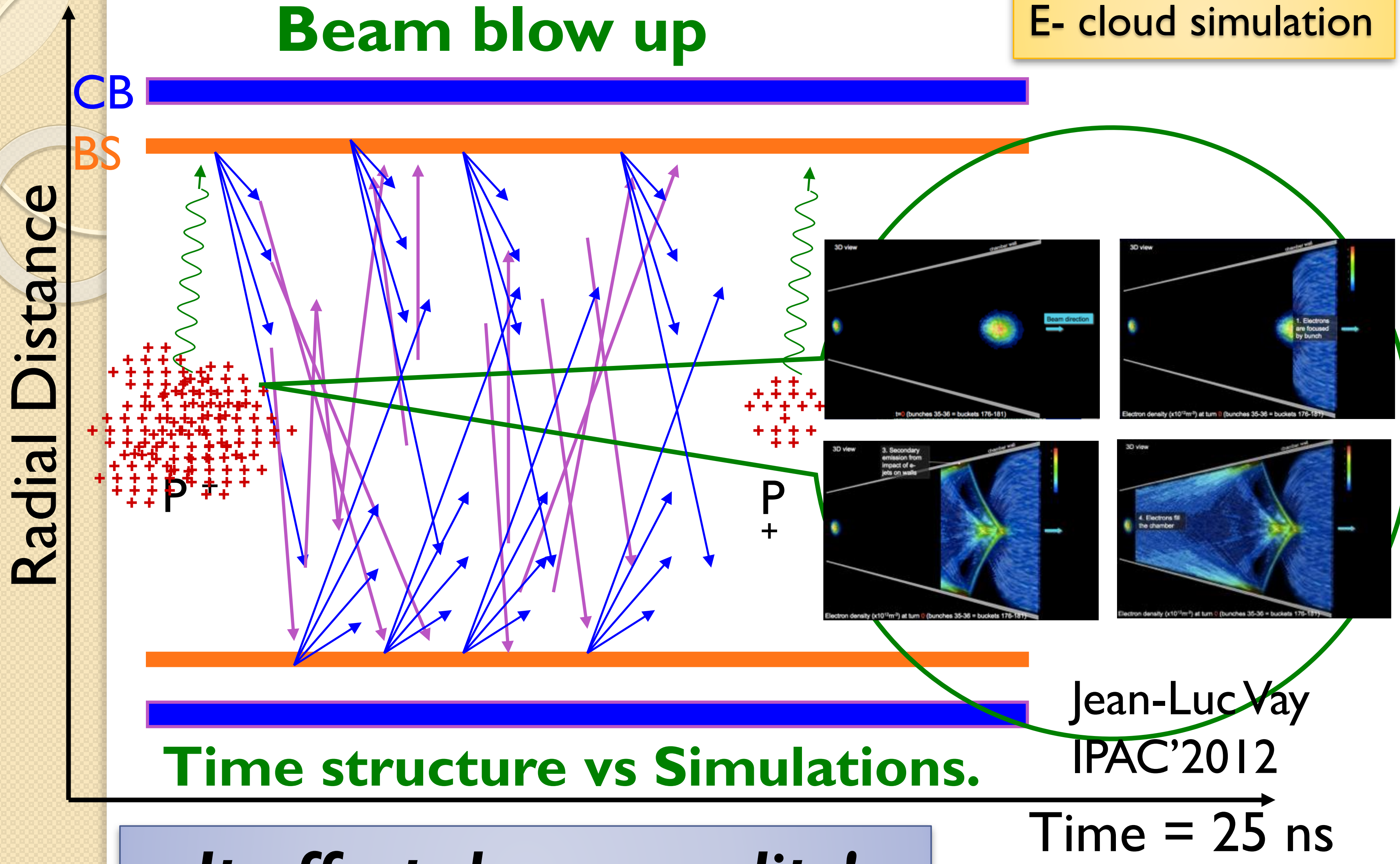


See: talk from **O. Malyshev**

It is a beam/Vacuum issue!

Beam blow up

E- cloud simulation



Jean-Luc Vay IPAC'2012

Time structure vs Simulations.

It affects beam quality!

Electron cloud in accelerators

- Phenomenology:

What happens to the Vacuum beam pipe in presence of the beam? (LHC Example)

- Numerical model

- The Surface Science properties of relevance:

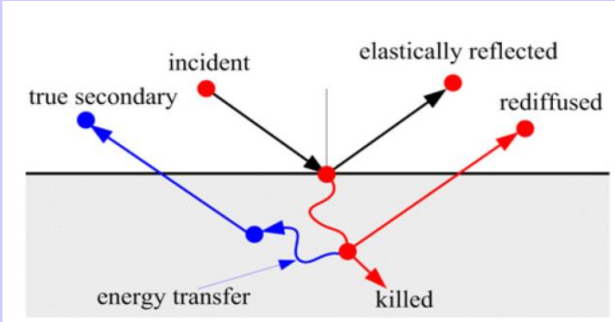
✓ SEY (Secondary Electron Yield);
✓ PY (Photo Yield);
✓ R (photon Reflectivity)

- Mitigation strategies

- Conclusion

R. Cimino and T. Demma
"Electron cloud in Accelerators"
Int. J. Mod. Phys. A 29 (2014) 1430023 (pag. 65).

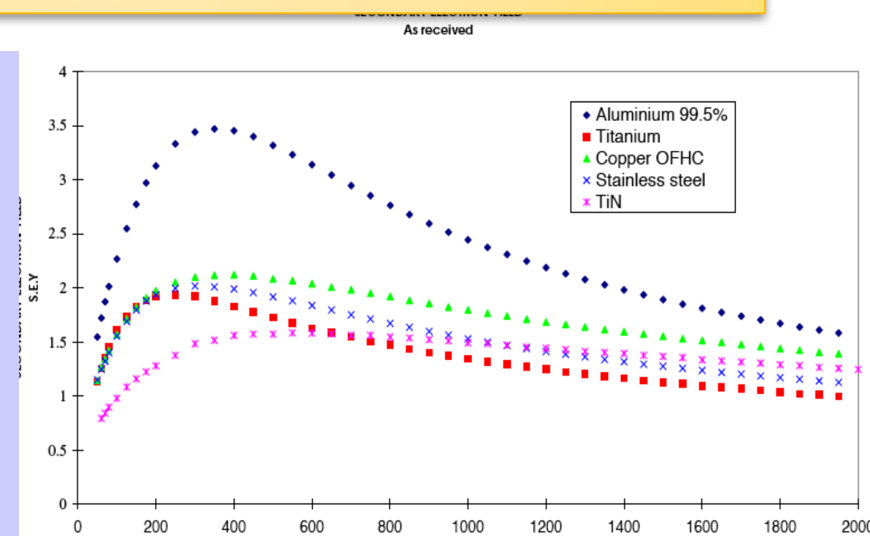
Secondary Electron Yield (SEY)



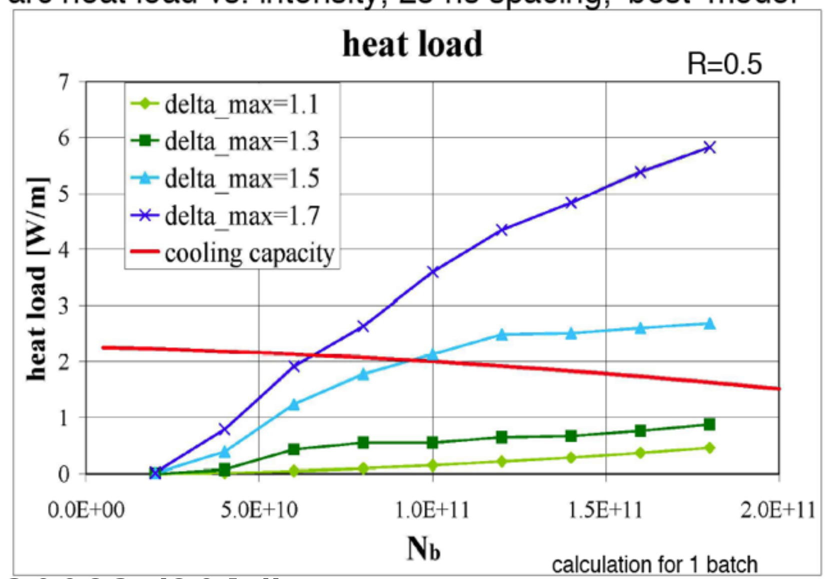
secondary electron emission

three-step process:

- production of SEs at a depth z
- transport of the SE toward the surface
- emission of SE across the surface barrier



arc heat load vs. intensity, 25 ns spacing, 'best' model



heat load for quadrupoles higher in 2nd batch; still to be clarified

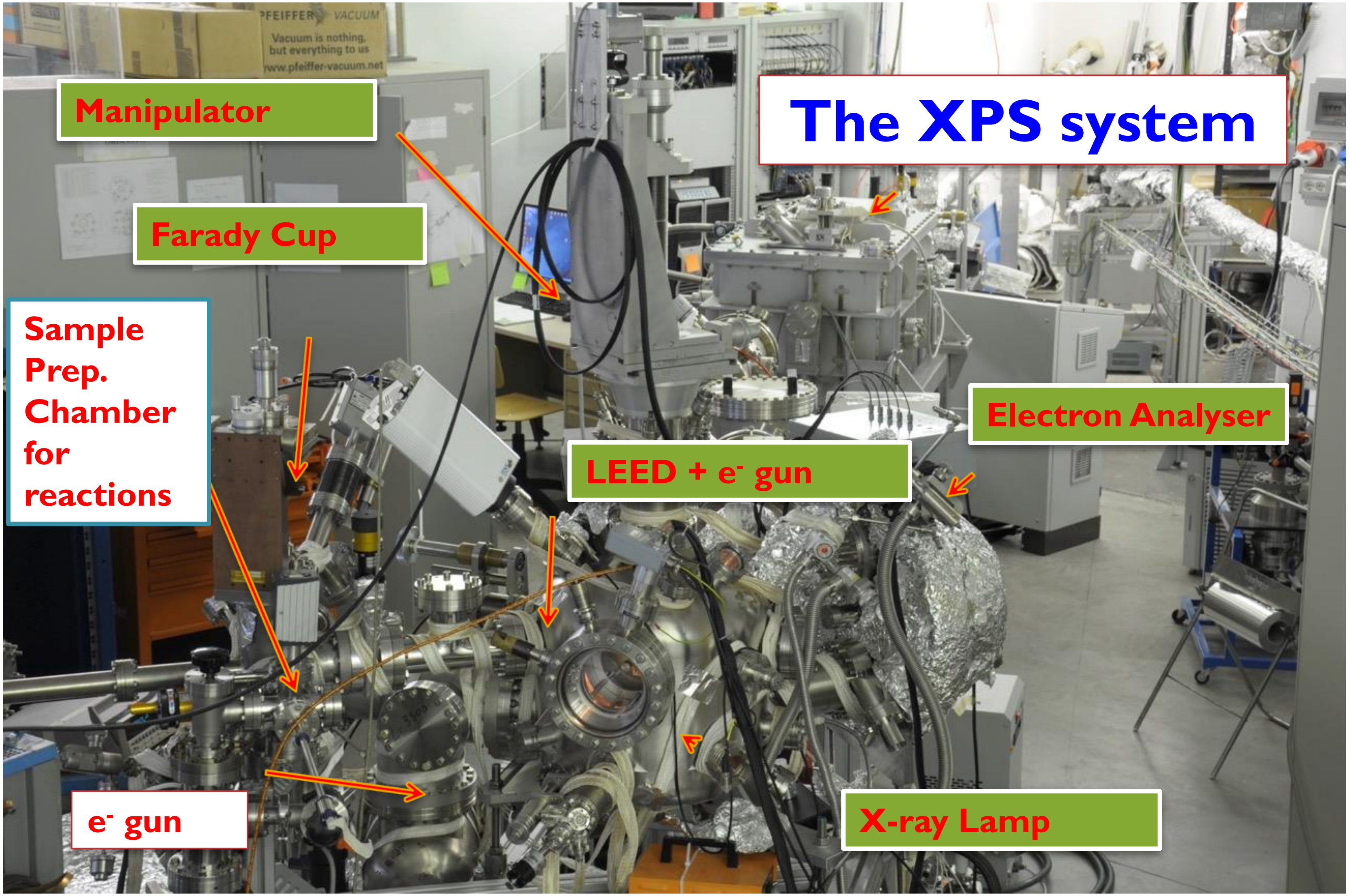
Frank Zimmermann, LTC 06.04.05

It depend on the surface type and condition: has a big impact to simulations (see calculation for LHC).

See: R. Cimino and T. Demma, "Electron cloud in Accelerators" Int. Jou. of Modern Physics A Vol. 29, 1430023 (2014).

Addendum

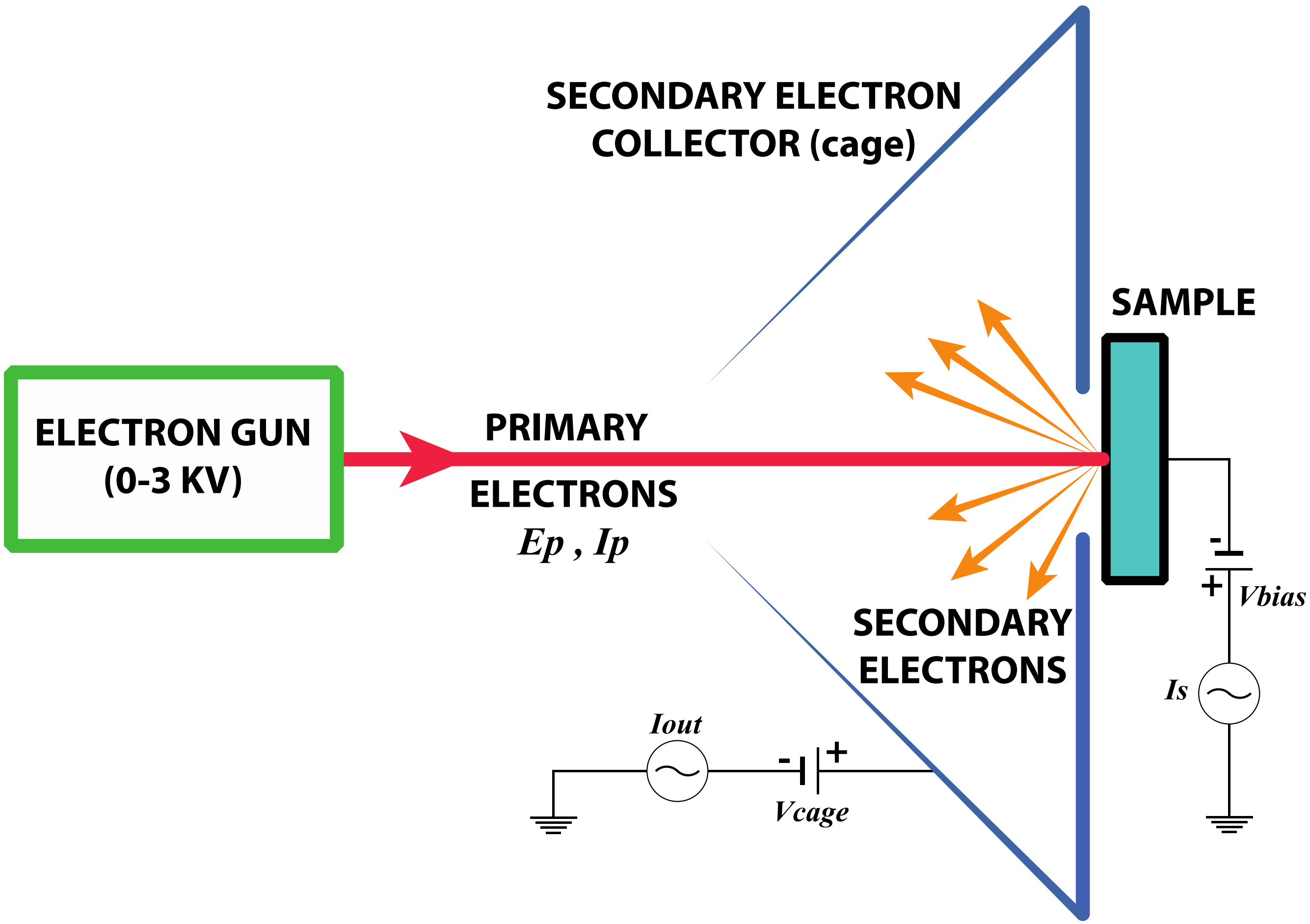
Need of "state of the art" Surface Science systems to study SEY



Addendum

Measure of Secondary e⁻ Yield: 2 methods

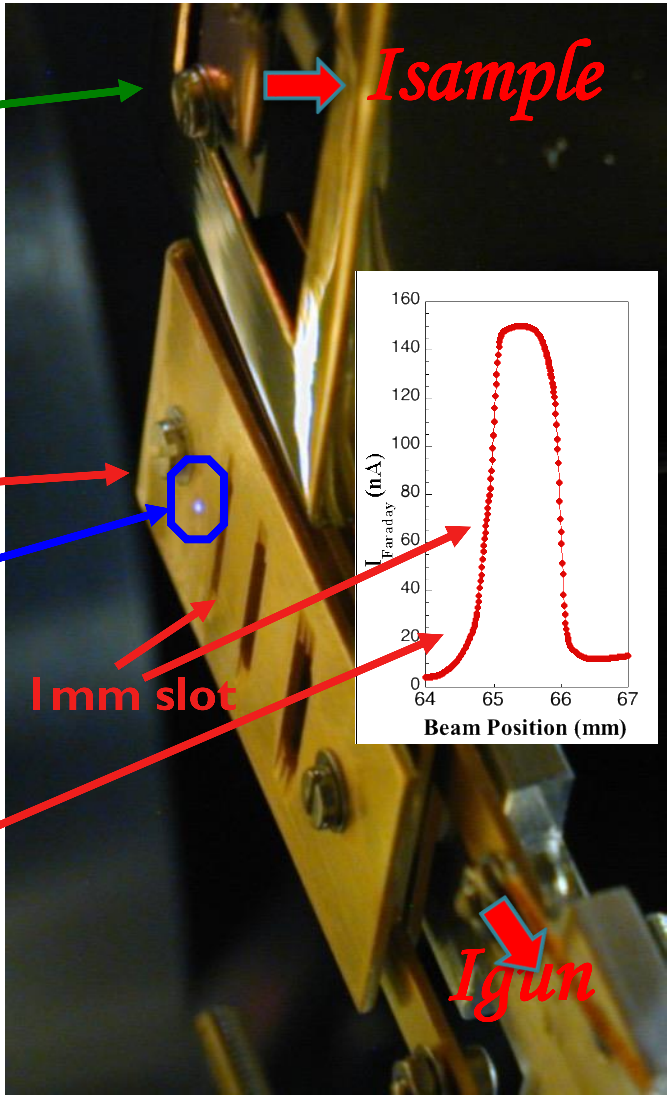
$$SEY = \delta = \frac{I_{out}}{I_{in}} = \frac{I_{gun} - I_{sample}}{I_{gun}}$$



Addendum

2^{nd} method: Measure of Secondary e^- Yield

- In a μ-metal chamber
- sample manipulator (also at Low T)
- Sample well insulated (to measure small current I_s)
- A **Faraday cup**
- A Low energy electron gun



- **e^- beam Stable between 30 - 500 eV**
- **Currents from few nA to μA (20μC/h/mm² - 20mC/h/mm²)**
- **Intense spot (ϕ < 0.5 mm) with low background**

$$SEY = \delta = \frac{I_{out}}{I_{in}} = \frac{I_{gun} - I_{sample}}{I_{gun}}$$

Addendum

Measure of Secondary e^- Yield: 2 methods

$$SEY = \delta = \frac{I_{out}}{I_{in}} = \frac{I_{gun} - I_{sample}}{I_{gun}}$$

I_{out} and I_{in} (N. Hilleret)

Advantages:

- Simultaneously measure δ at each energy: very fast.
- Effective also for "dispersive samples" (i.e. Sponges)

Disadvantages

- Gun far from the sample (difficult to control LE e^-)
- Big(er) spot and no LE-SEY
- Loose Normal emitted e^-

I_{Sample} and I_{in}

Advantages:

- Gun close to sample.
- Reduce noise for low current measurements (i.e. insulators)
- LE-SEY accessible!?!

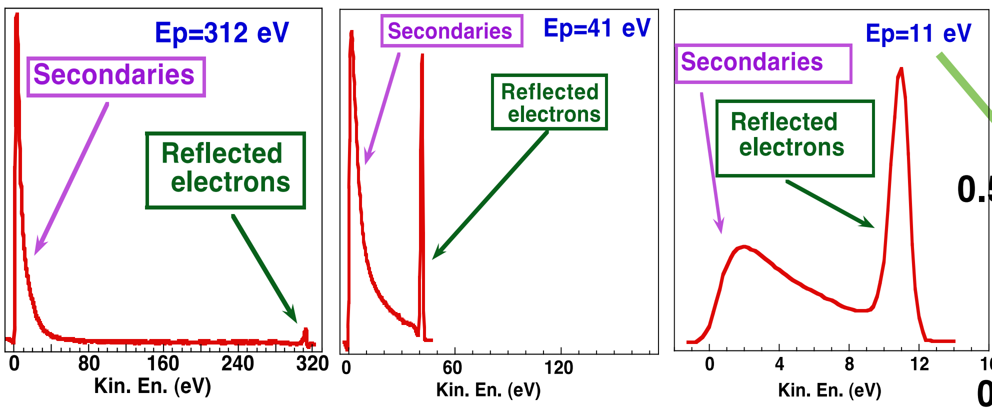
Disadvantages

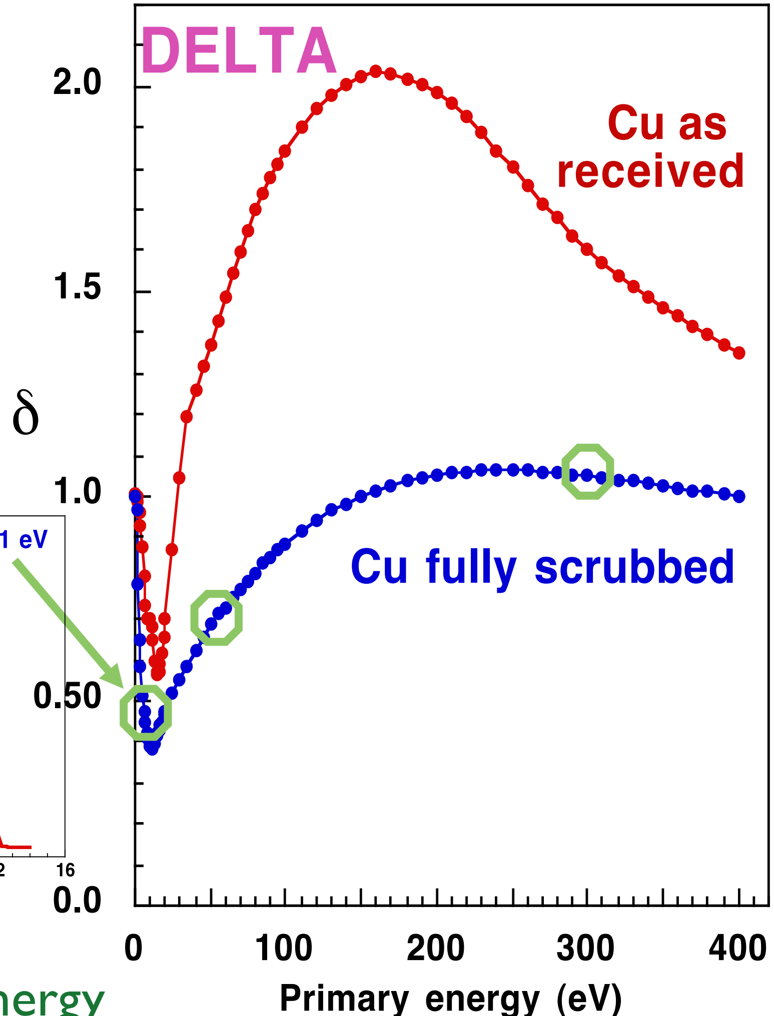
- Gun need to be very stable (takes time)
- More work (2 separate runs)

Measure of Secondary e$^-$ Yield

$$SEY = \delta = \frac{Igun - Isample}{Igun}$$

At each Primary energy we measure **Igun** **(with the Faraday cup)** and **Isample.**





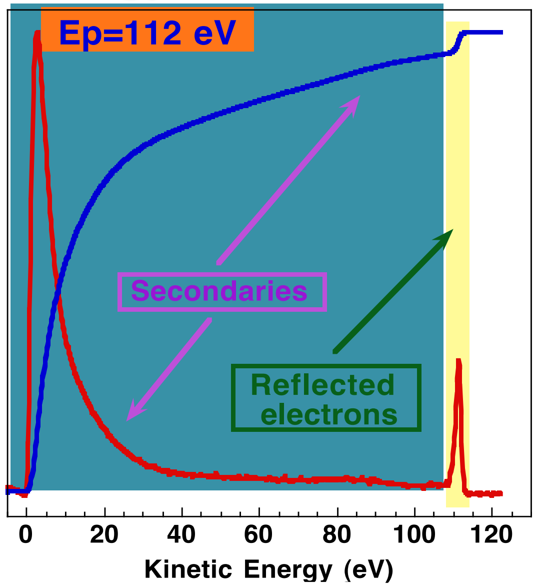
- Each point in δ is the integral of the energy distribution of the emitted electrons

R. Cimino et al. ***Phys. Rev. Lett.*** **93, 14801 (2004).**

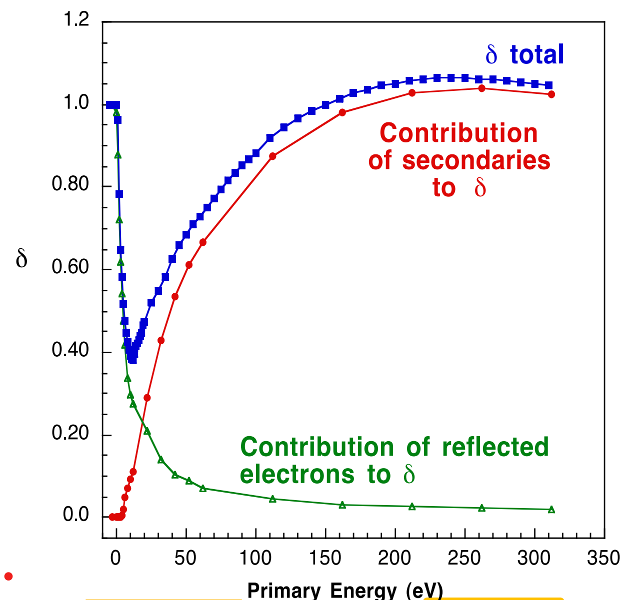
SEY of LHC Cu @ Low energy

Integrating the curves gives the Percentage of Secondaries and Reflected electrons

To separate "true secondaries from "re-diffused electrons is arbitrary and has not been considered in this analysis.



We observe that the contribution to □□ of the reflected electrons at very low primary energy is, in this material, very high.

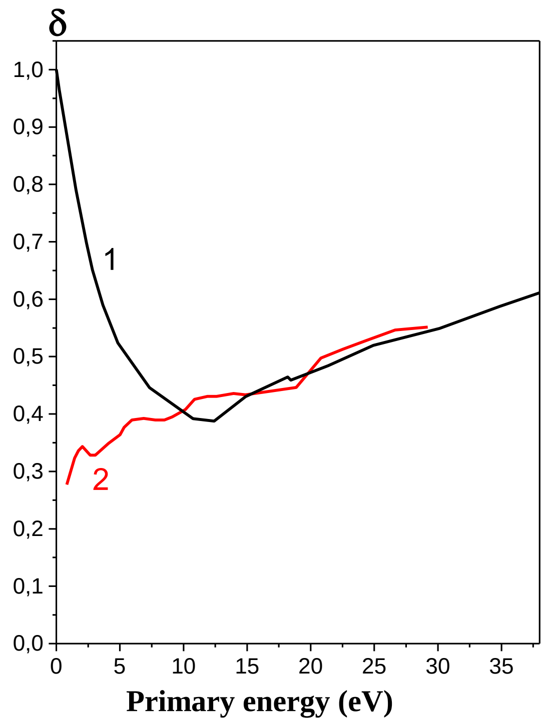


R. Cimino et al. *Phys. Rev. Lett.* 93, 14801 (2004).

Addendum

Such Low energy part of SEY was, up to recently, somehow controversial.

Total secondary electron yield of Cu as a function of incident electron energy. 1. from the letter for fully scrubbed Cu (T=10 K). 2. Experimental data for bulk Cu after heating in vacuum (room temperature).



From: A. N. Andronov, A. S. Smirnov, I. D. Kaganovich, E. A. Startsev, Y. Raitses, and V. I. Demidov, (in Proceedings of ECLOUD'12 (2013), CERN-2013-002, p. 161)

1. R. Cimino, et al, Phys. Rev. Lett. **93**, 014801 (2004).
2. I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 408 (1969).

Other measurements reported the reflection coefficient of about 7% for incident electron energy below few electron volts for most pure metals.

I.H. Khan, J. P. Hobson, and R.A. Armstrong, Phys. Rev. 129, 1513 (1963).

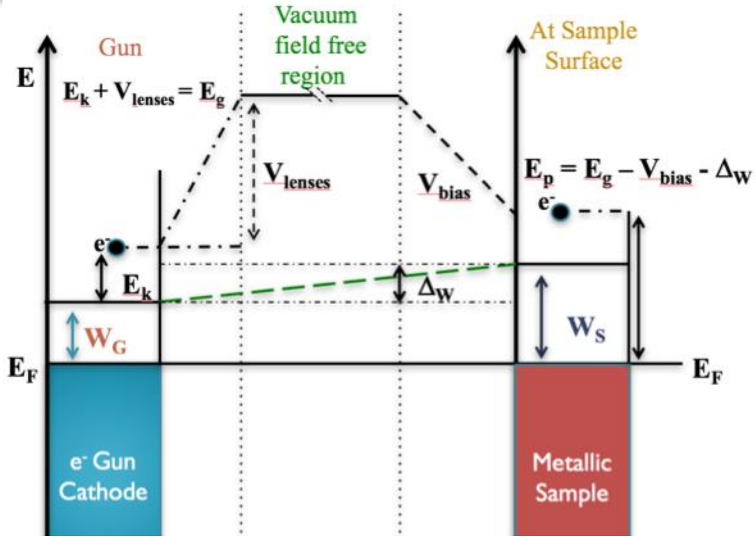
H. Heil, Phys. Rev. **164**, 887, (1967).

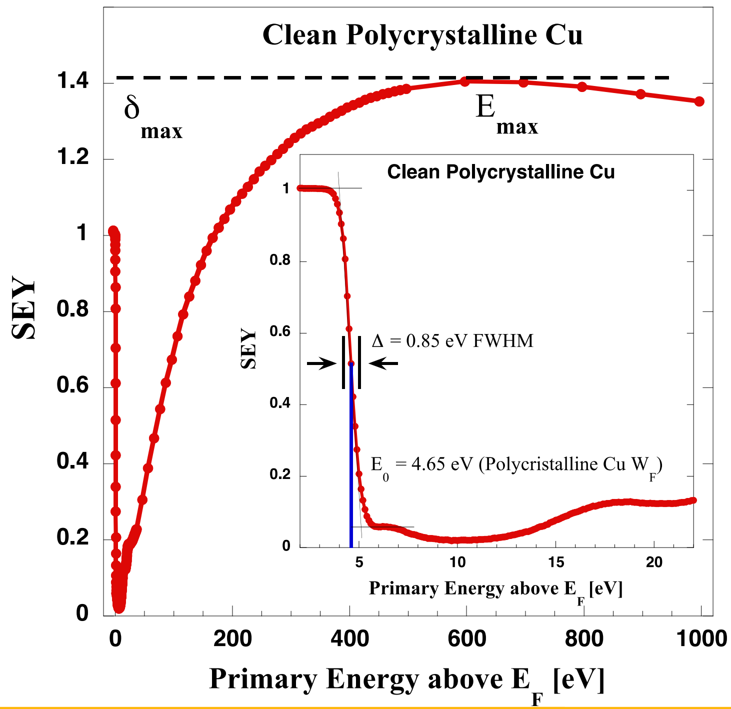
Z. Yakubova and N.A. Gorbatyi, Russian Physics Journal, 13 1477 (1970).

See: R. Cimino et al. PR ST 18, 051002 (2015)

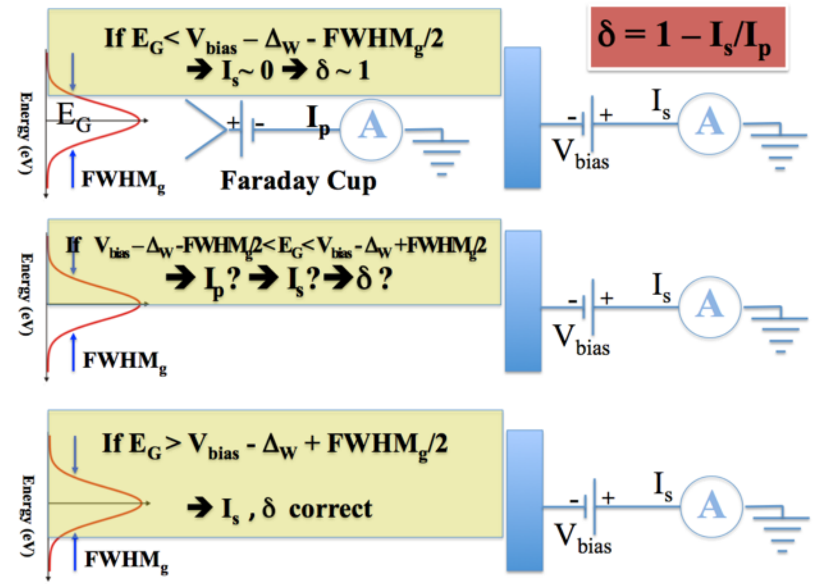
Addendum

Setting the energy scale.





Expected Setup limitations at Low energy

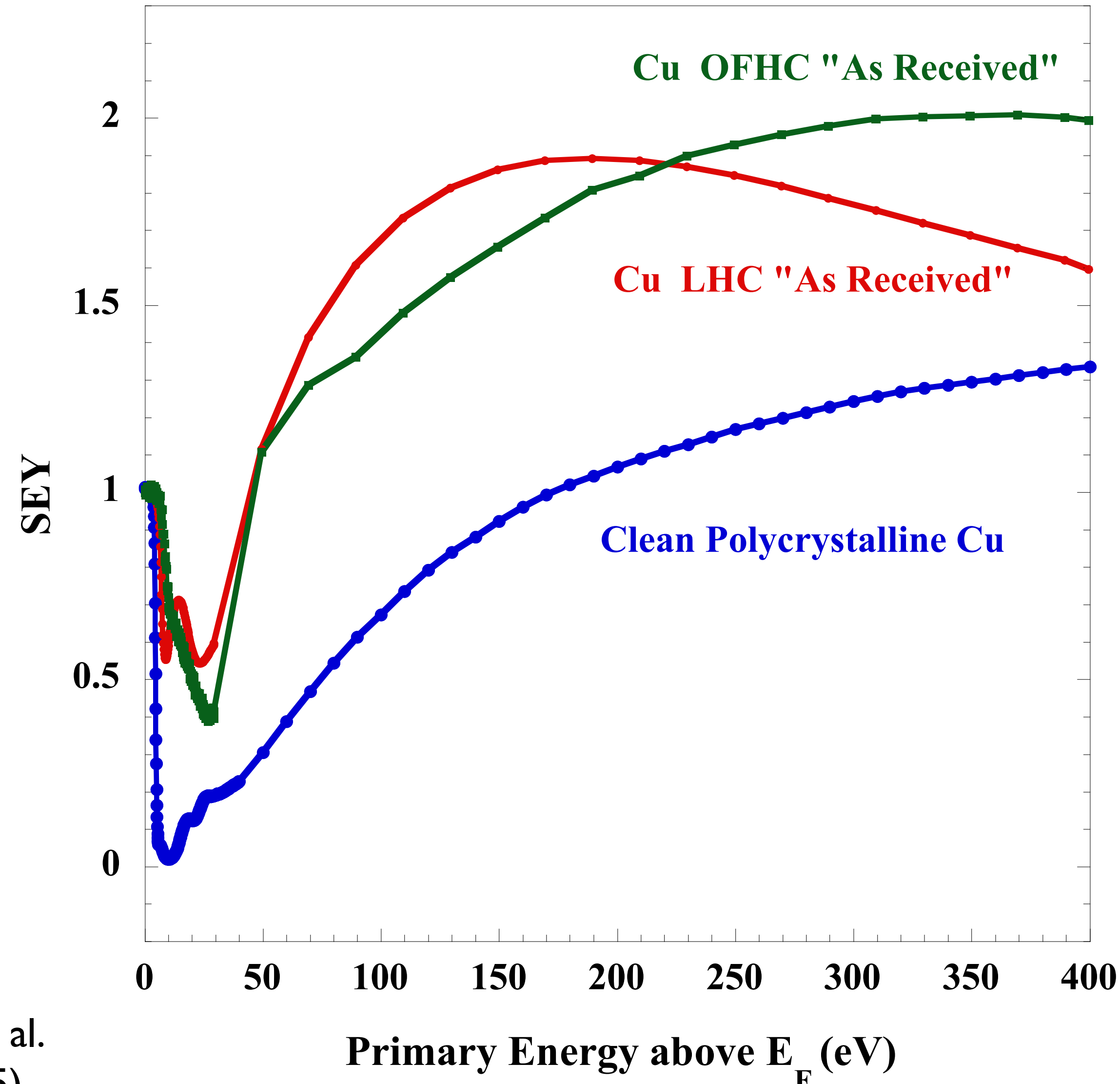


- Study in identical conditions (same geometry etc.) atomically clean (XPS) Cu obtained by cycles of Ar^+ sputtering of the "as received" Cu.
- Compare it to "as received" Cu samples.
- "As received" is NOT a well defined chemical state!

See: R. Cimino et al. PR ST (2015)

Addendum

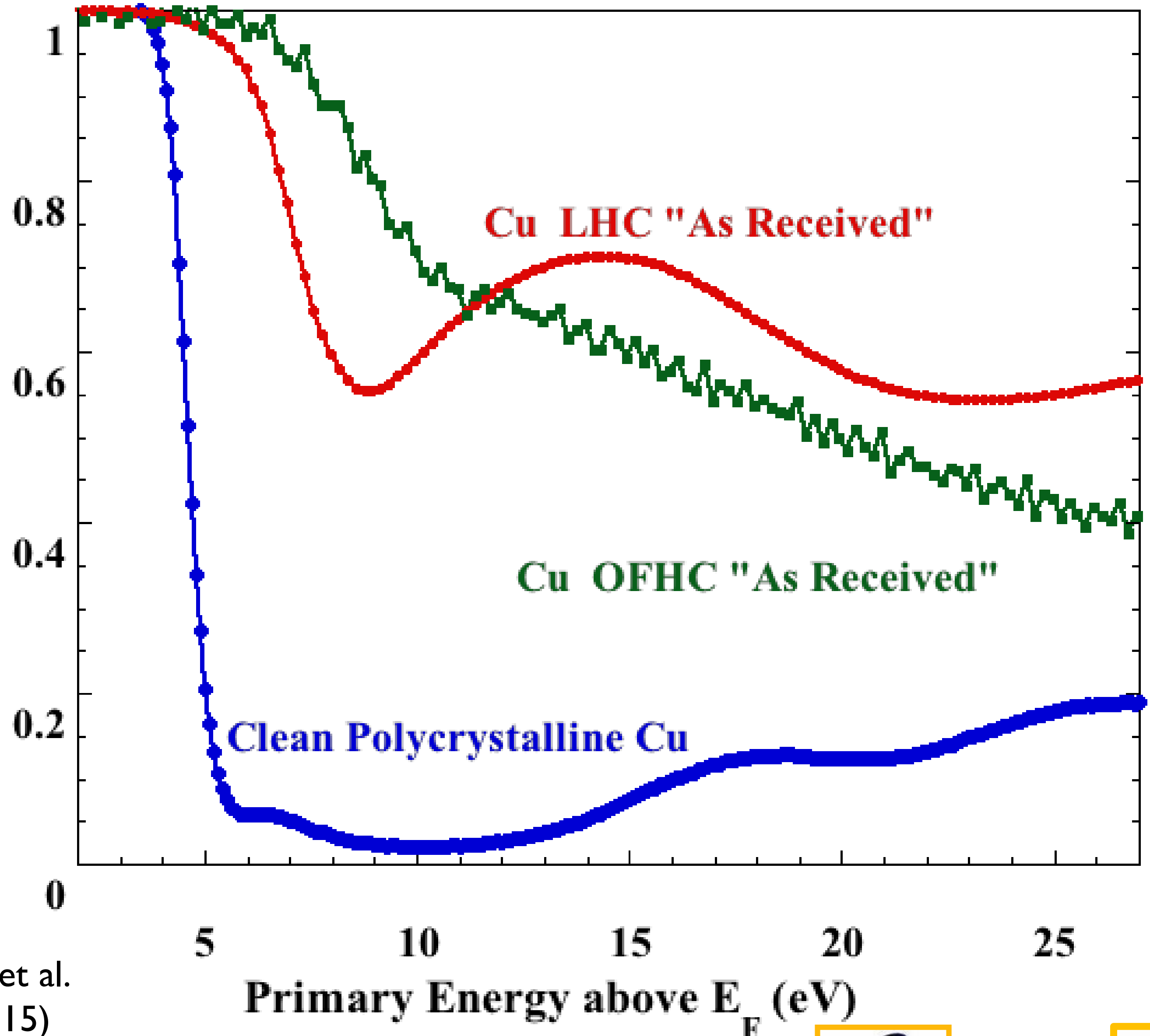
“As received” vs. Clean Cu



R. Cimino et al.
PR ST (2015)

Addendum

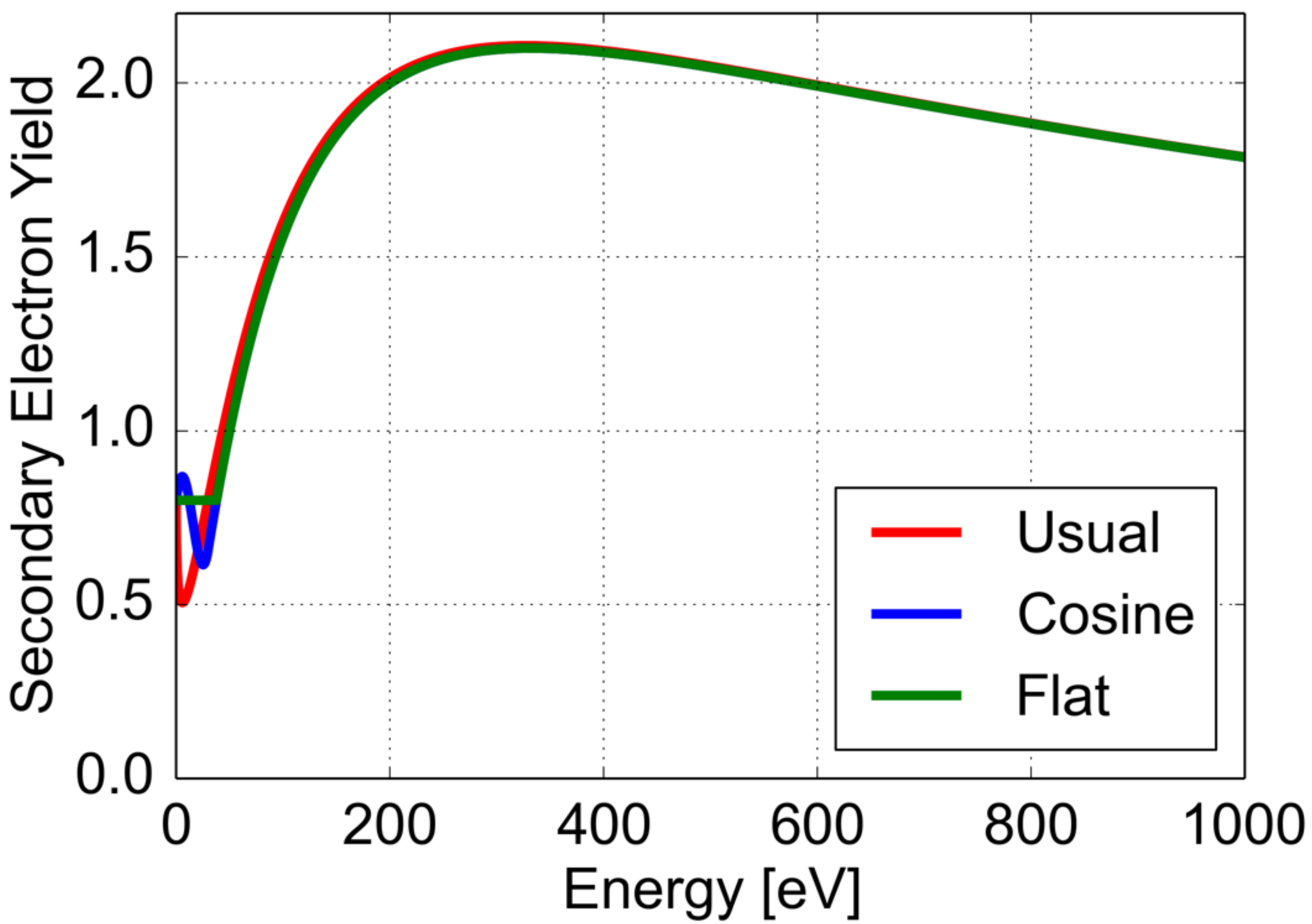
"As received" vs. Clean Cu



R. Cimino et al.
PR ST (2015)

Addendum

For the LHC: test HL simulations.



R. Cimino et al. PR ST (2015)

Addendum

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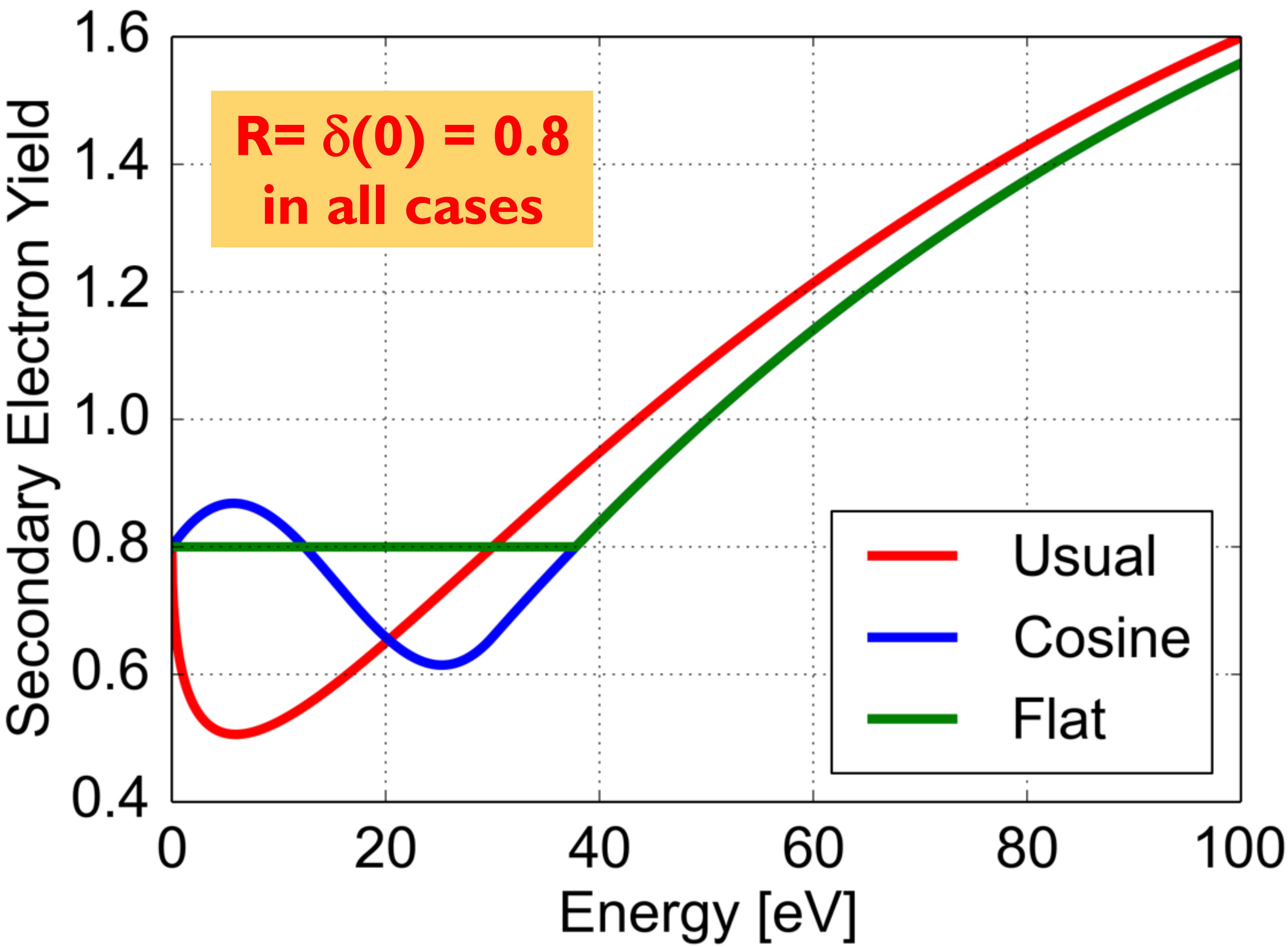

R. Cimino et al. PR ST (2015)

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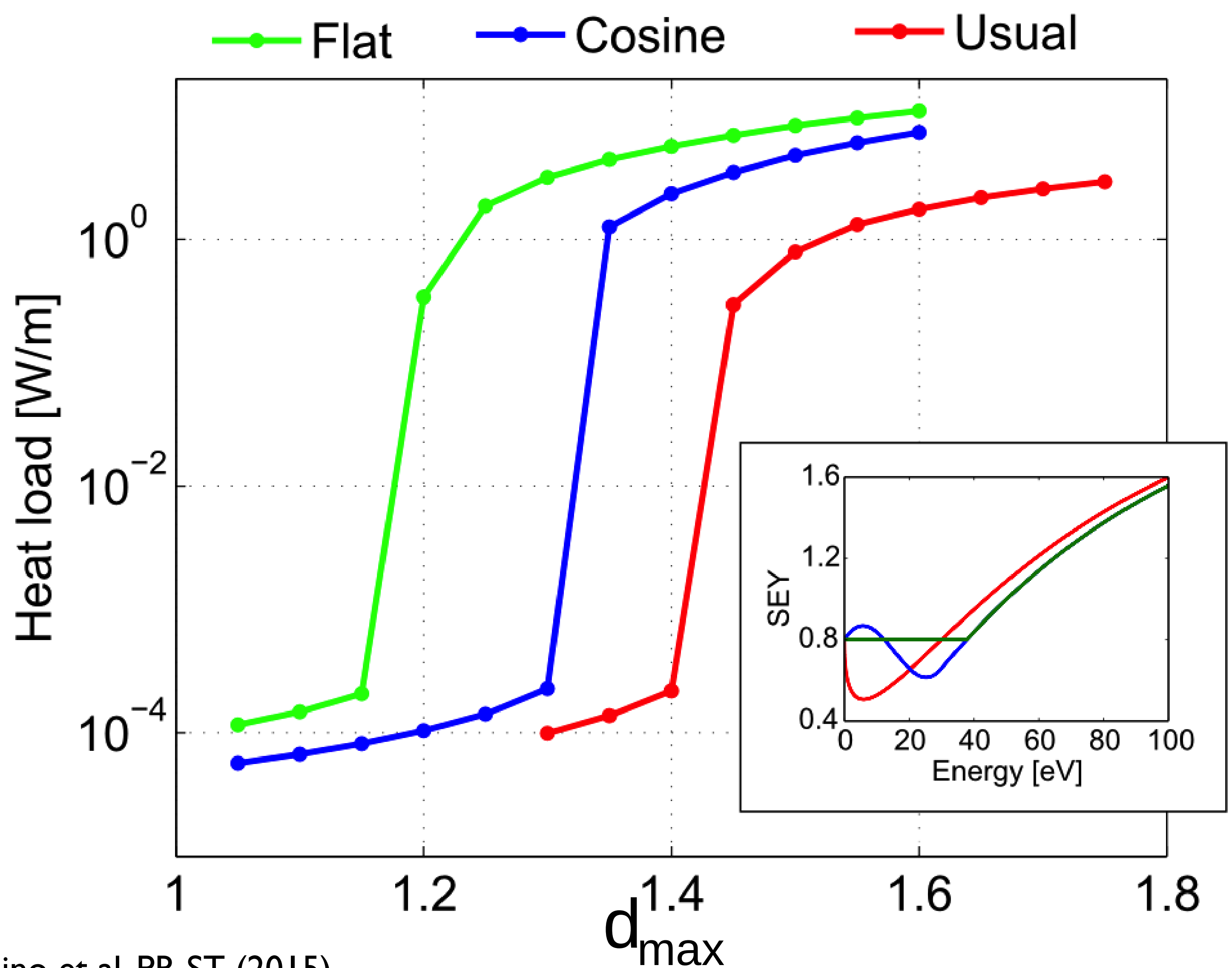


R. Cimino et al. PR ST (2015)

Electron cloud in accelerators

- Phenomenology:

What happens to the Vacuum beam pipe in presence of the beam? (LHC Example)

- Numerical model

- The Surface Science properties of relevance:

✓ SEY (Secondary Electron Yield);
✓ PY (Photo Yield);
✓ R (photon Reflectivity)

- Mitigation strategies

- Conclusion

R. Cimino and T. Demma
"Electron cloud in Accelerators"
Int. J. Mod. Phys. A 29 (2014)
1430023 (pag. 65).

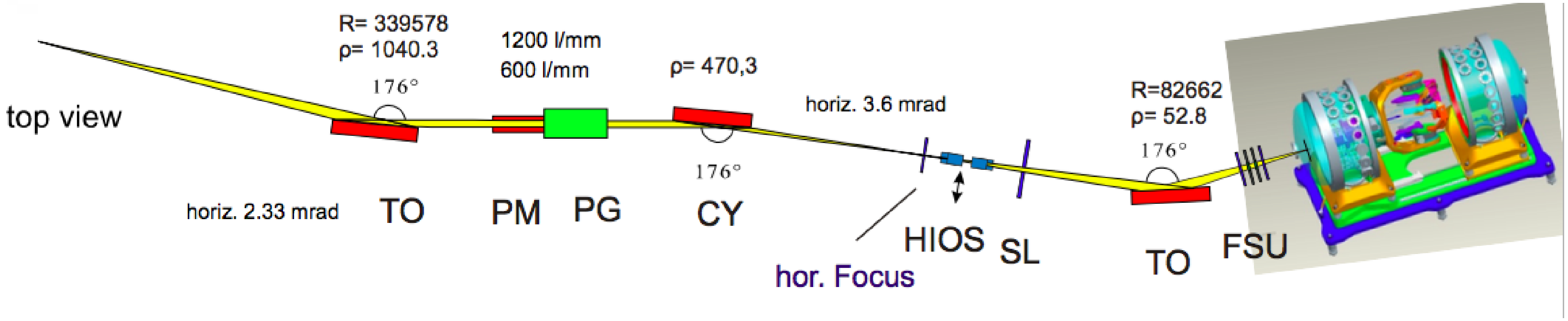
Why?

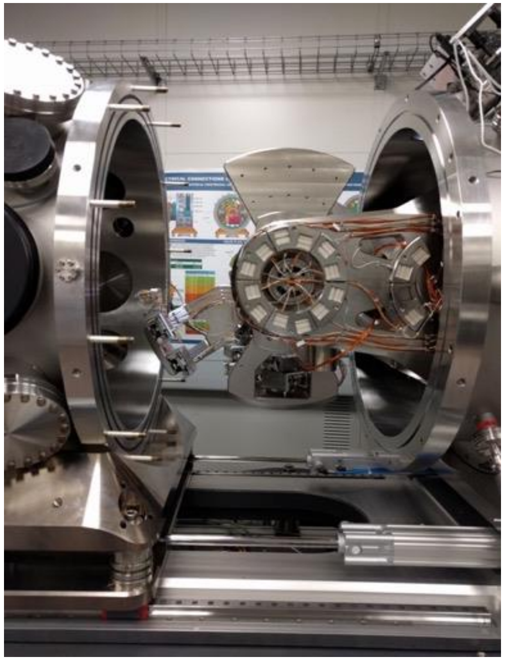
- Not only to study the input parameters used in simulations of multipacting and e-cloud build-ups, related instabilities

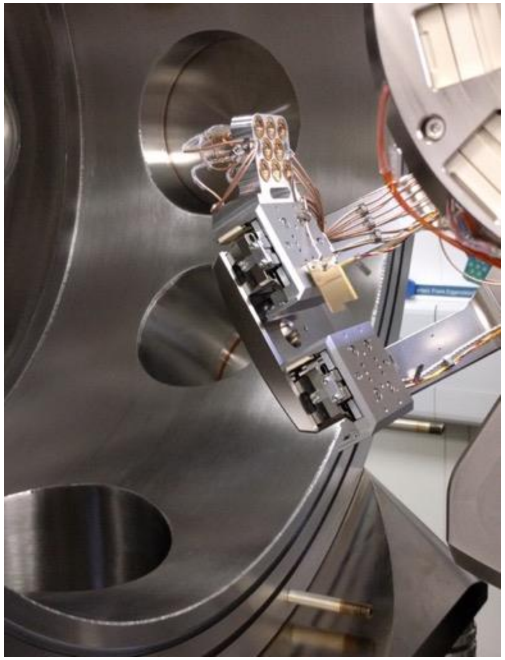
- But also to simulate and prevent single bunch instabilities just connected to the mere existence of a certain density of e^- in the accelerator chambers.

(K. Ohmi and F. Zimmermann PRL 2000)

Experimental set up to measure R & PY @ BESSY II - Optic Beamline and Reflectometer







A.A.Sokolov,et al,Proc.of SPIE92060J-1-13(2014)

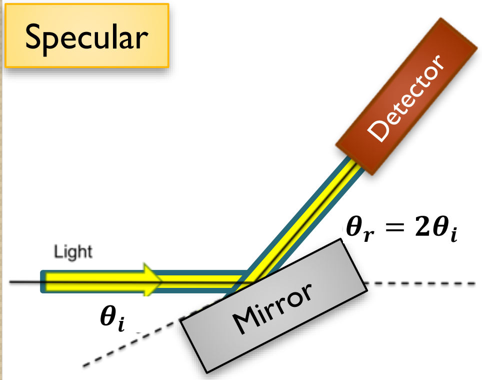
See: Eliana La Francesca @ FCC Week 2017, Berlin

Reflectivity and PY Measurements

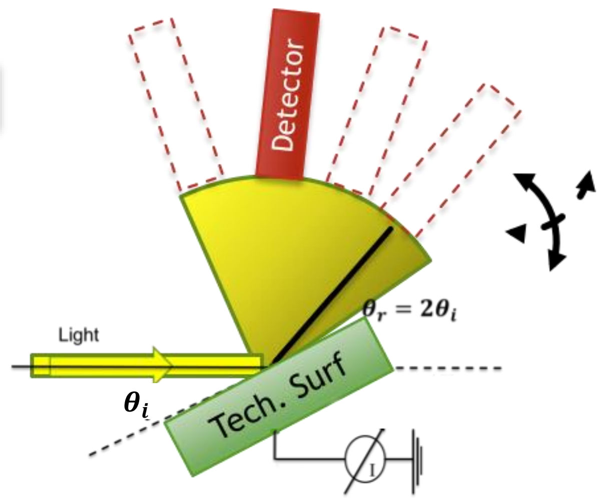
- Photon Energy range 35÷1800 eV
- Beam height h=0.3 mm
- Incident Beam measurement
- GaAsP Photodiodes (4x4mm) (1.2*4mm)
- Incidence angle 0.25, 0.5 deg
- Reflectivity measurement → Specular Reflectivity / Scattered Light

Photo Yield:
PY= $N_e/N\gamma$

Specular

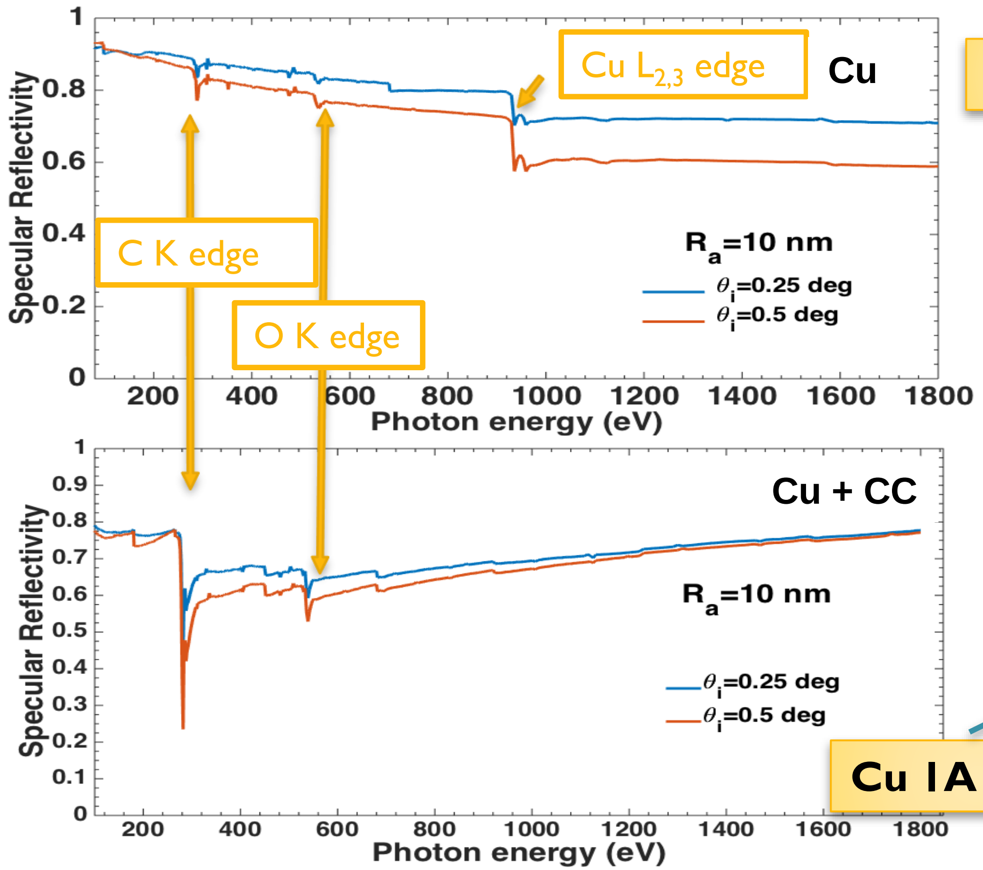


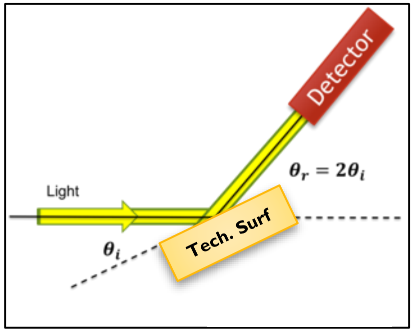
Total



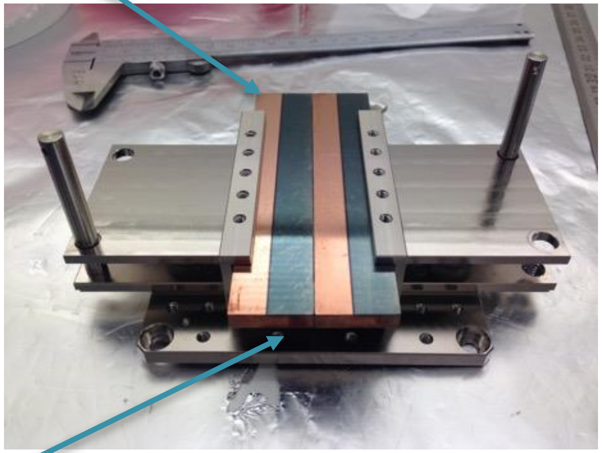
See: Eliana La Francesca @ **FCC Week 2017, Berlin**

Specular Reflectivity VS Photon energy





Cu IA



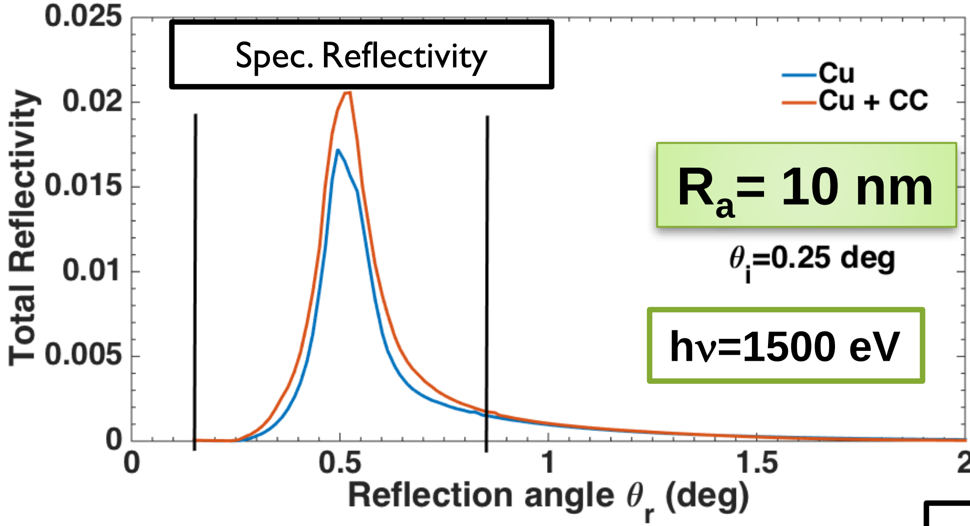
Cu IA + CC

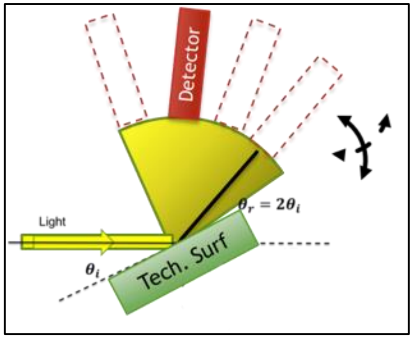
At grazing incidence angle, contaminants are influencing Cu Reflectivity

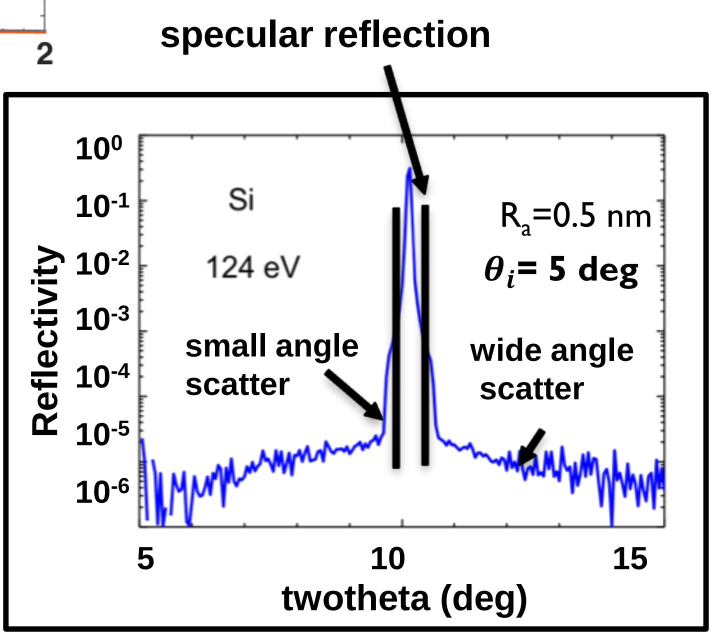
At high energy reflectivity is significantly enhanced

See: Eliana La Francesca @ FCC Week 2017, Berlin

Total Reflectivity VS Specular Reflectivity





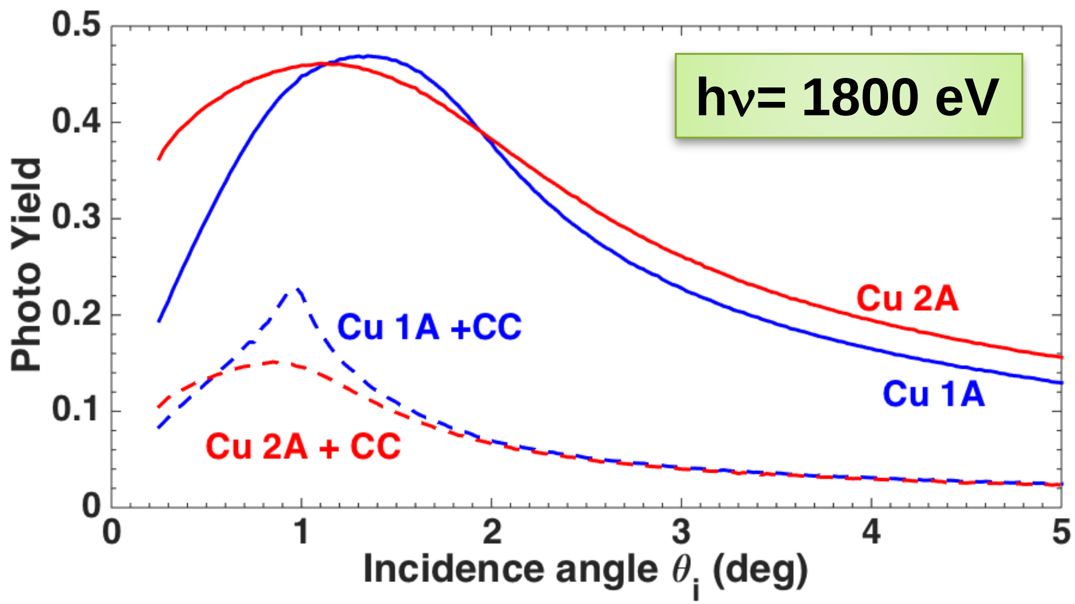


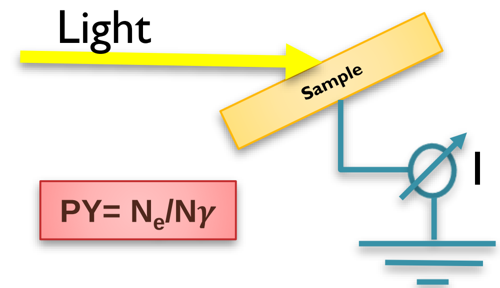
Sample	Specular Reflectivity	Total Reflectivity
Cu 1A	0.61	0.73
Cu 1A + CC	0.78	0.90

Scattered photons goes top & bottom

See: Eliana La Francesca @ **FCC Week 2017, Berlin**

Photo Yield VS Incidence angle





I Sample need to be normalised to Nγ to be a Yield

Preliminary Results:

- little dependence on roughness
- Carbon coating seems to reduce PY

Sample	Cu 1A (R_a=10 nm) Max value	Cu 2A (R_a=30 nm) Max value
Cu	0.47	0.46
Cu + CC	0.23	0.15

See: Eliana La Francesca @ **FCC Week 2017, Berlin**

Electron cloud in accelerators

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- **Mitigation strategies**

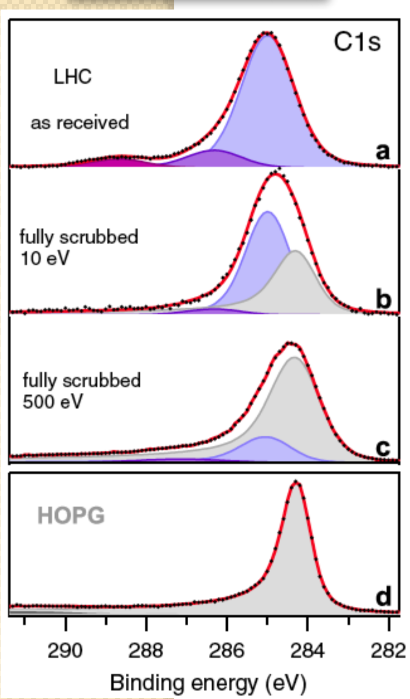
- Conclusion

R. Cimino and T. Demma
"Electron cloud in Accelerators"
Int. J. Mod. Phys. A 29 (2014) 1430023 (pag. 65).

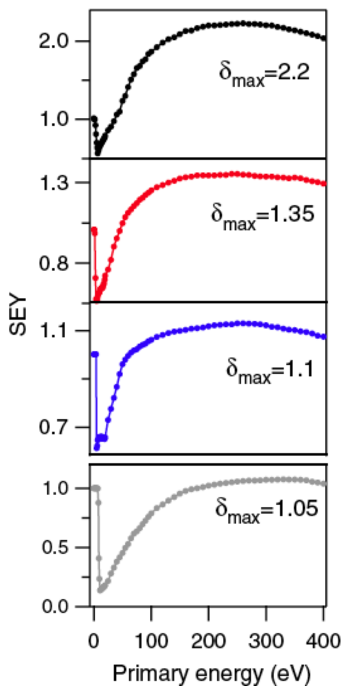
Towards mitigation Strategies….

- ✓ **We measure and feed material parameters (R, PY, and SEY) into simulations.**
- ✓ **Understand their profound nature to:**
- ✓ **Optimize chemical (mech.) processes to reduce their detrimental influence on beam.**
- ✓ **Search for new material / coatings with intrinsically "good" parameters.**

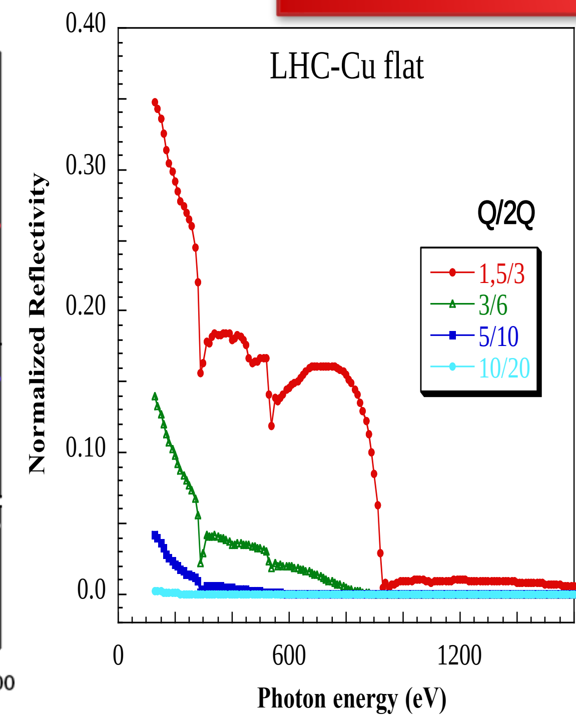
XPS

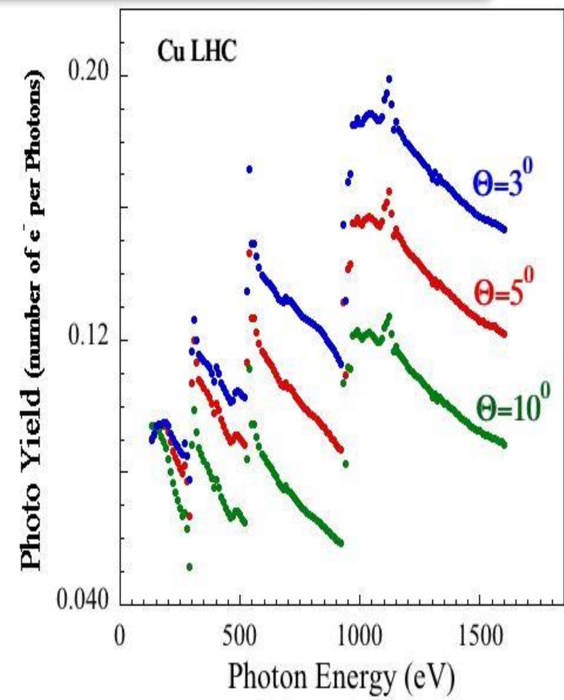


SEY



SR Reflectivity and PY (@BESSY-II)





Most of the existing and planned accelerator machines base the reaching of their design parameters to the capability of obtaining walls with a SEY ~1.3 or below!

Mitigation Strategies

- External solenoid field
- Electrodes in the lattice
- Surface Scrubbing (or conditioning)
- Intrinsically low SEY material
- Geometrical modifications

External solenoid field.	→	Not always possible…
Electrodes in the lattice.	→	If possible… (Impedance, costs.)
Scrubbing (or conditioning)	→	-Efficiency (time & final SEY)…
Intrinsically low SEY material	→	Stability and material choice…
Geometrical modifications	→	Impedance. Space, Machining costs.

External solenoid field. → Not always possible…

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Presented at 31st ICFA Beam Dynamics Workshop: Electron Cloud Effects (ECLOUD04) , 19-23 Apr 2004, Napa, CA

SLAC-PUB-10750

SOLENOID EFFECTS ON AN ELECTRON CLOUD

L. Wang, BNL, Upton, NY 11973, USA
S. Kurokawa, H. Fukuma, S.S. Win, Tsukuba, KEK, Japan
A. Chao, SLAC, Menlo Park, California, USA

No field

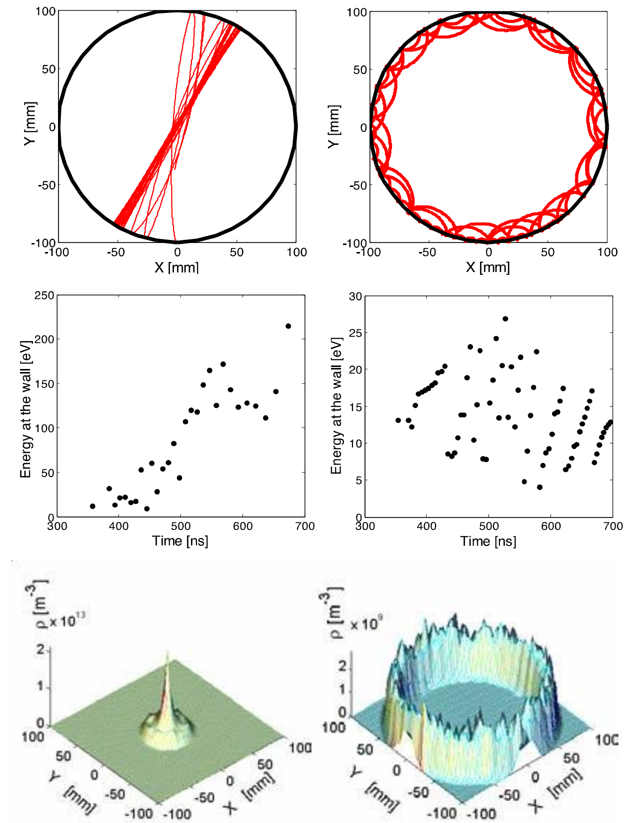


Figure 2: Electron orbit (top row), energy at the wall (middle row), and electron-cloud distribution (bottom row) with 0 G (left column) and 60G (right column) solenoid fields in the SNS's accumulator drift region

60 Gauss solenoid field

Adopted solution for SuperKEK bellows

External solenoid field. → Not always possible…

Electrodes in the lattice. → If possible… (Impedance, costs.)

Scrubbing (or conditioning) → -Efficiency (time & final SEY)…

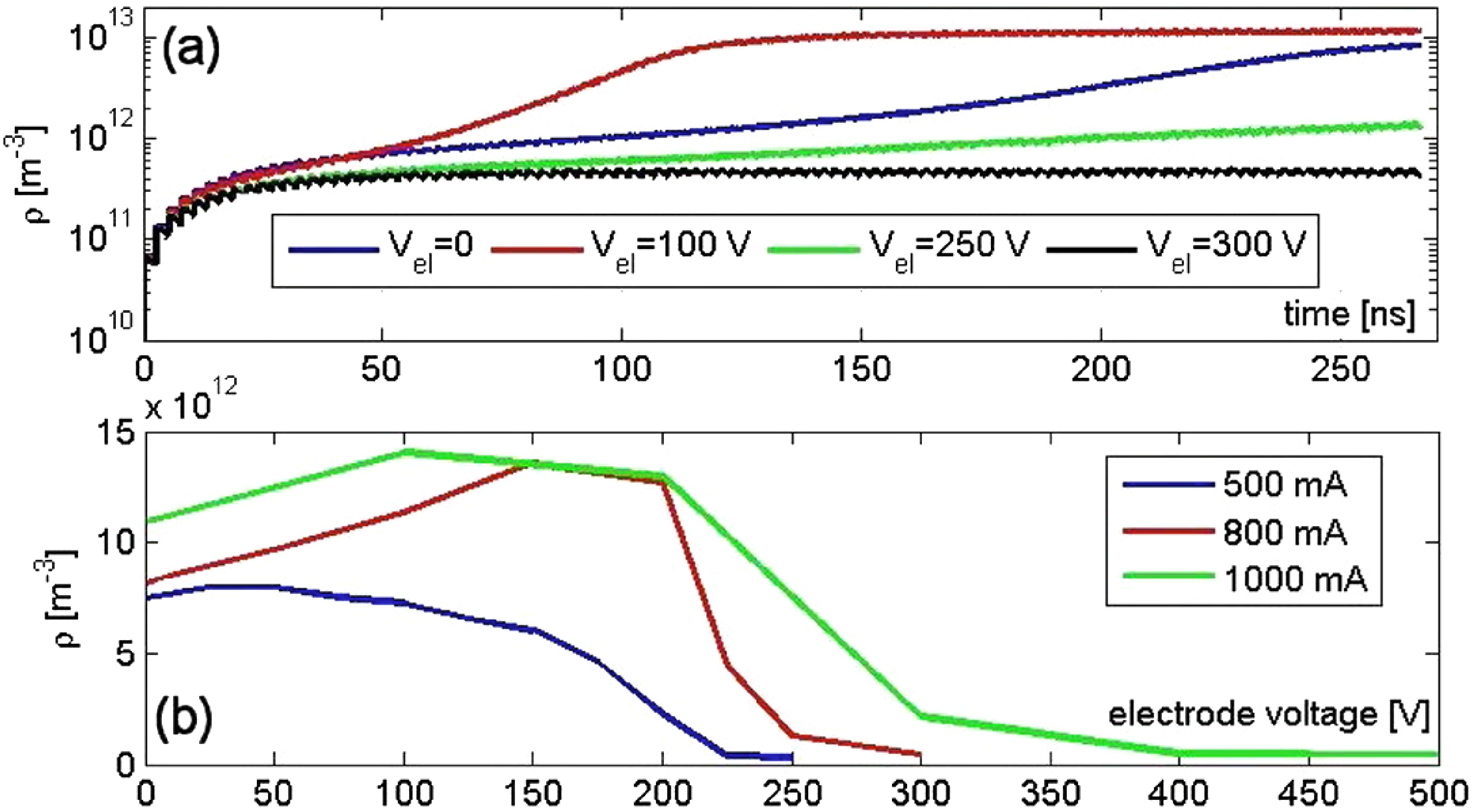
Intrinsically low SEY material → Stability and material choice…

Geometrical modifications → Impedance. Space, Machining costs.

Electrodes at DAΦNE

D. Alesini et al. *Phys. Rev. Lett.* **110**, 124801 (2013)

Electrodes at DAΦNE



(a) Evolution of the averaged cloud density for different values of the electrode voltage. (b) e− cloud density at the end of the bunch train.

D. Alesini et al. *Phys. Rev. Lett.* **110**, 124801 (2013)

External solenoid field. → Not always possible…

Electrodes in the lattice. → If possible… (Impedance, costs.)

Scrubbing (or conditioning) → **-Efficiency (time & final SEY)…**

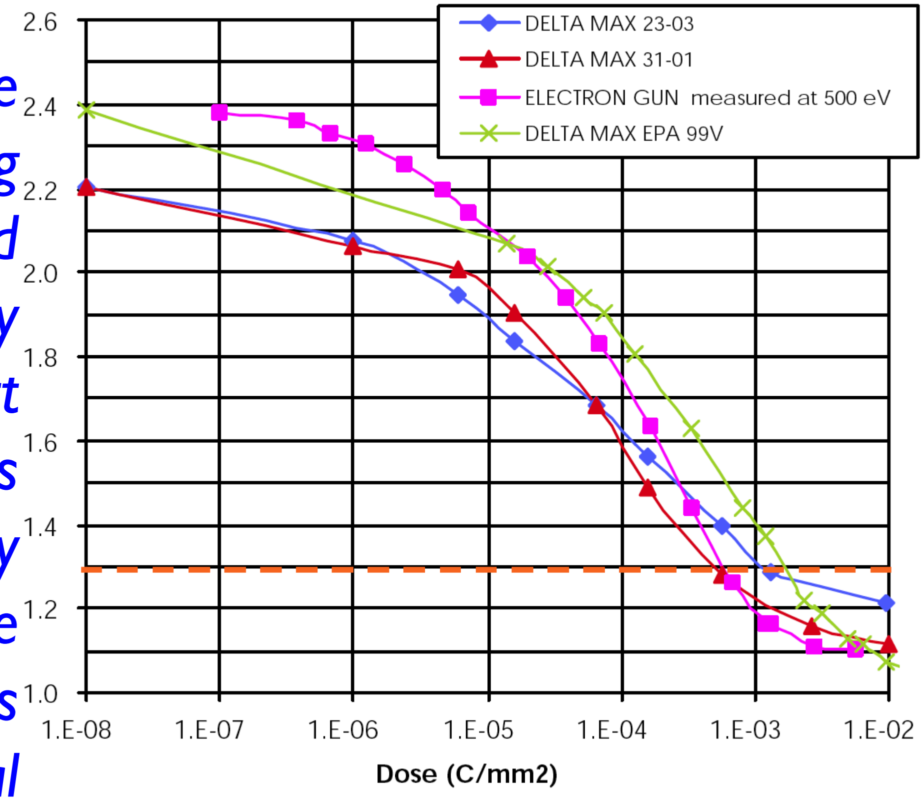
Intrinsically low SEY material → Stability and material choice…

Geometrical modifications → Impedance. Space, Machining costs.

The Beam "scrubbing" effect is the ability of a surface to reduce its SEY after e- bombardment.

from LHC PR 472 (Aug. 2001):

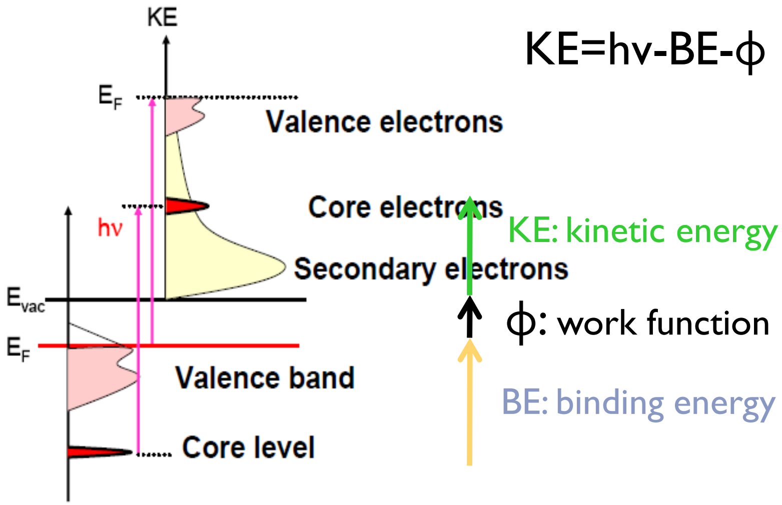
" …Although the phenomenon of conditioning has been obtained reproducibly on many samples, the exact mechanism leading to this effect is not properly understood. This is of course not a comfortable situation as the LHC operation at nominal intensities relies on this effect… "

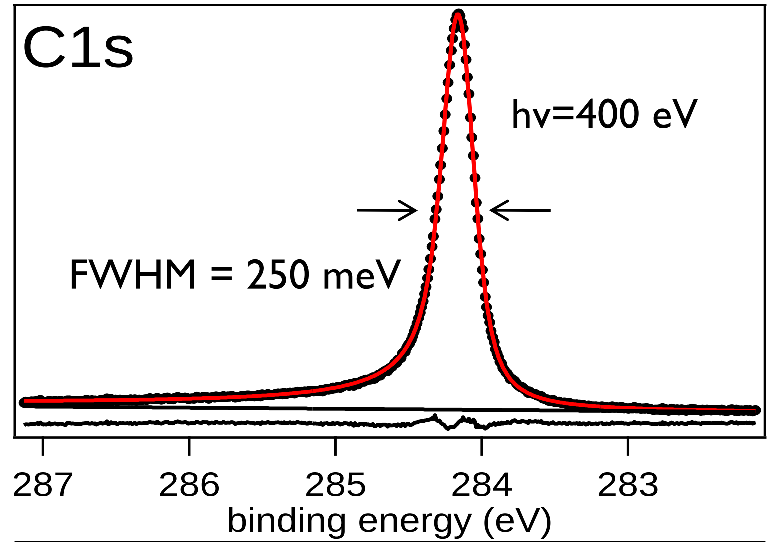


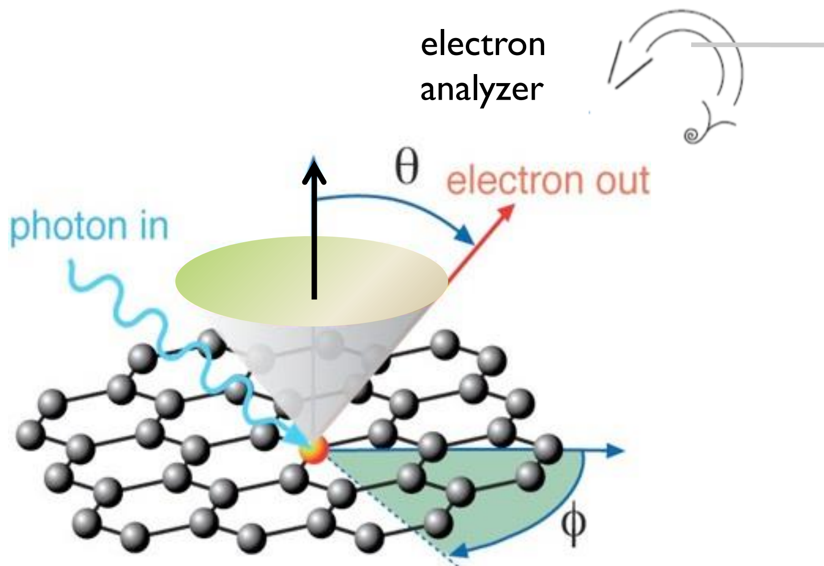
V. Baglin et al, LHC Project Report 472, CERN, 2001.

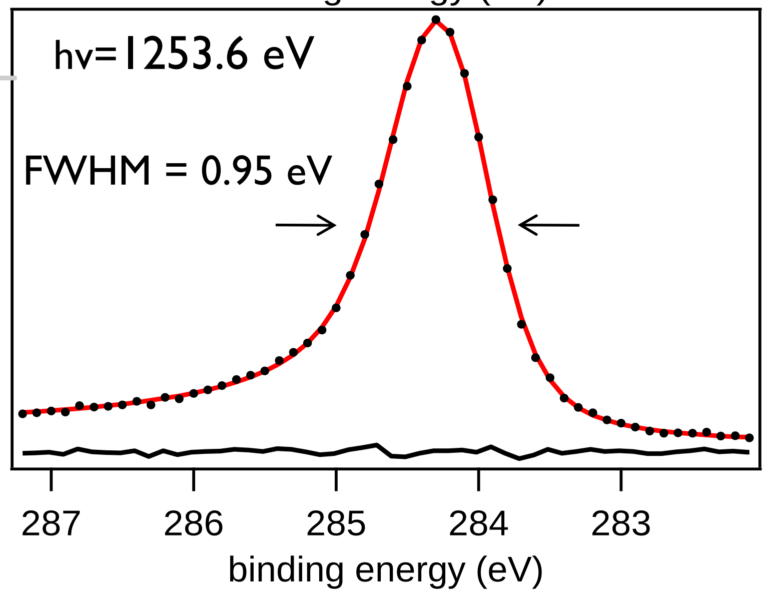
Addendum

X-ray photoelectron spectroscopy $\theta_{emiss}=0°$





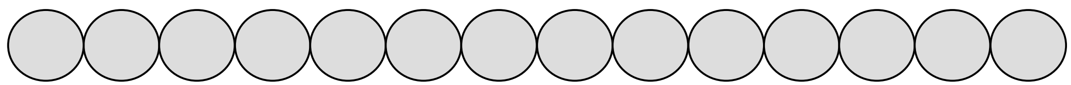


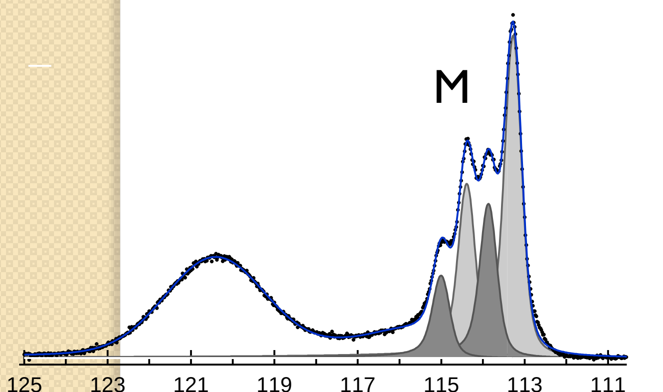


Addendum

XPS spectroscopy of technical samples

Metal
(Rb)





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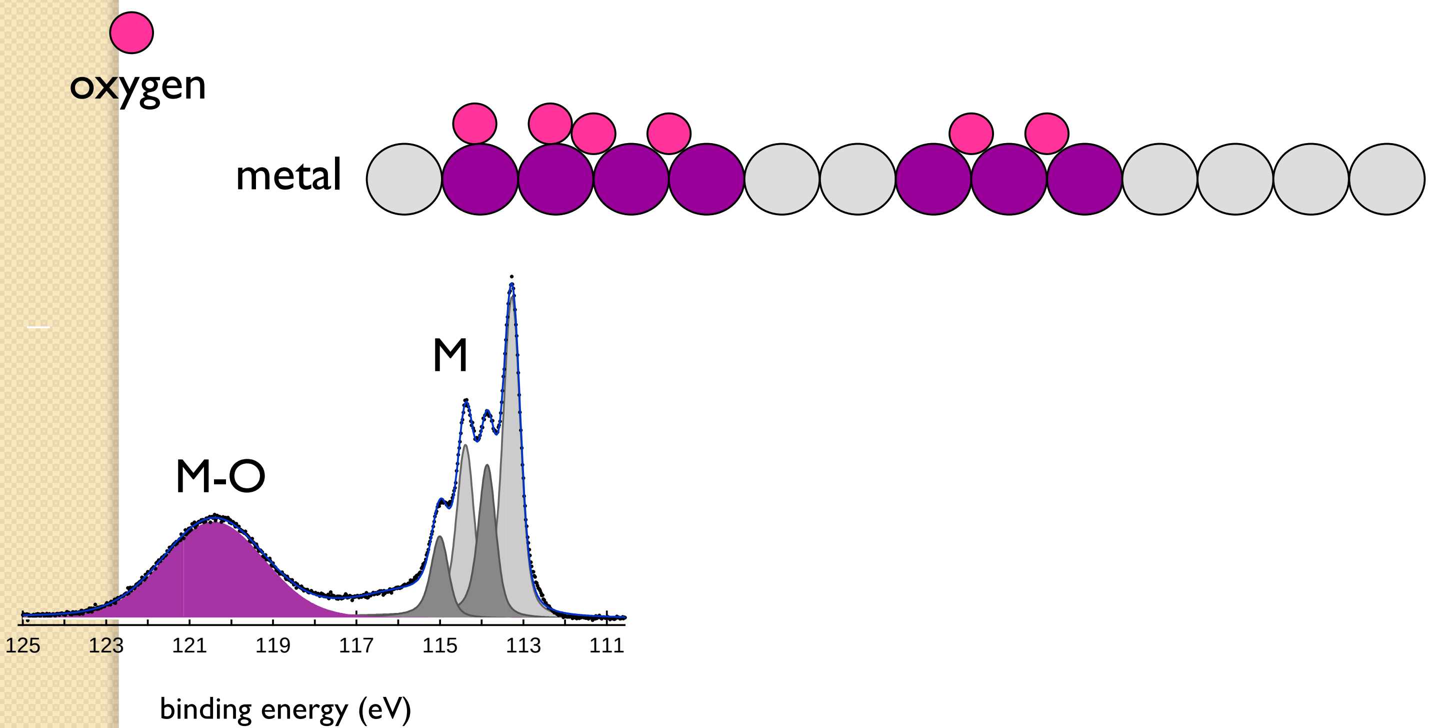
XPS spectroscopy of technical samples



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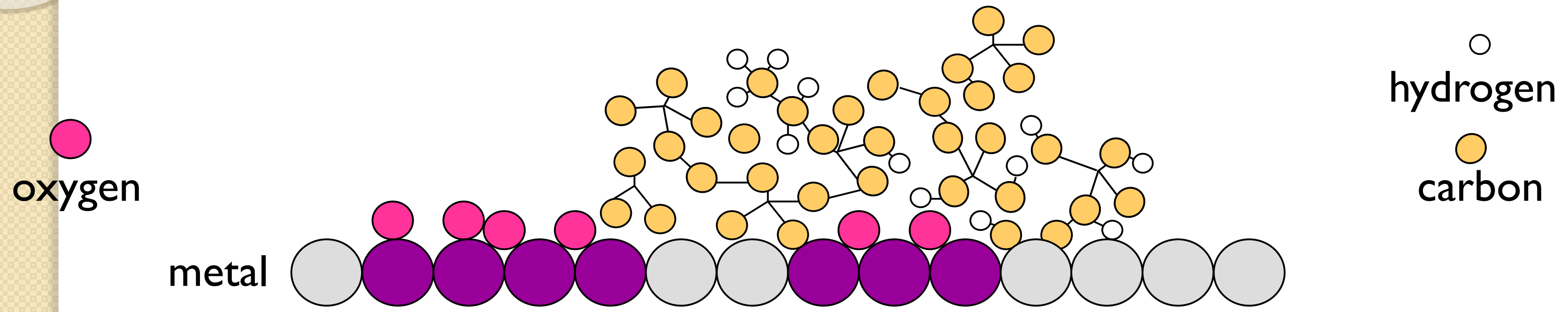
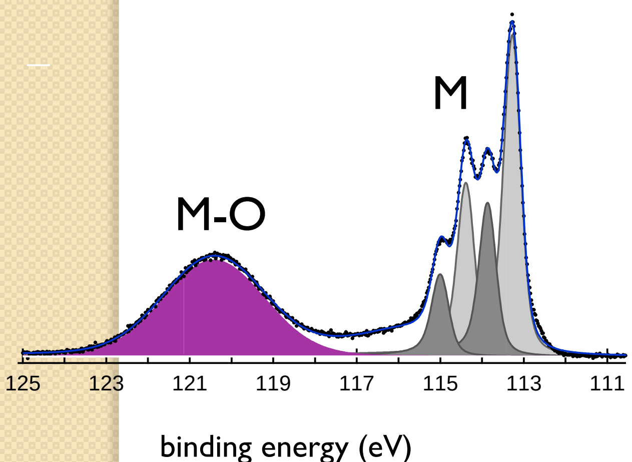
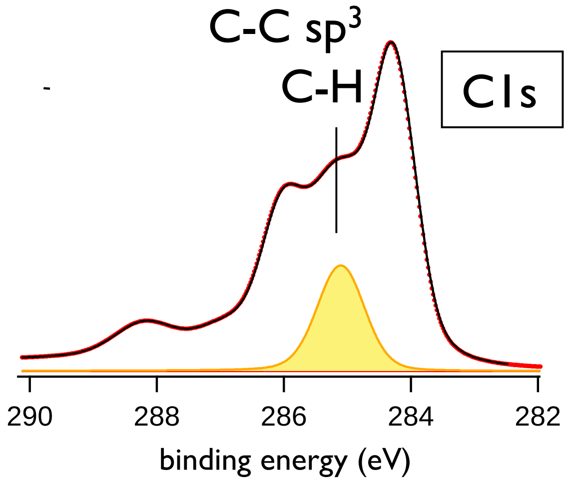
XPS spectroscopy of technical samples







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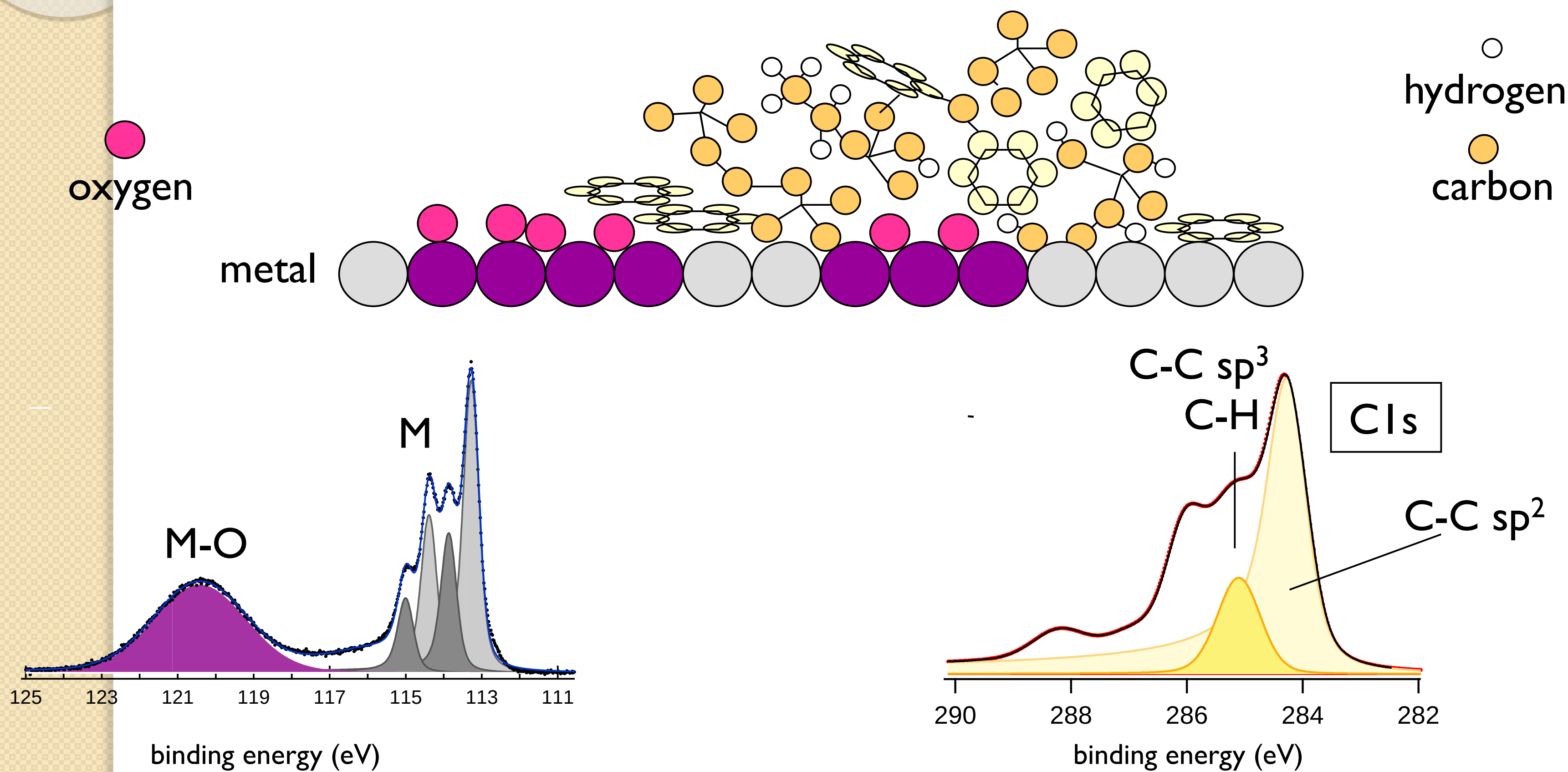

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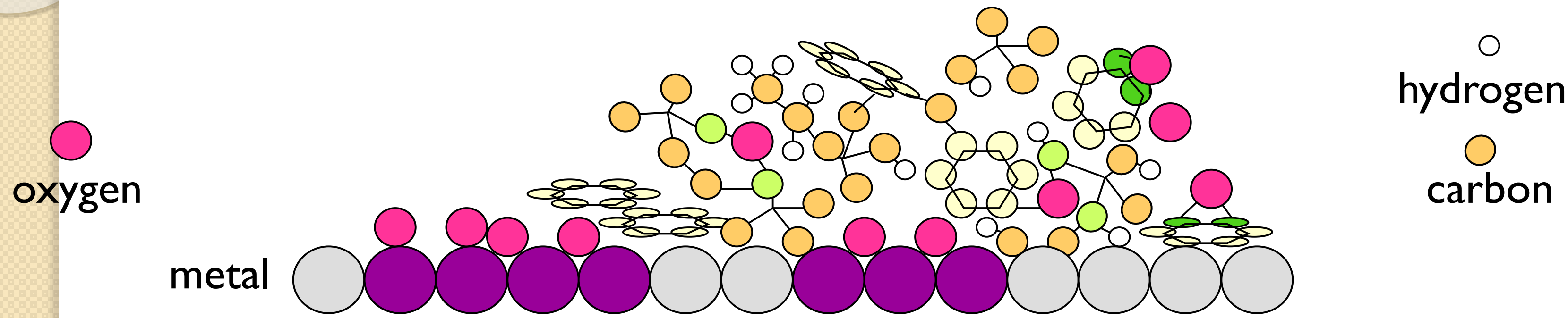
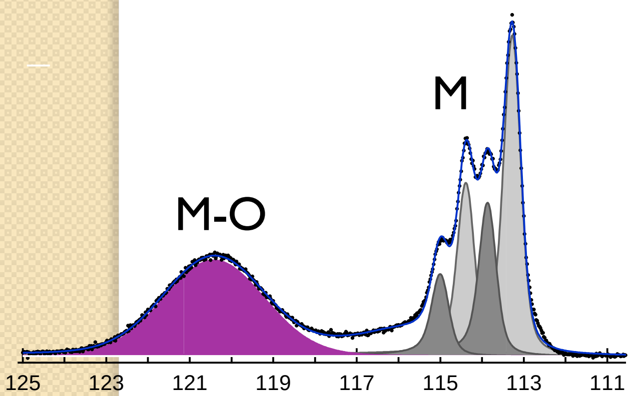
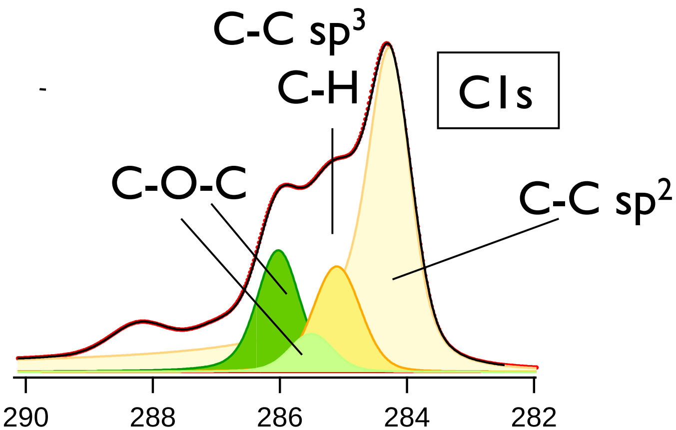
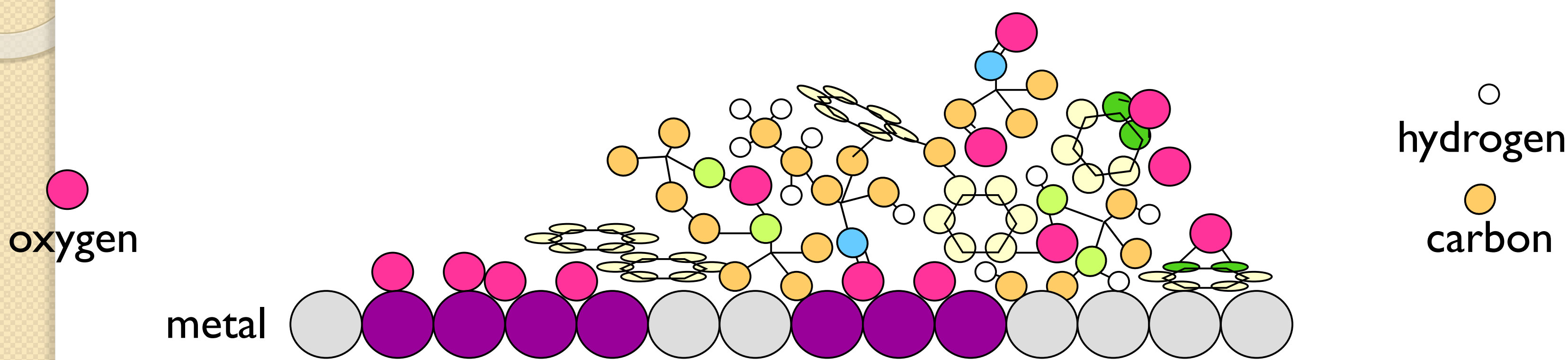
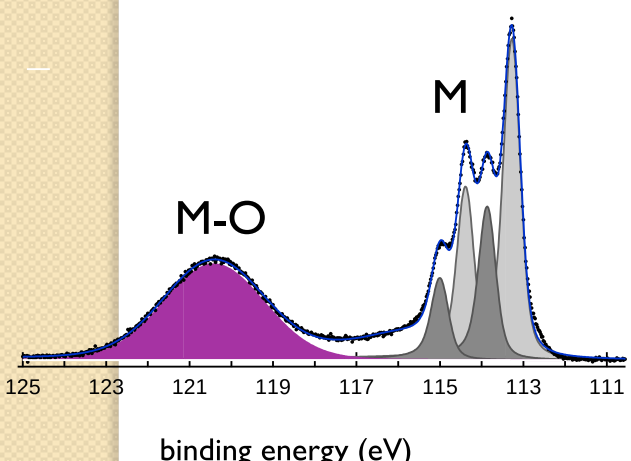


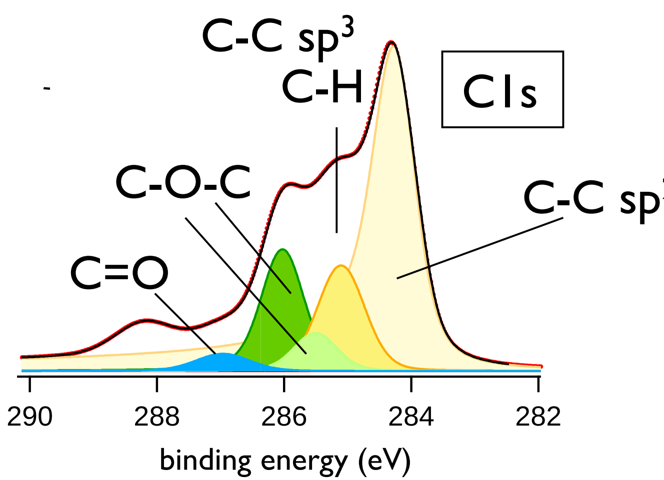




XPS spectroscopy of technical samples

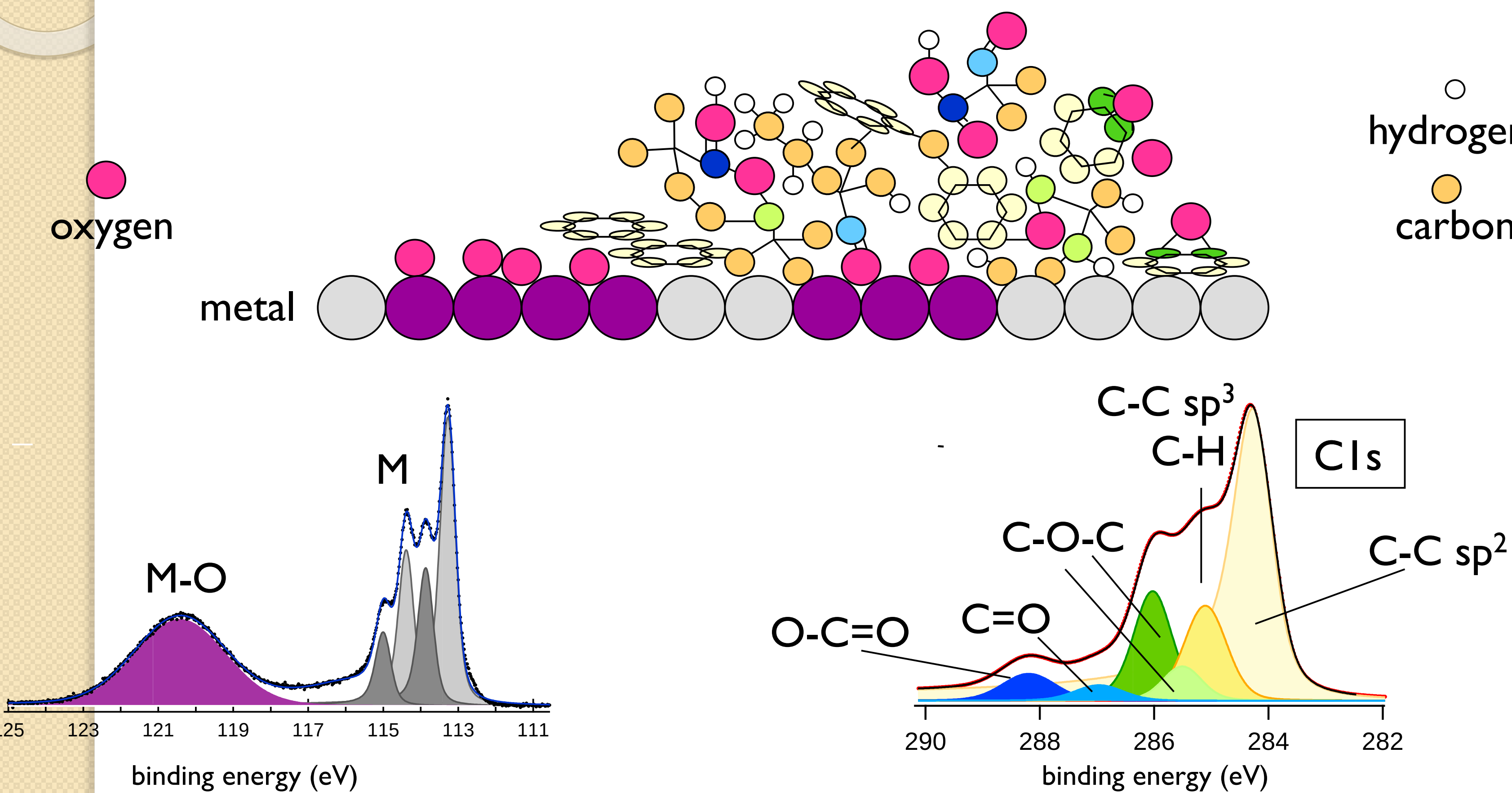






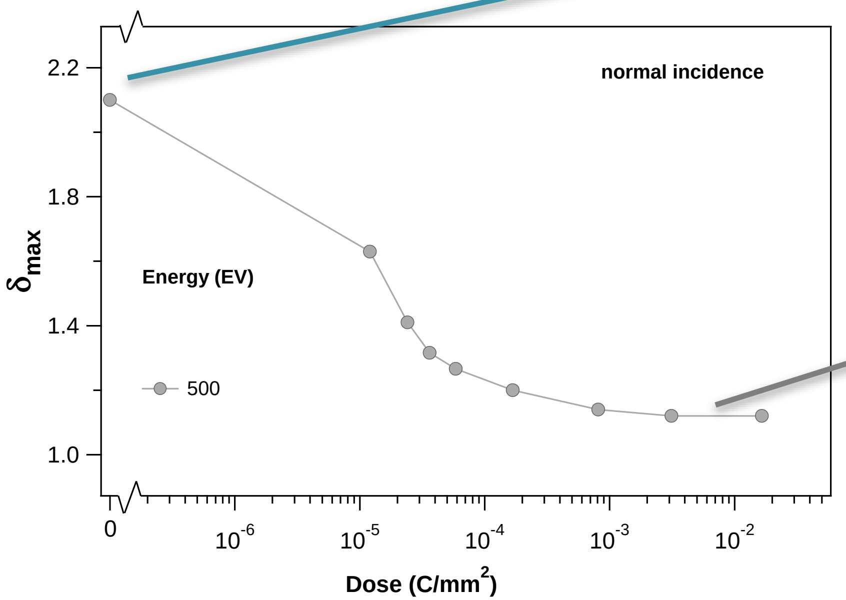
Addendum

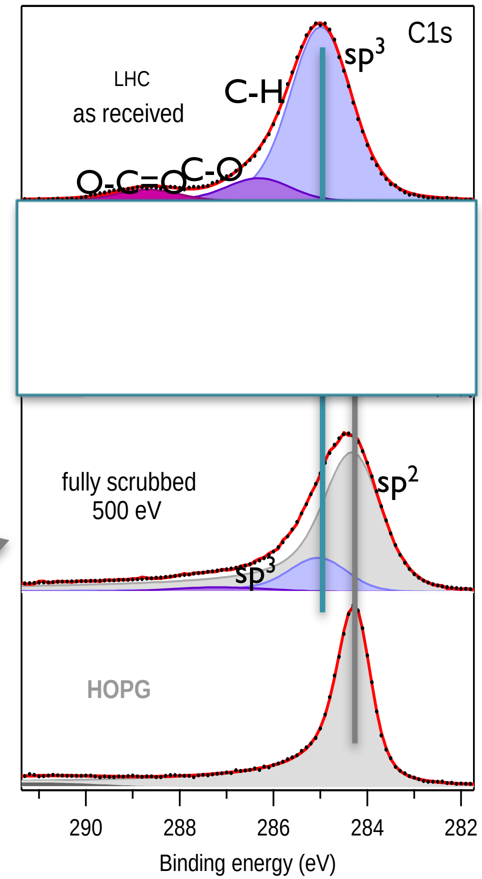
XPS spectroscopy of technical samples

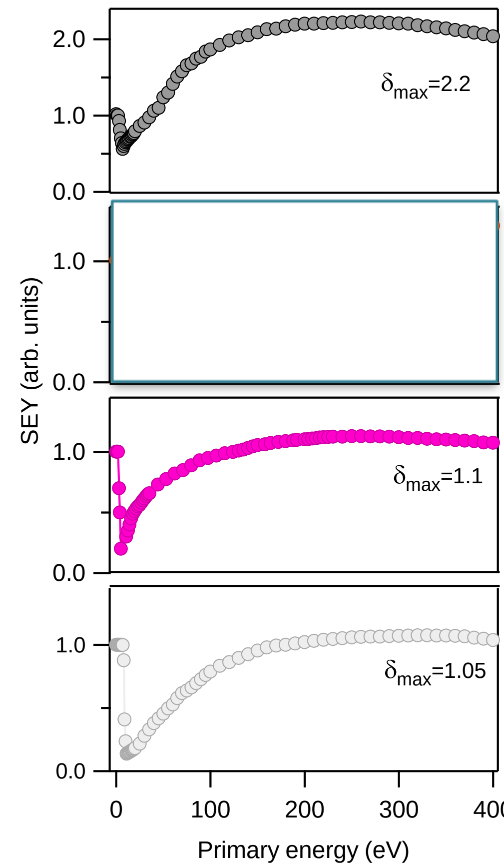


co-laminated Cu for LHC: fully scrubbed

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



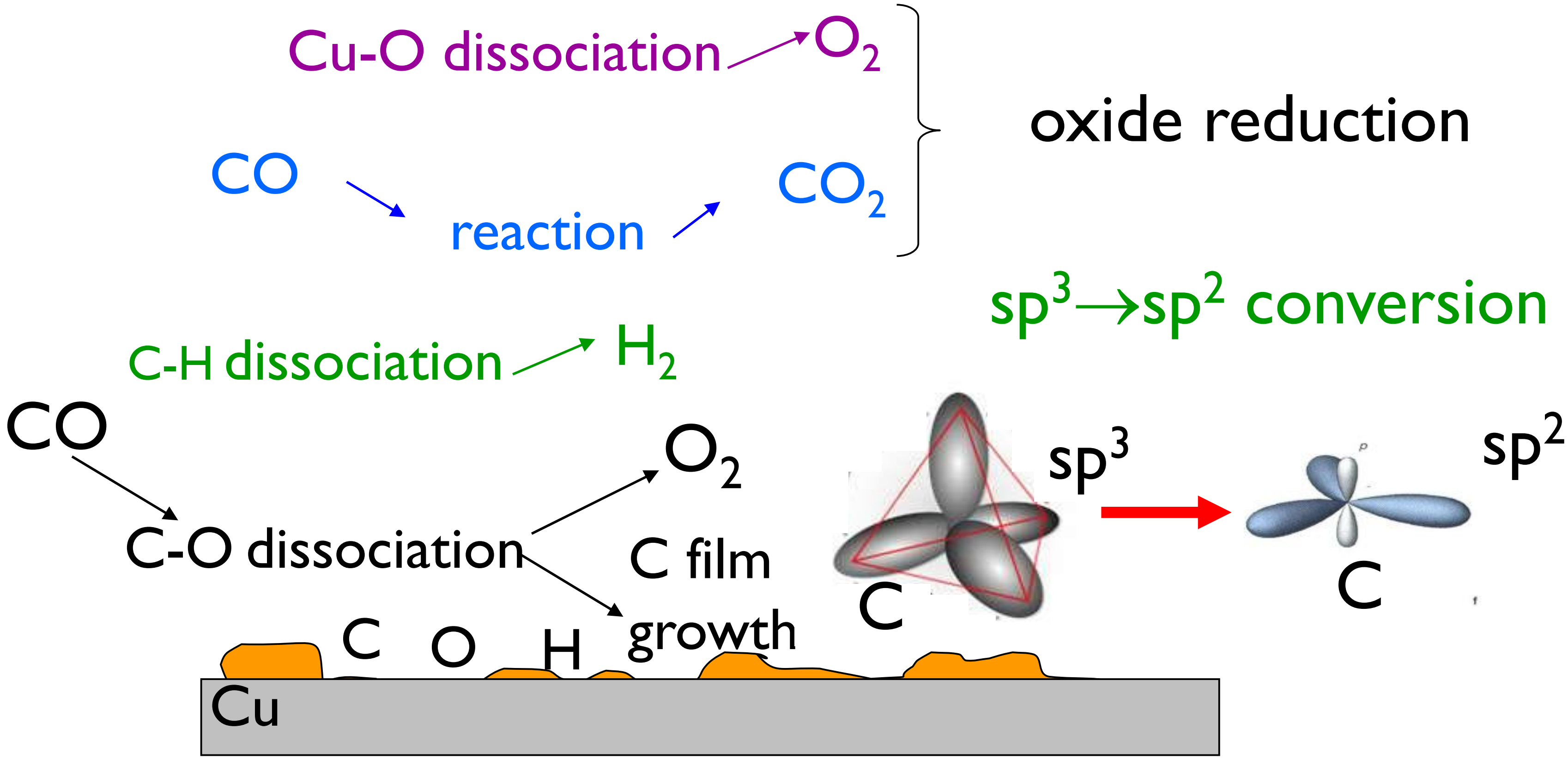




SEY and XPS are directly related

e^- beam induced surface reactions

R. Cimino et al. PRL (2012) & R. Larciprete PR ST (2013)

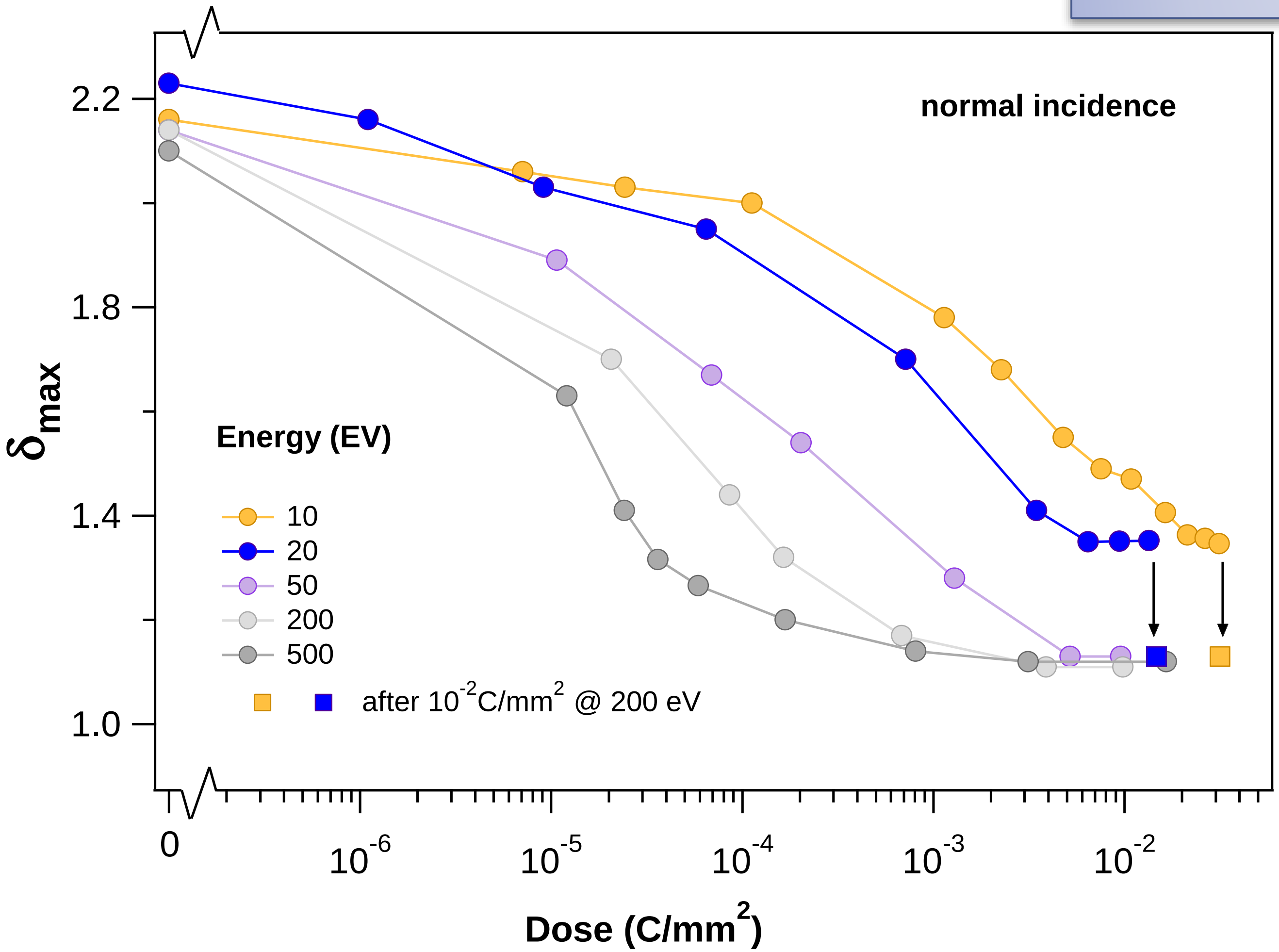


the contribution of all electron-induced surface reaction reduces δ_{max} from 2.2 to 1.1

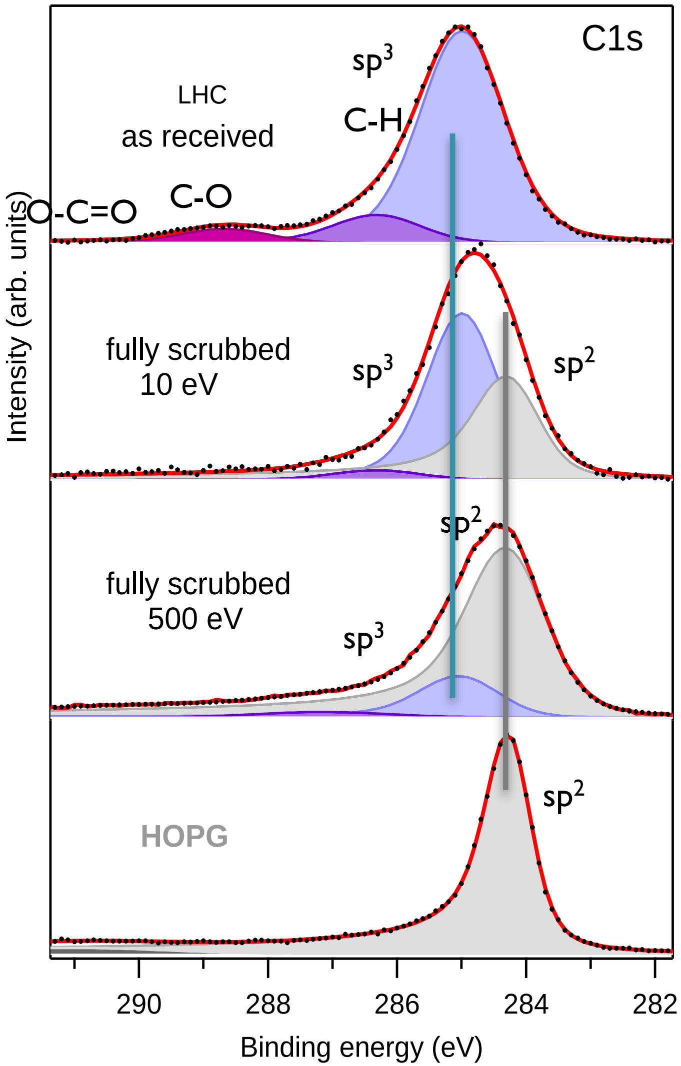
co-laminated Cu for LHC beam screen

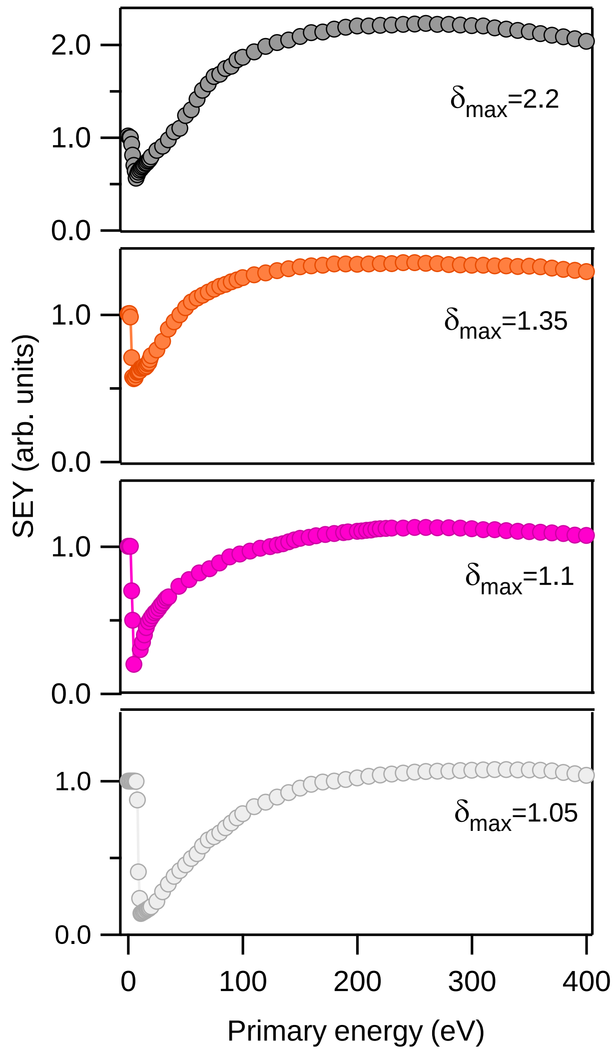
R. Cimino et al. PRL **109 064801 (2012)**

e^- Beam energy counts!



co-laminated Cu for LHC beam screen





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

Table 1: Parameters used for ECLOUD simulations.

parameter	units	value
beam particle energy	GeV	7000
bunch spacing t_b	ns	25; 50; 75
bunch length	m	0.075
number of trains N_t	-	4
number of bunches per train N_b	-	72; 36; 24
bunch gap N_g	-	8
no. of particles per bunch	10^{10}	10; 3.0
length of chamber section	m	1
chamber radius	m	0.02
circumference	m	27000
primary photo-emission yield	-	$7.98 \cdot 10^{-4}$
maximum SEY δ_{max}	-	1.2(0.2)2.0
energy for max. SEY E_{max}	eV	237

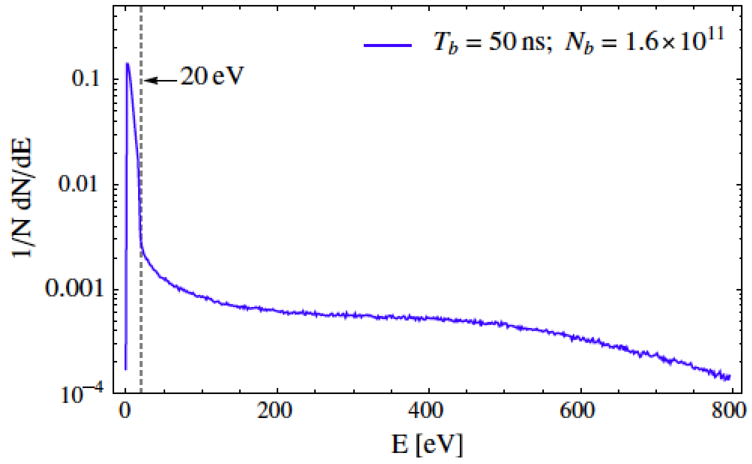
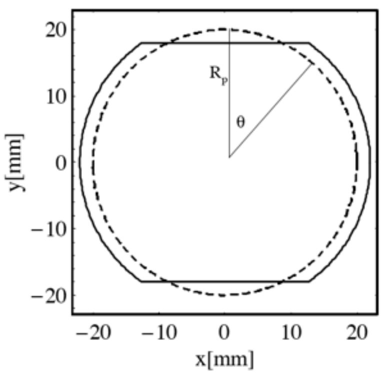


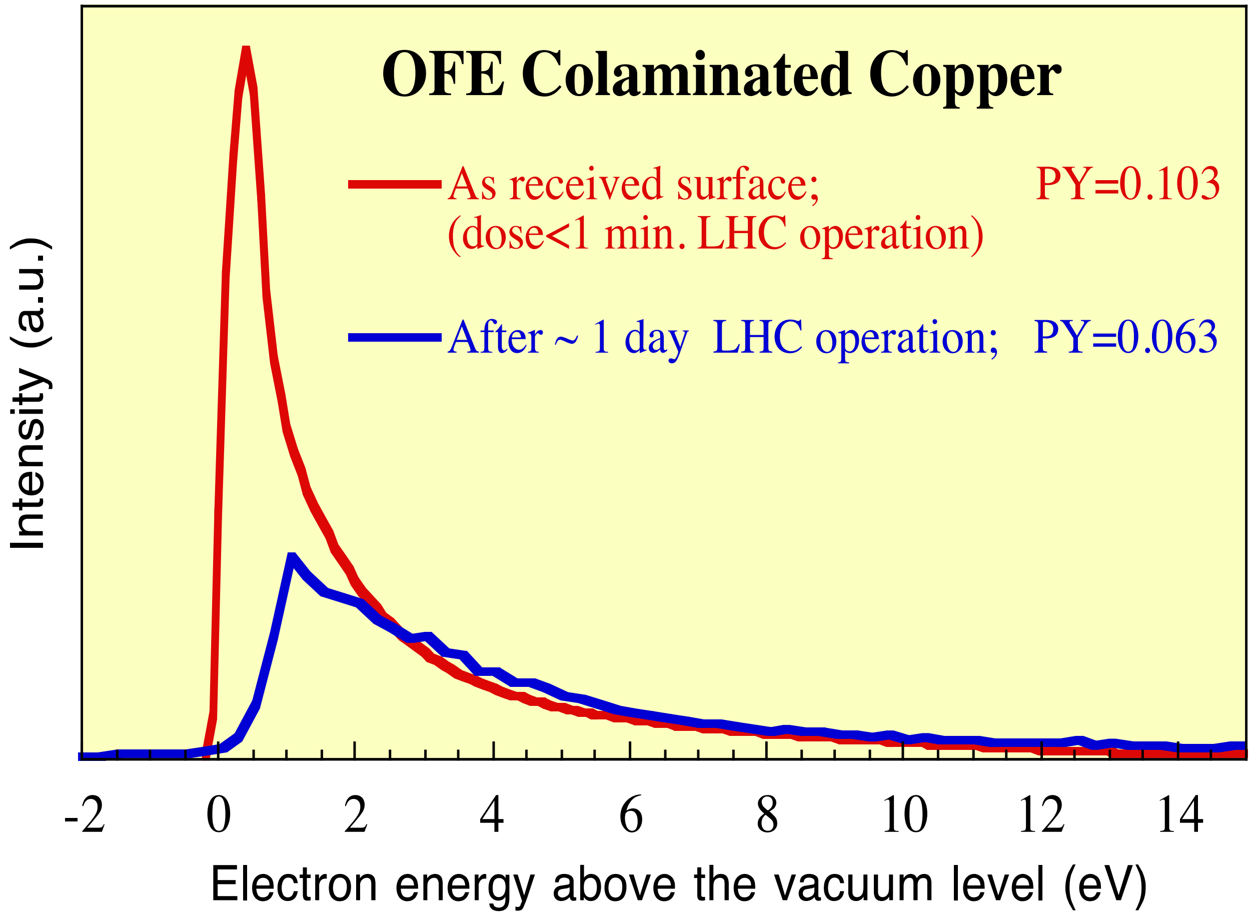
FIG. 3 (color online). Calculated electron energy distribution at the LHC accelerator wall. The number of electrons below and above 20 eV (dotted line) is nearly equal.



- **optimize the "scrubbing" process @ LHC with beam parameters enhancing the presence, in the cloud, of higher energy el.**
- **Give a more reliable estimate of the needed scrubbing time.**

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

Beam scrubbing effect with photon



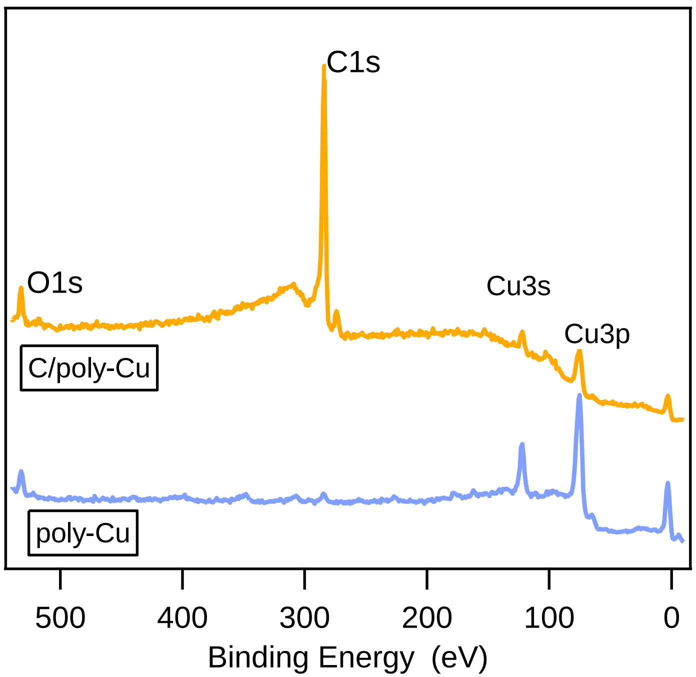
See: R. Cimino et al Phys. Rew. AB-ST 2 063201 (1999)

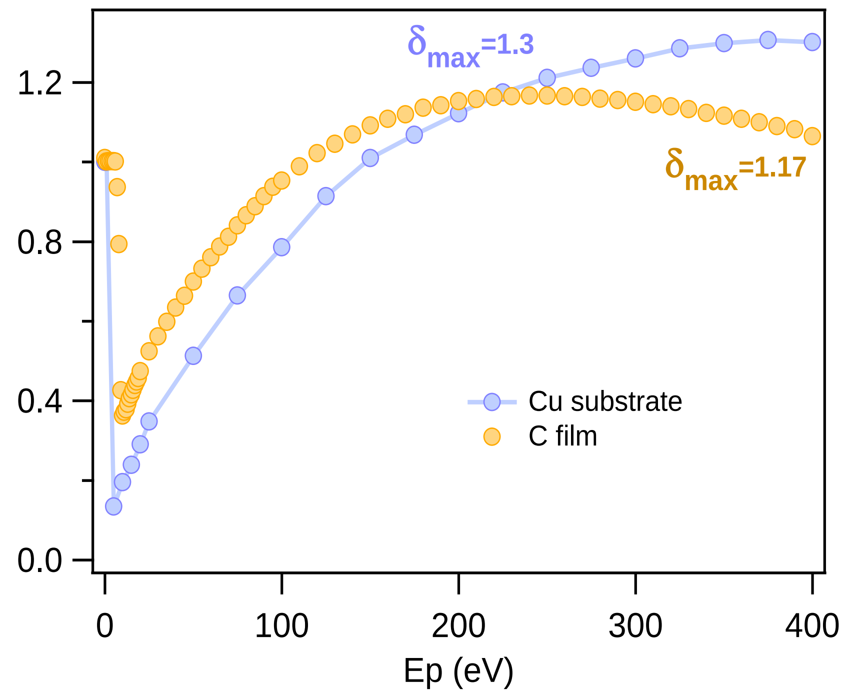
External solenoid field.	→	Not always possible…
Electrodes in the lattice.	→	If possible… (Impedance, costs.)
Scrubbing (or conditioning)	→	-Efficiency (time & final SEY)…
Intrinsically low SEY material	→	Stability and material choice…
Geometrical modifications	→	Impedance. Space, Machining costs.

C films on polycristalline Cu

a-C films
magnetron sputtering @ RT
p(Ar)= 10^{-2} mbar Δt = 2min

C film thickness 2-3 nm

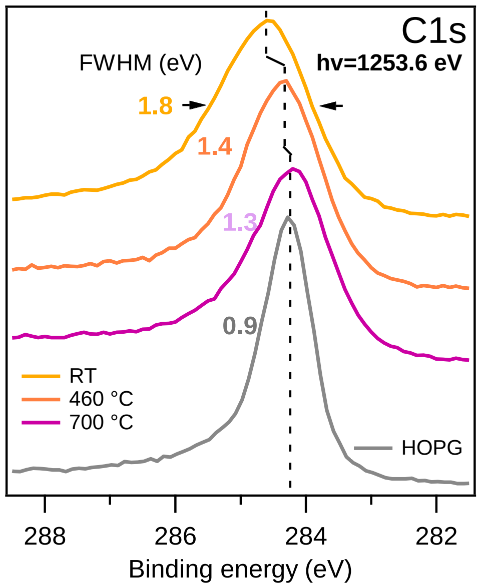


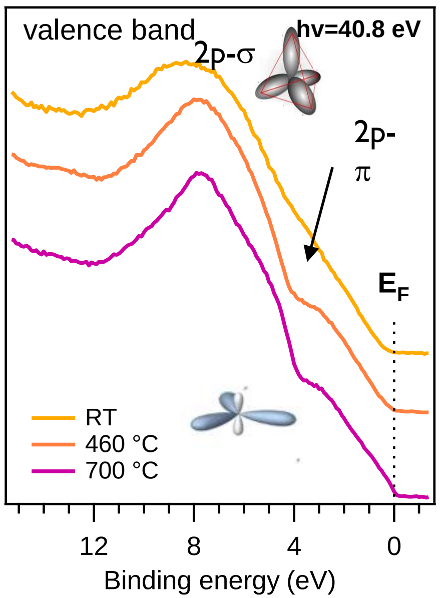


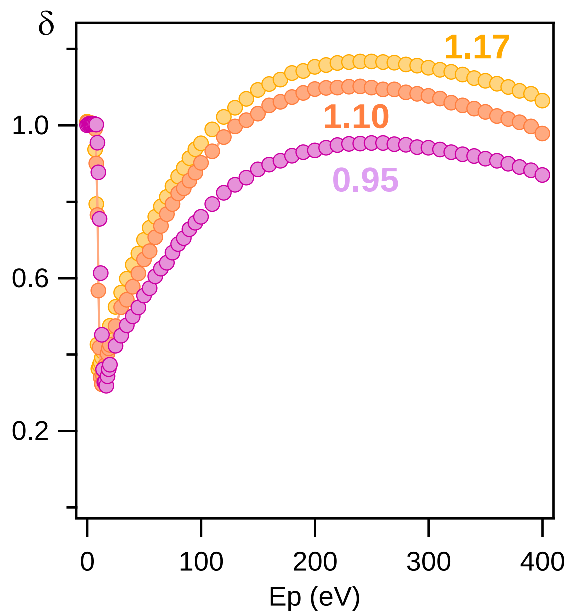
R. Larciprete et al, App. Surf. Science 2015

C films on polycristalline Cu

the graphitization of the C films corresponds to a lower SEY



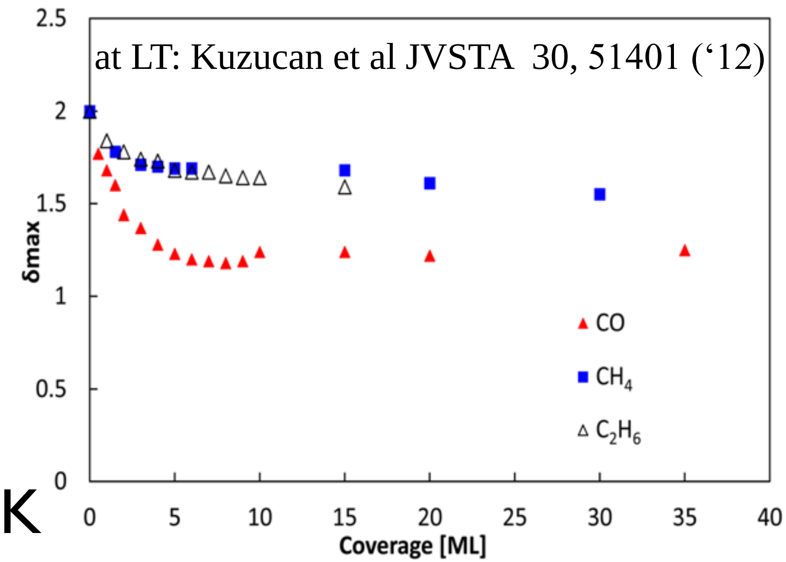




a-C bases its stability on its low reactivity

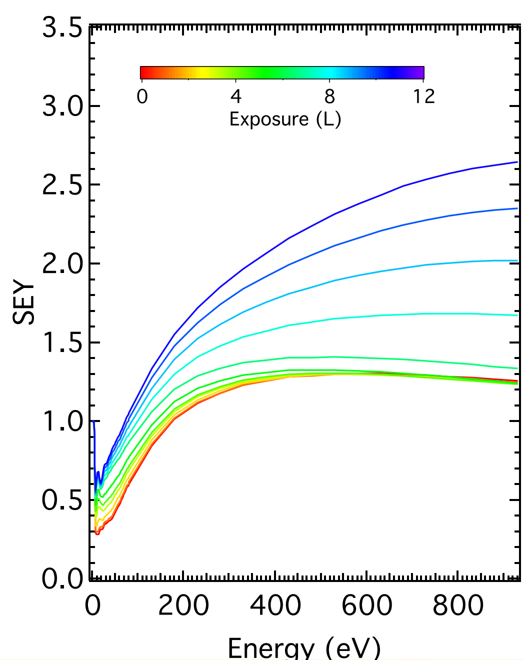
R. Larciprete et al, App. Surf. Science 2015

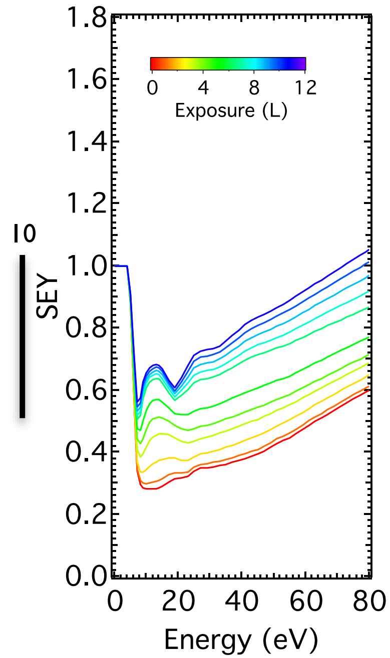
If condensed gas is physi-sorbed on a cold the surface the resulting SEY will be the one of the contaminant layer.

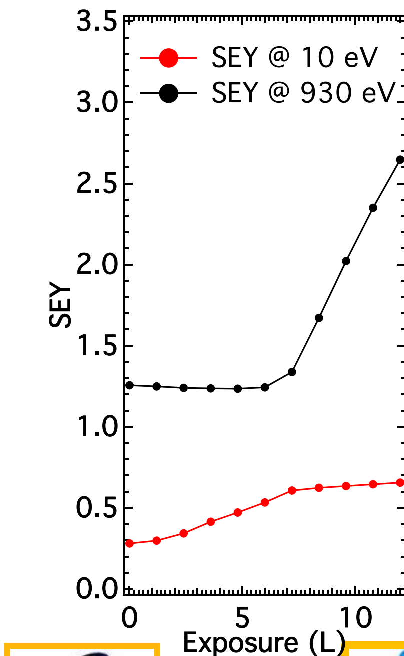


Argon on Clean Cu sample at 10 K

(see M.Angelucci et al: EuroCirCol coll and
@ Beam Dynamics meets Vacuum, Collimations, and Surfaces 2017)

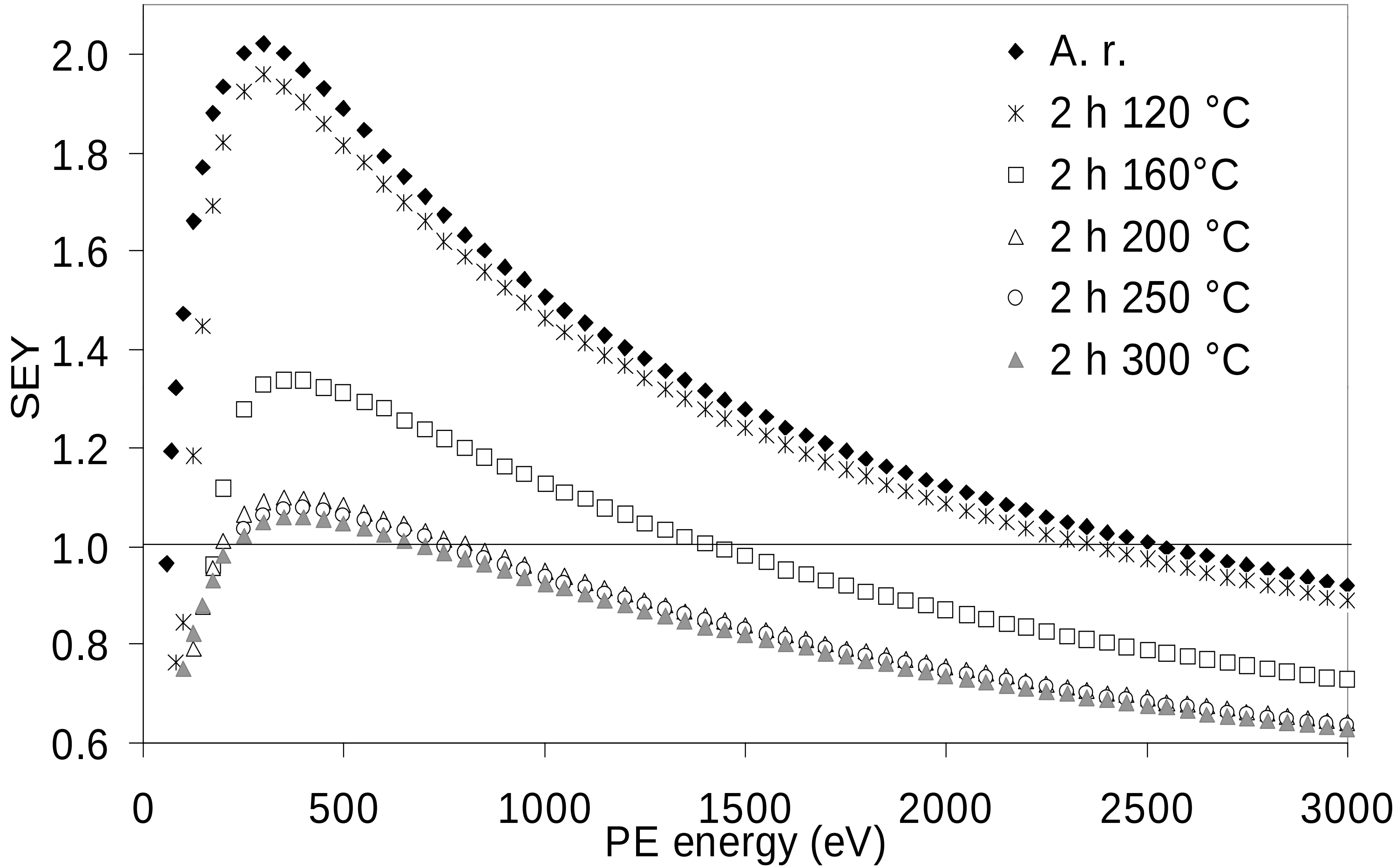






If annealing (@ ~ 200 °C) is possible: TiZrV

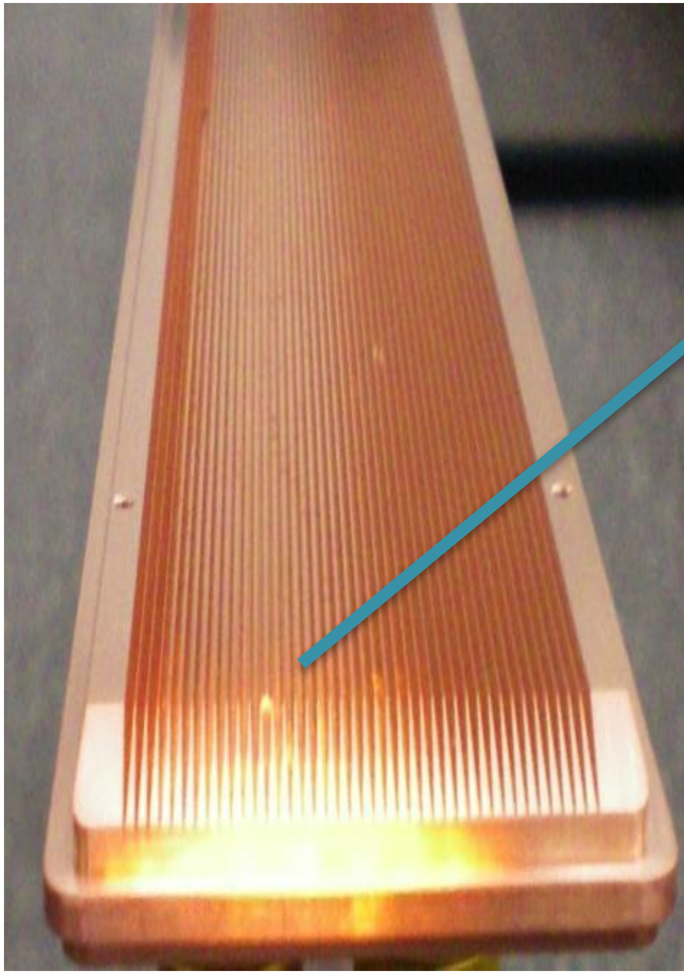
Scheuerlein et al. *Appl. Surf. Sci. 172 (2001) 95-102*

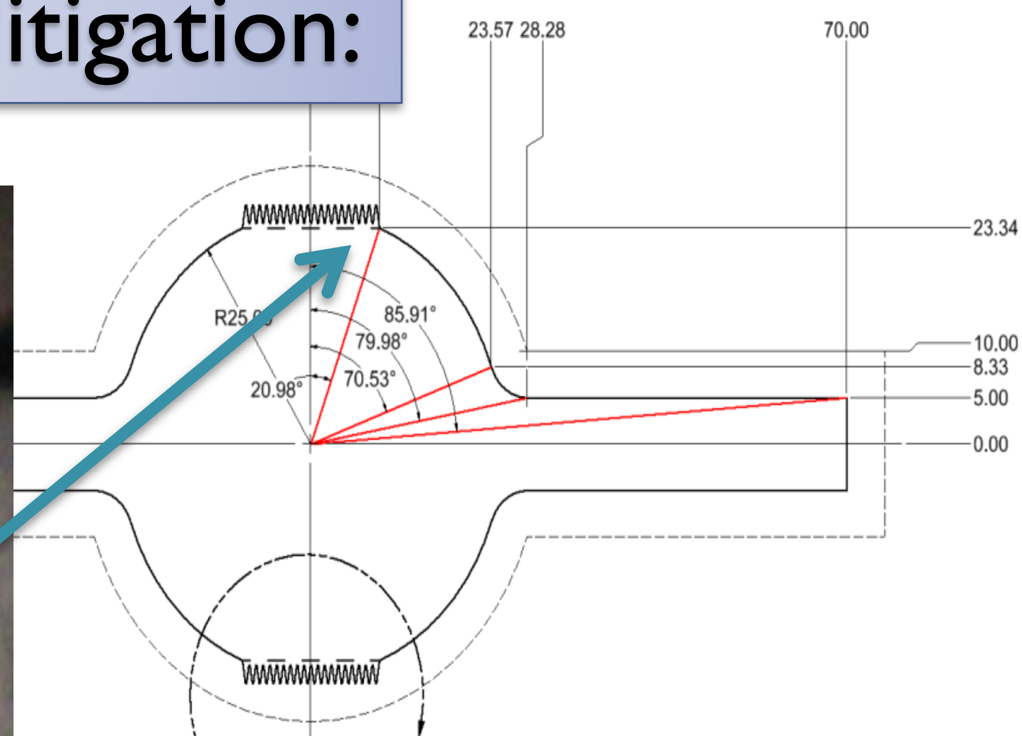


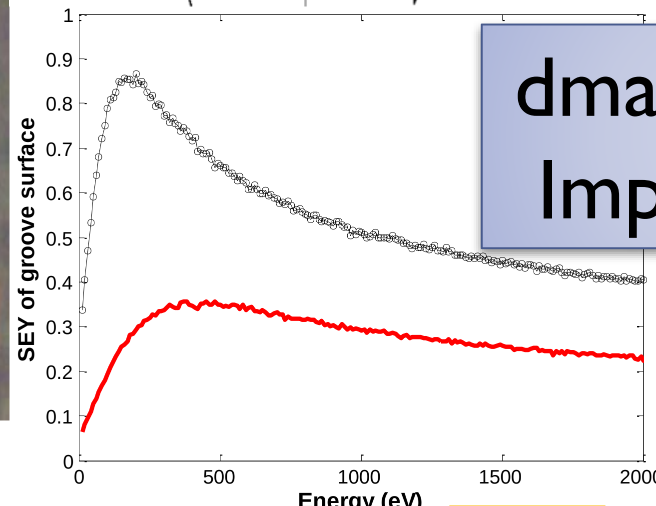
Activated NEG: it pumps, low SEY, stable: ideal mitigator ... If Resistive Wall Impedance is acceptable.

External solenoid field.	→	Not always possible…
Electrodes in the lattice.	→	If possible… (Impedance, costs.)
Scrubbing (or conditioning)	→	-Efficiency (time & final SEY)…
Intrinsically low SEY material	→	Stability and material choice…
Geometrical modifications	→	Impedance. Space, Machining costs.

Geometrical Mitigation:







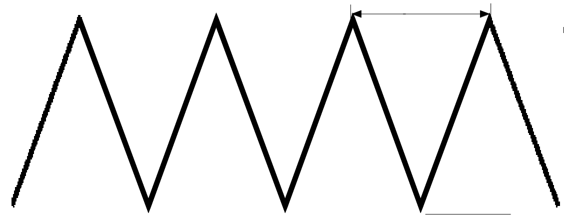
dmax,< .8 …
Impedence?

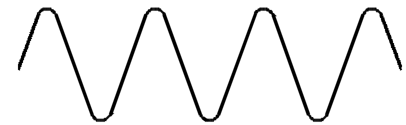
See: .A. Krasnov, Vacuum 73, 195 (2004).
M. T. F. Pivi et al., J. Appl. Phys. 104, 104904 (2008).

Impedance enhancement factor

(Code : Finite Element Method, PAC07 THPAS067, L Wang)

$$h = \frac{Z_{groovedsurface}}{Z_{smoothsurface}} = \frac{\int H^2 ds}{H_0^2 W}$$





The total impedance enhancement = η * *percentage of grooved surface*

p=1.25mm (period)

d=2.5mm (depth)

t=0.125mm (thickness)

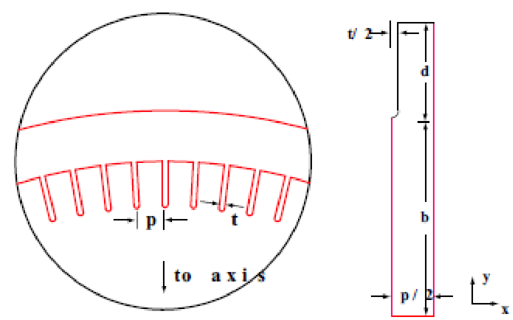
$h = 1.64$

p=1.25mm

d=2.5mm

t=0.25mm

$h = 1.42$

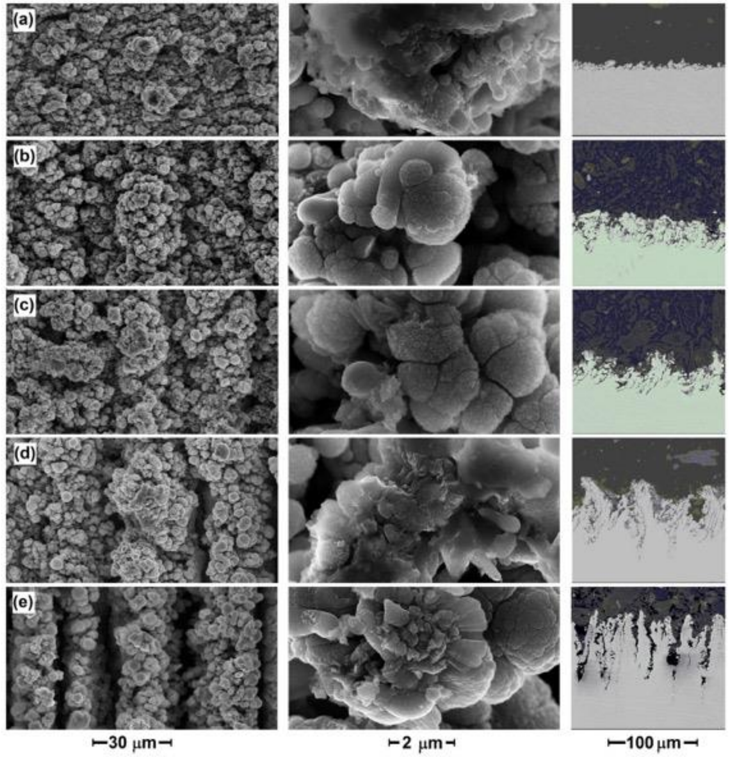


a) b)

Figure 1: a)—detail of the grooved vacuum chamber wall; dimensions shown are period p and fin thickness t; b)—

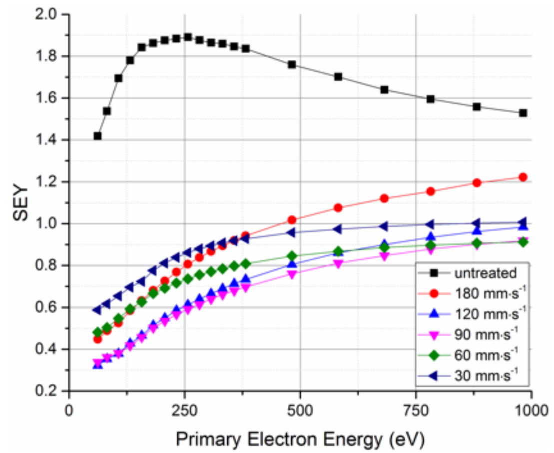
micro/nano geometrical effects

laser treatment for e⁻cloud mitigation



Investigation at **STFC** includes:

- Laser scan speed
- Laser wavelenght



See: R. Valizadeh, O.B. Malyshev, S. Wang, T. Sian, M. D. Cropper and N. Sykes. Reduction of Secondary Electron Yield for E-cloud Mitigation by Laser Ablation Surface Engineering. Appl. Surf. Sci. 404 (2017) 370–379

See also: 185. I. Montero et al., in Proc. ECLOUD'12, CERN-2013-002

Conclusion

- The beam interact with the accelerator wall and the accelerator wall interact with the beam.
- Electron-Cloud is and will be an important issue in circular accelerators in years to come!
- Numerical simulations are able to predict observed effects.
- Mitigation techniques are developing.
- **Synergic efforts, dedicated Surface, Material and Vacuum science laboratories are required to reach desired performances.**
- **Still a lot of interesting R&D!**

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