

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).

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Logos: INFN LNF, CERN, FCC

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Beam dynamic experts design a complex and high performing machine and than somebody will design a metallic shell around it: **It is a technical issue!!!** with:

- Pressure better than 10^{-9} mbar rapidly reached and stable
- Few pumps, no bake out (typically no space nor budget),
- Very low desorption yield
- High thermal conductivity
- High electrical conductivity
- No effect on the magnetic field!!
- Mechanically robust
-And, of course, cheap!

But: Vacuum interact with the beam!

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One real example to see it:

8-10-2010

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

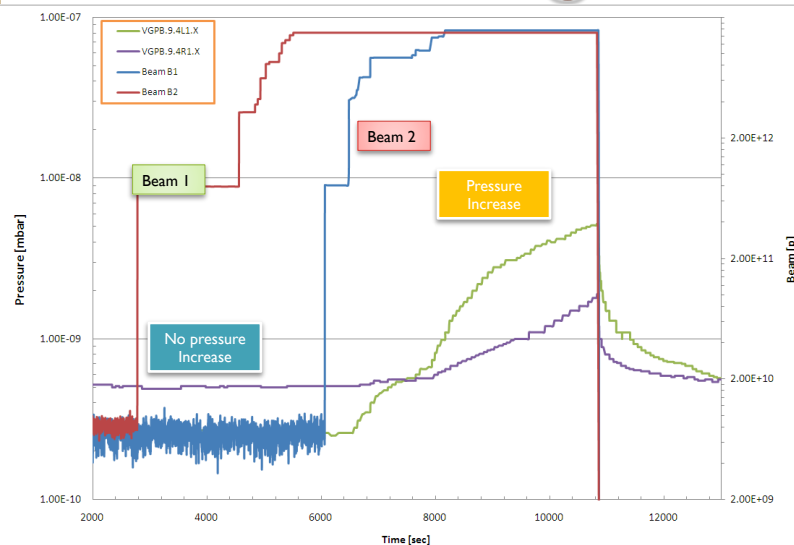
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Exotic Vacuum behavior @ LHC:



450 GeV – 150 ns bunch spacing: Merged vacuum

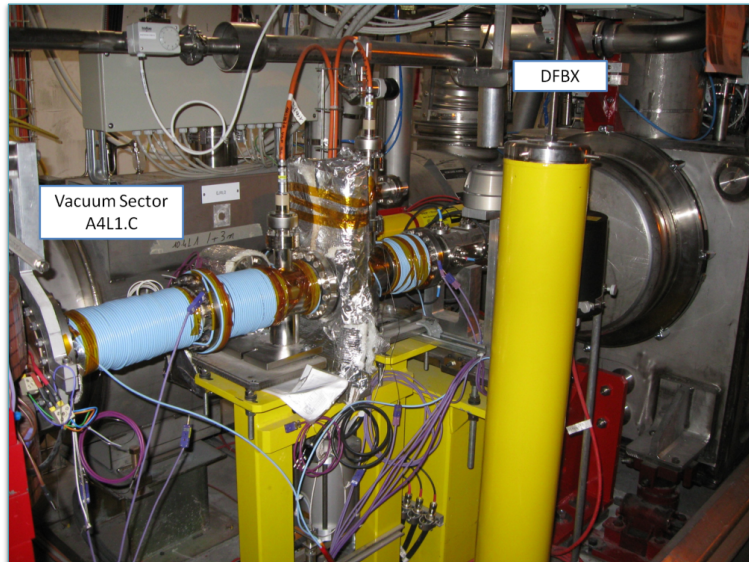
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Easily solved: Installation of Solenoids



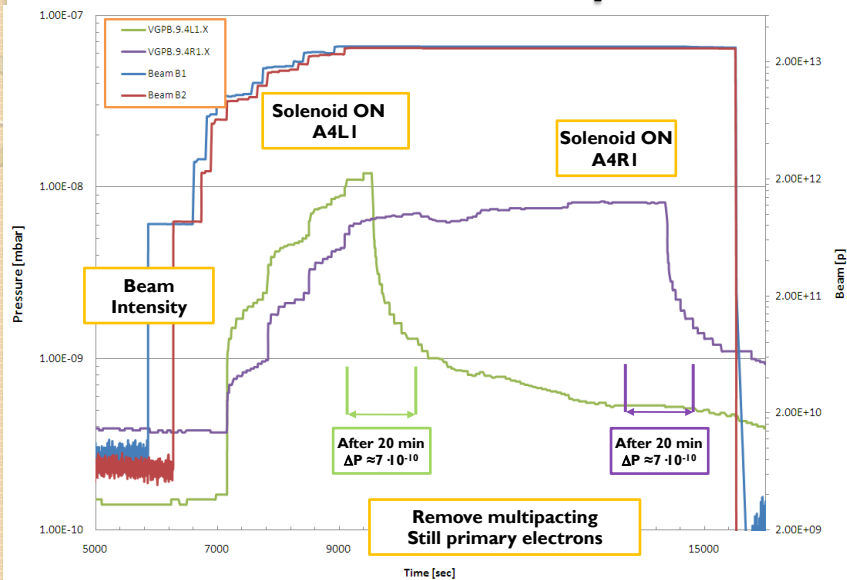
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Solenoids have effect on pressure!!!

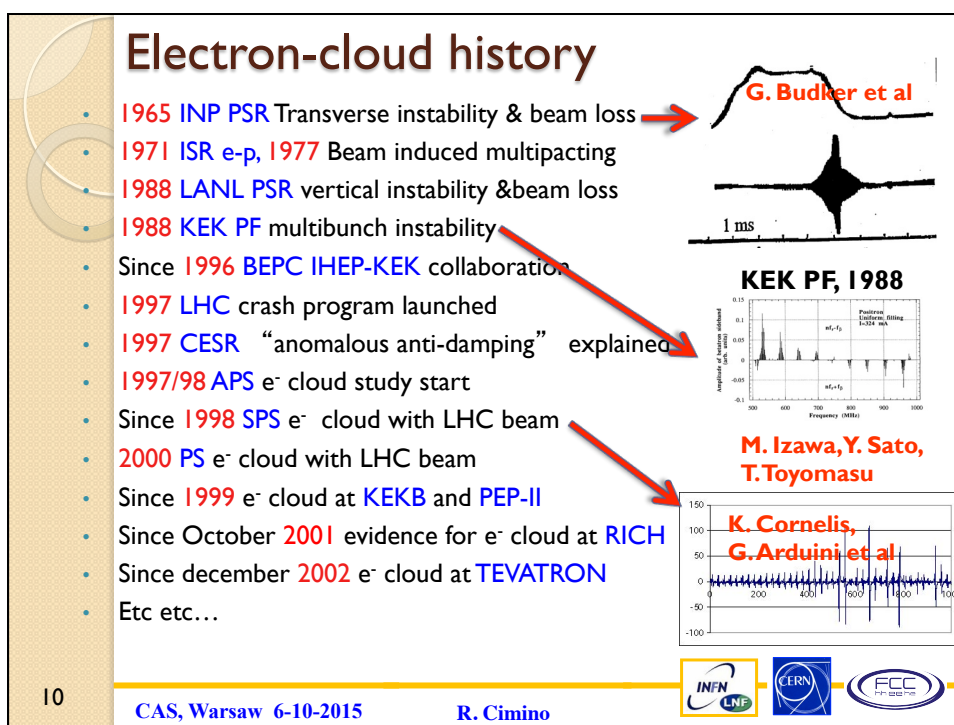
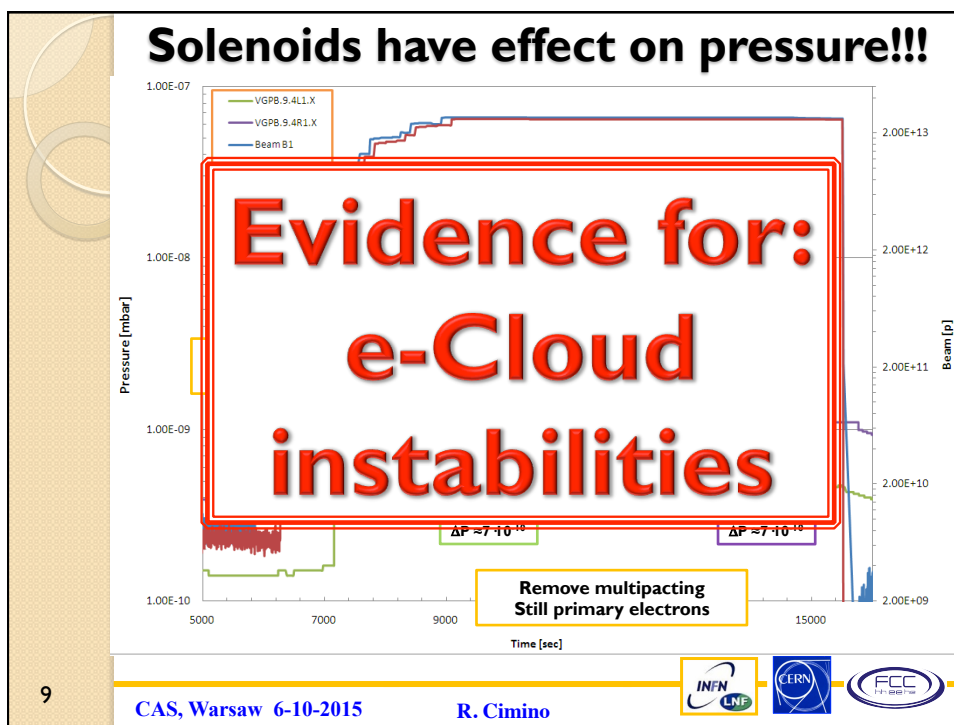


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Vacuum in new generation accelerators is much “more” than a technical issue!

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

LHC arcs

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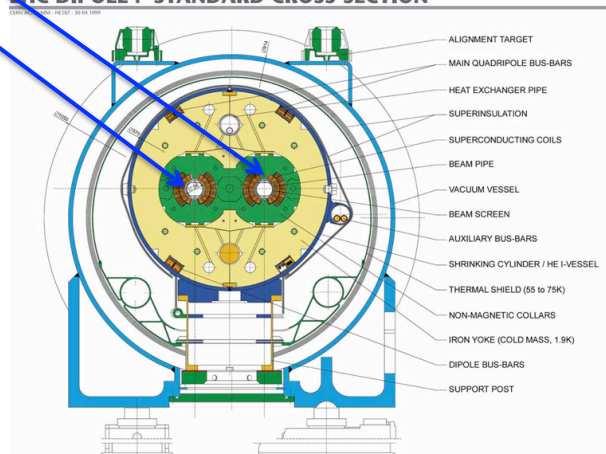
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Cold Bore @ 1.9 K

Static

LHC DIPOLE : STANDARD CROSS-SECTION



Extreme High Static Vacuum ($\ll 10^{-13}$ Torr)

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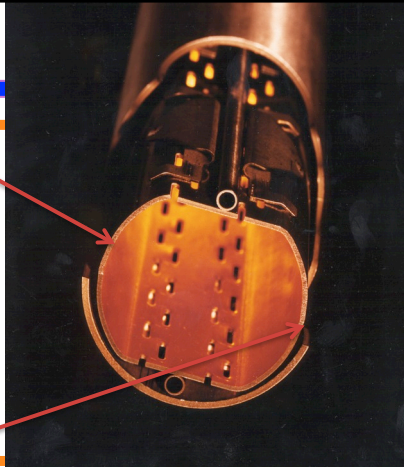
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Static Cold Bore @ 1.9 K

Radial Distance


Need of a Beam Screen
@ $5\text{K} < T < 20\text{K}$
to reduce heat load (SR, Eddy current, Impedance, etc...) on Cold bore for thermal load issues



T=0, without beam

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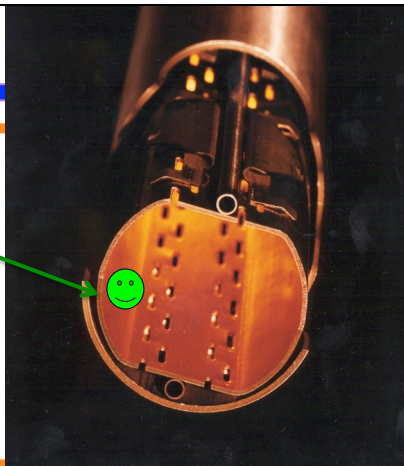
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Static Cold Bore @ 1.9 K

Radial Distance


Let us see what happens to the Beam screen Surface during operation

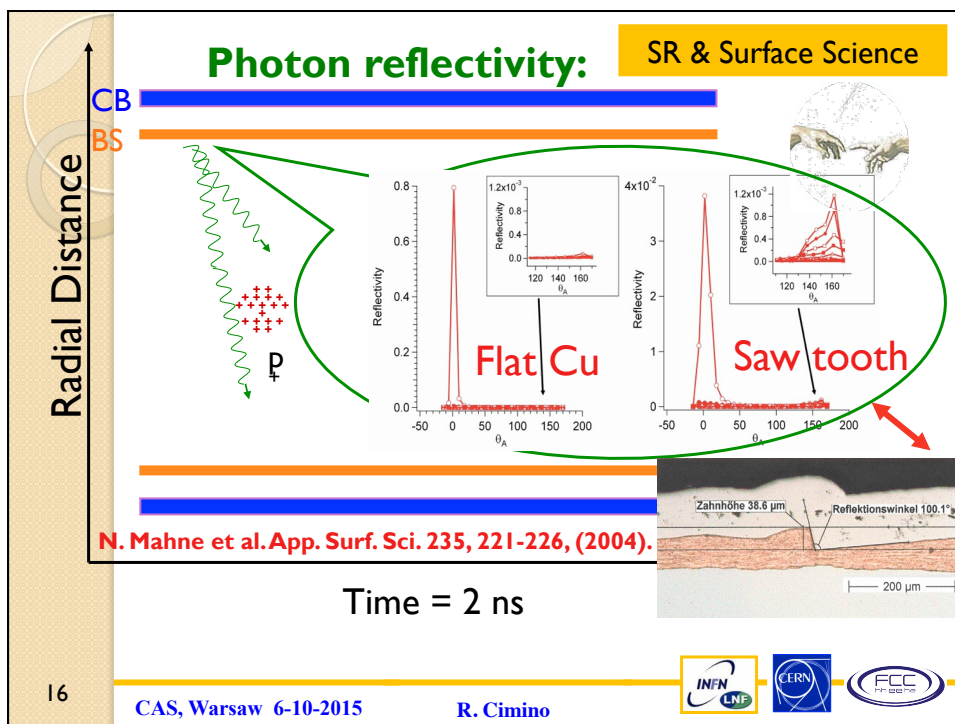
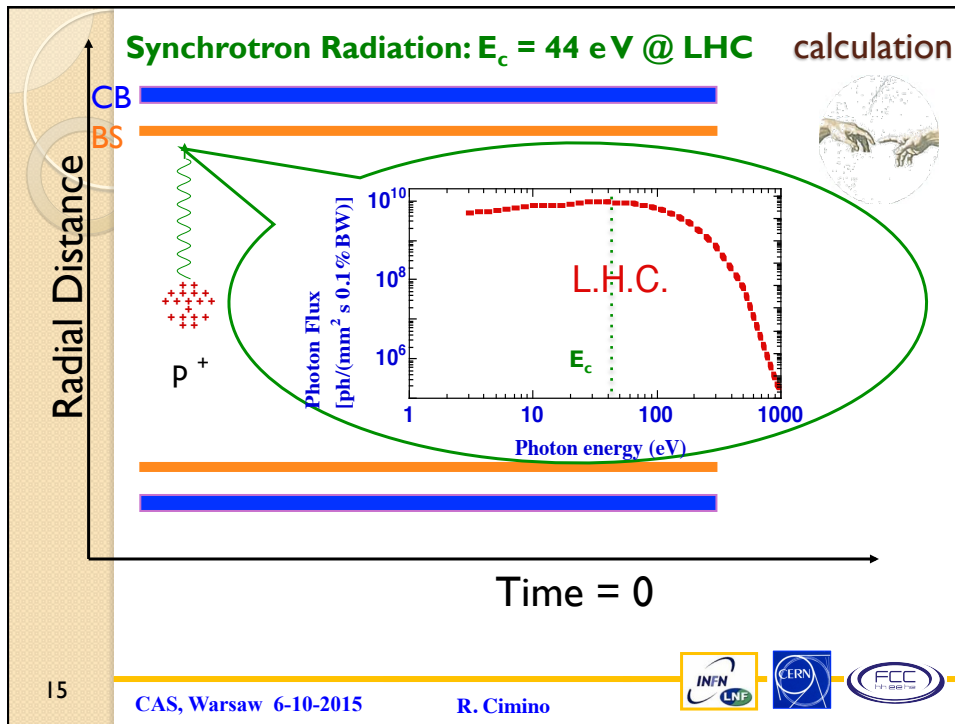


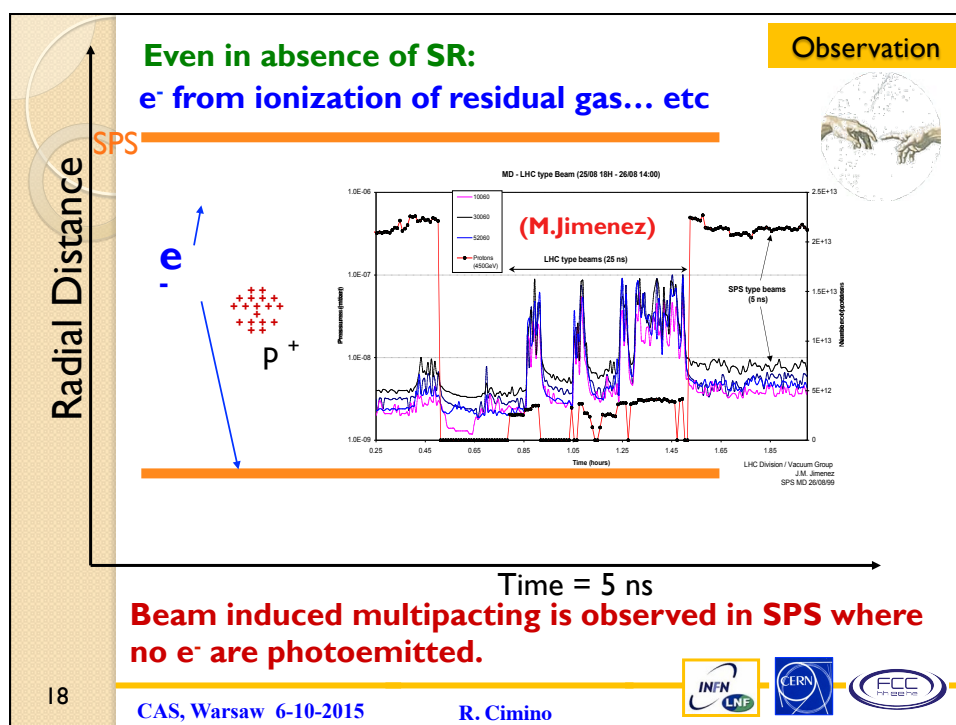
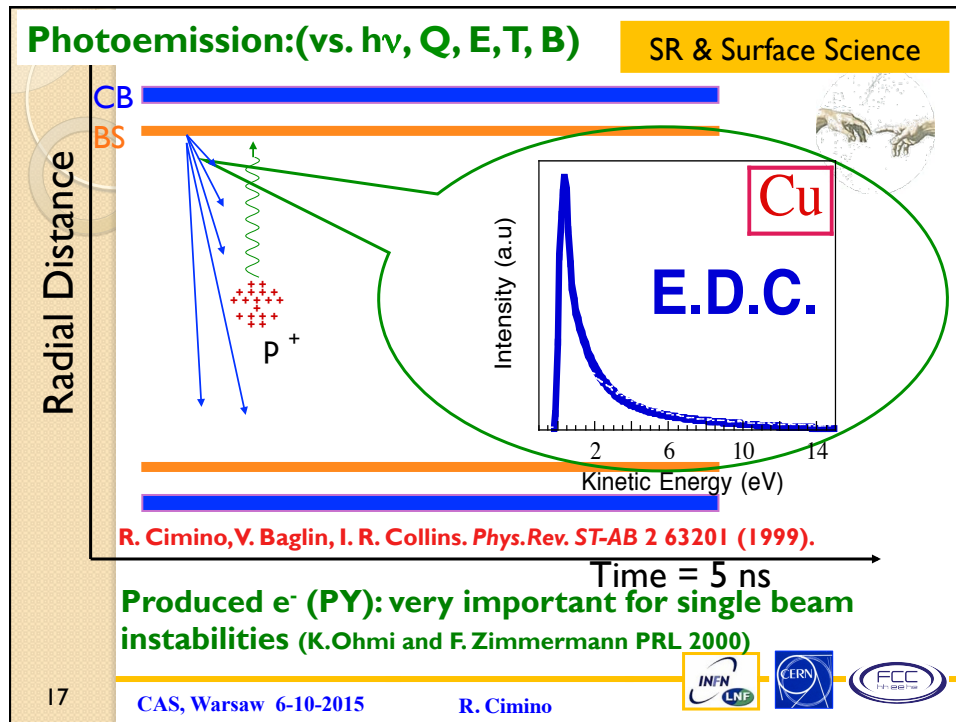
T=0, without beam

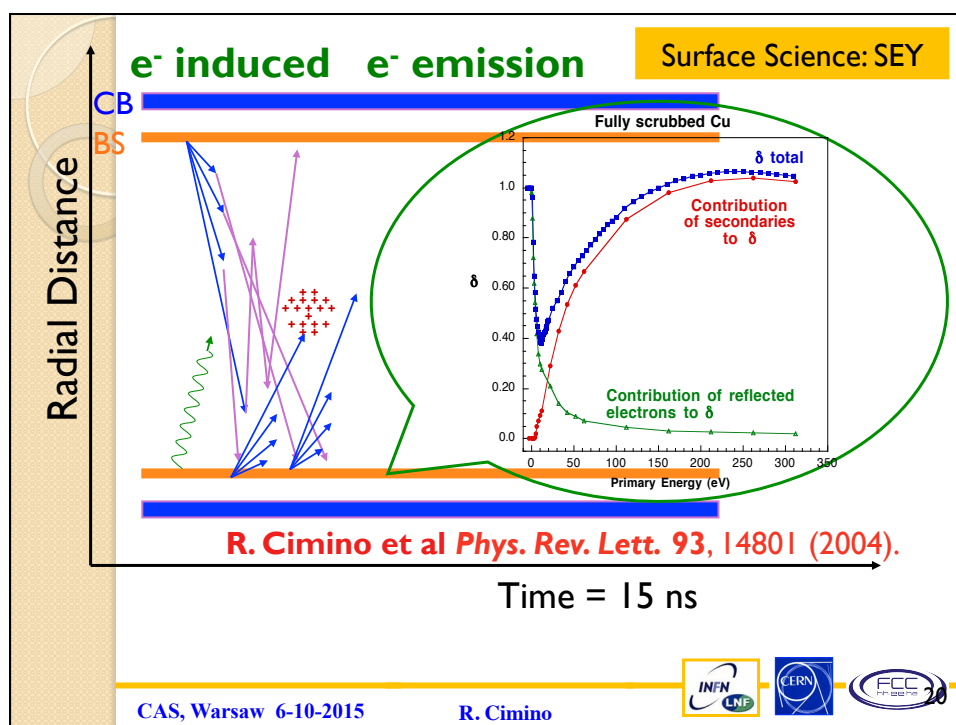
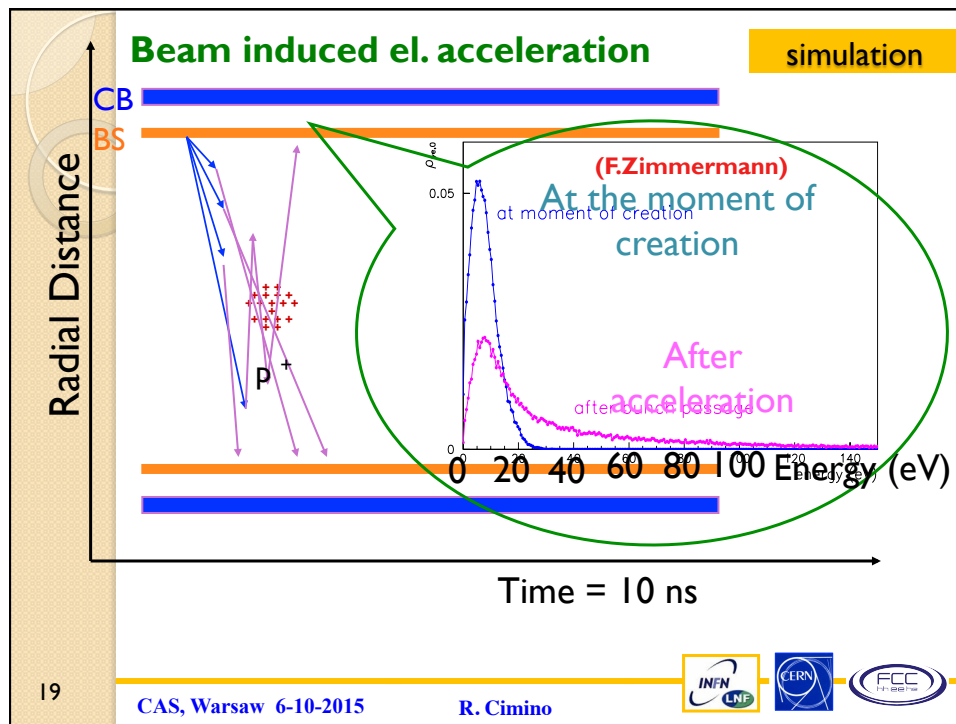
14

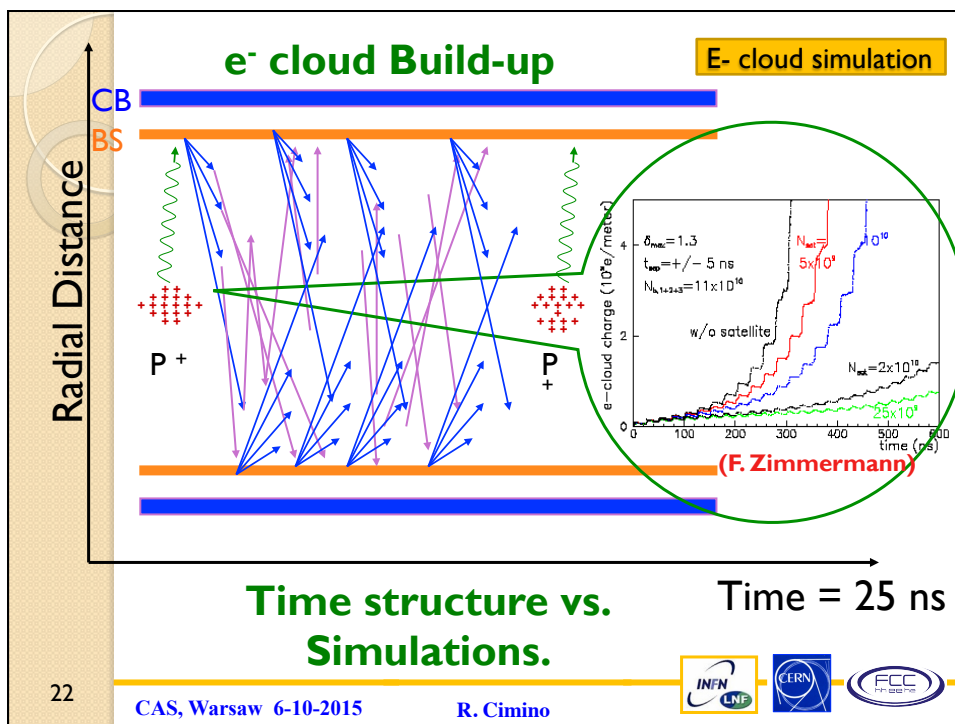
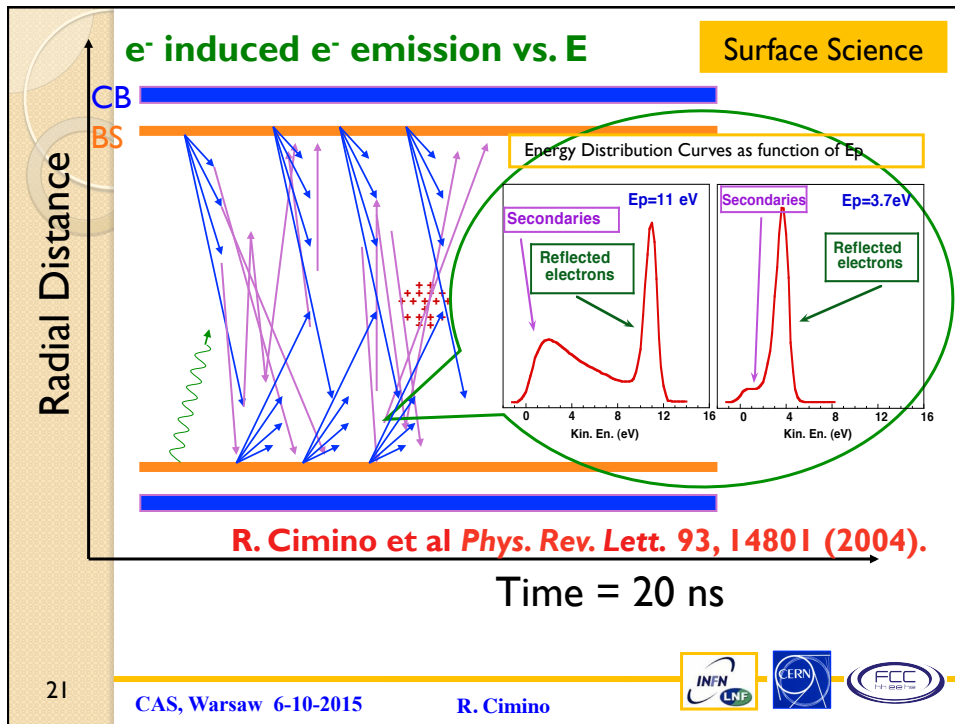
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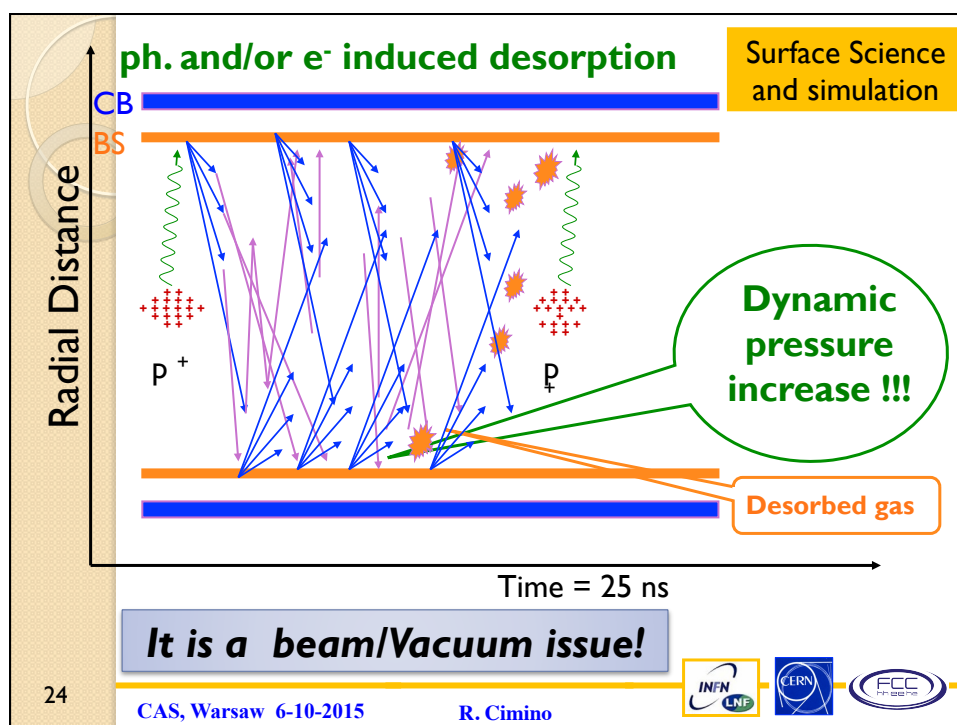
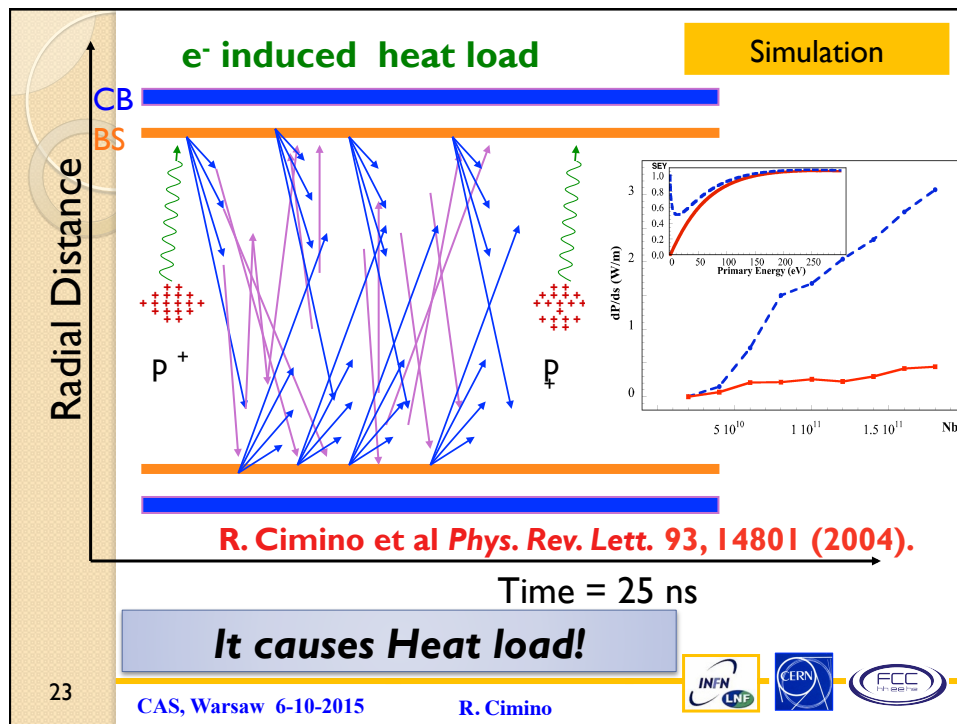


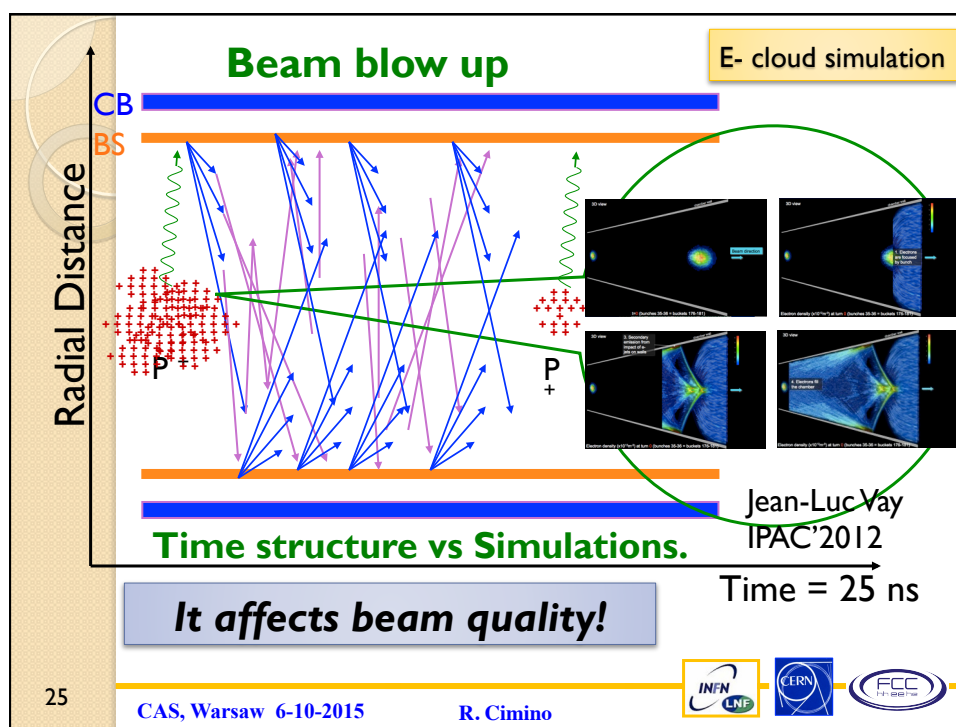












Electron cloud in accelerators

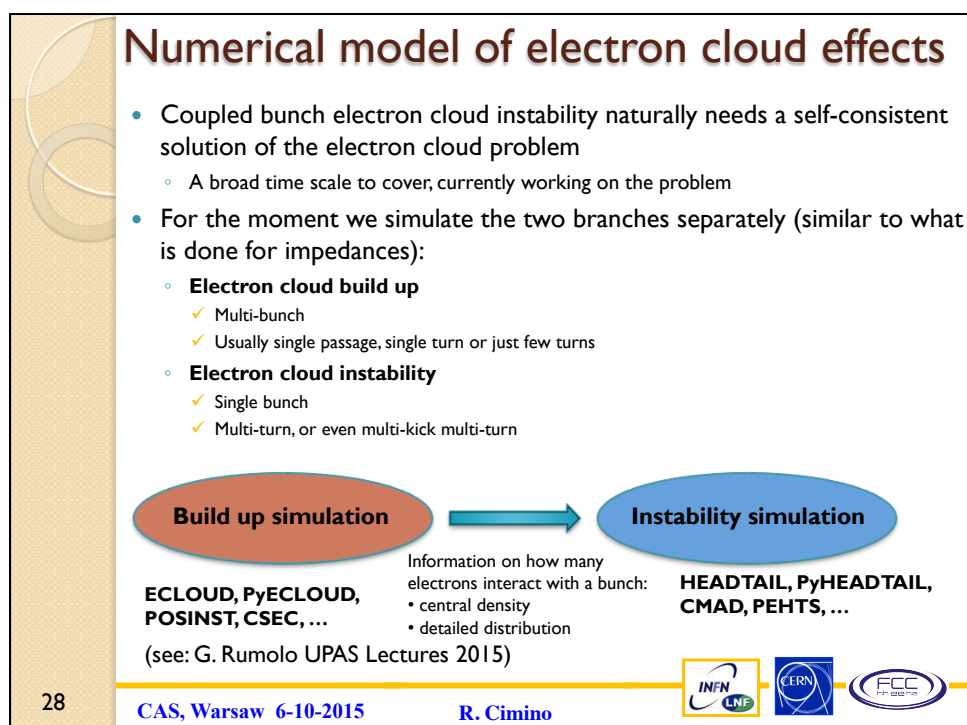
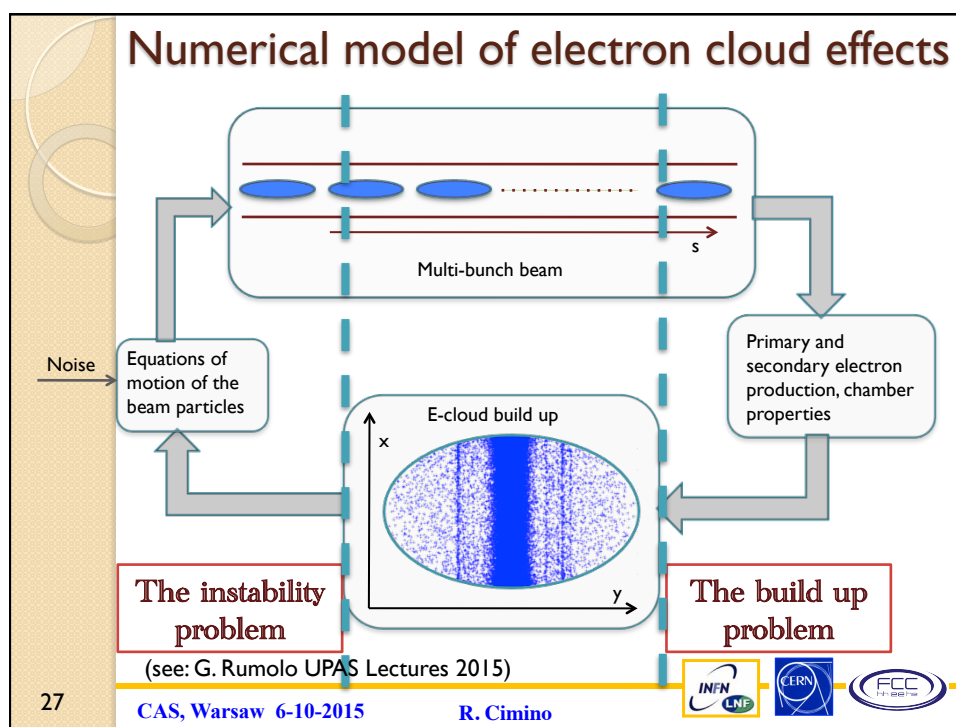
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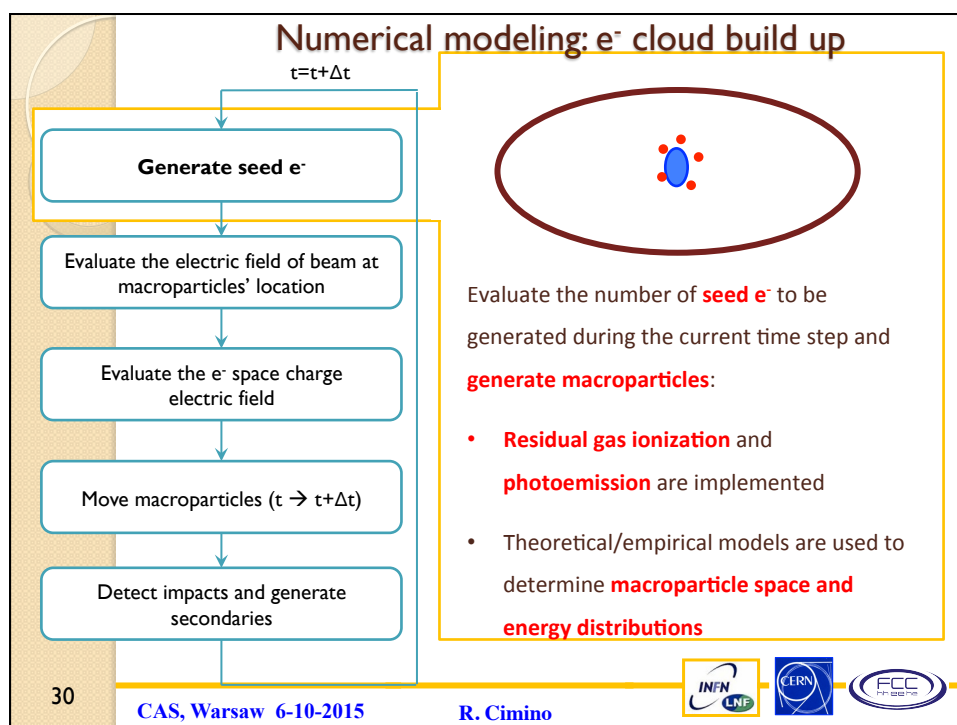
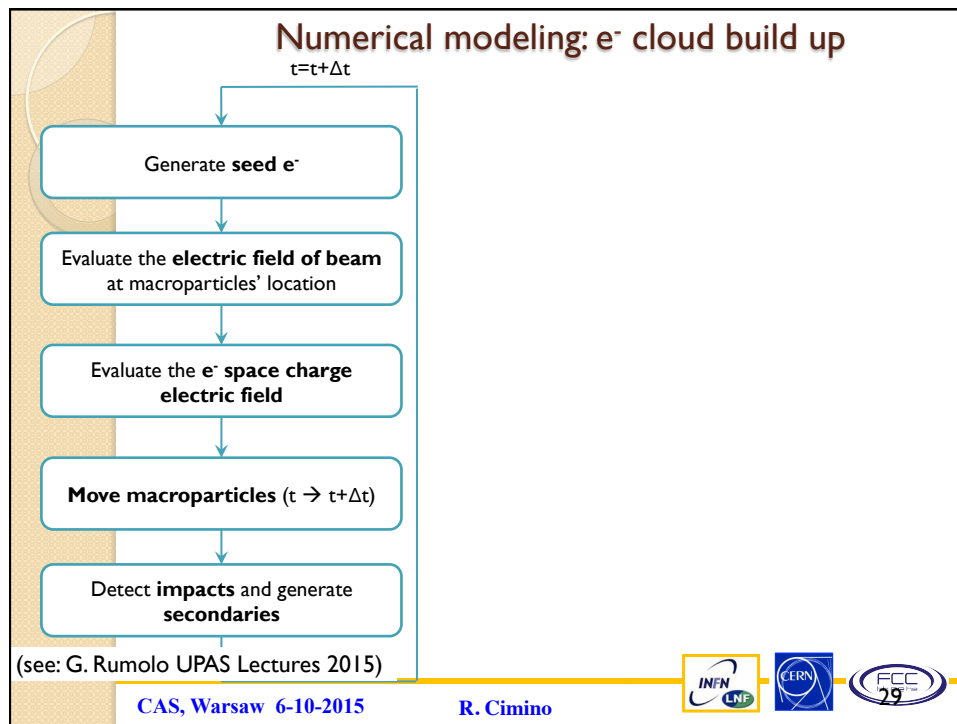
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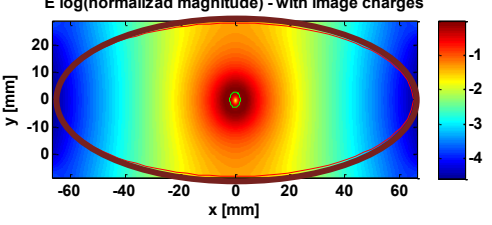
Numerical modeling: e⁻ cloud build up

$t = t + \Delta t$

```




graph TD
    A[Generate seed e-] --> B[Evaluate the electric field of beam at macroparticles' location]
    B --> C[Evaluate the e- space charge electric field]
    C --> D[Move macroparticles (t → t+Δt)]
    D --> E[Detect impacts and generate secondaries]
    E --> A
        
```

E log(normalized magnitude) - with image charges



- The field map for the relevant chamber geometry and beam shape is **pre-computed on a suitable rectangular grid and loaded from file** in the initialization stage
- When the field at a certain location is needed a **linear (4 points) interpolation algorithm** is employed

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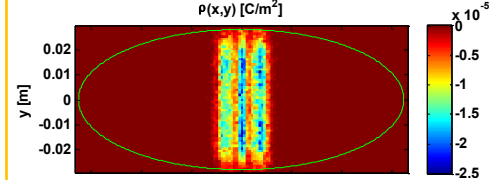
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```

$\rho(x,y) [C/m^2]$



Use of PIC (Particle in Cell) algorithm for e⁻ space charge field: **Poisson equation**:

$$\nabla^2 \phi(x, y) = -\frac{\rho(x, y)}{\epsilon_0}$$




with $\phi(x, y) = 0$ on the boundary

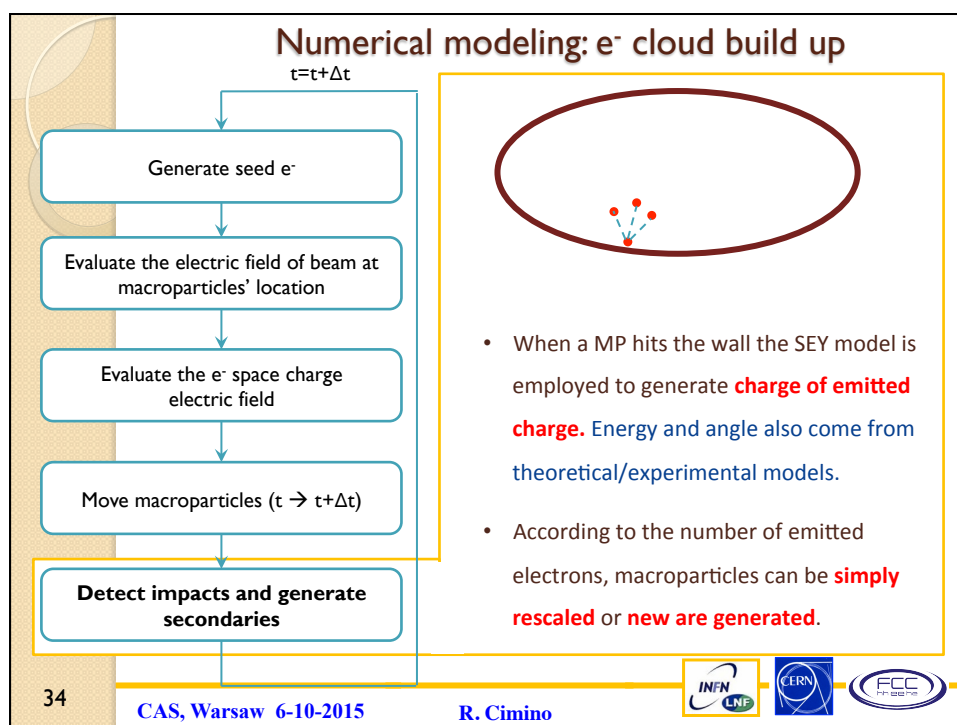
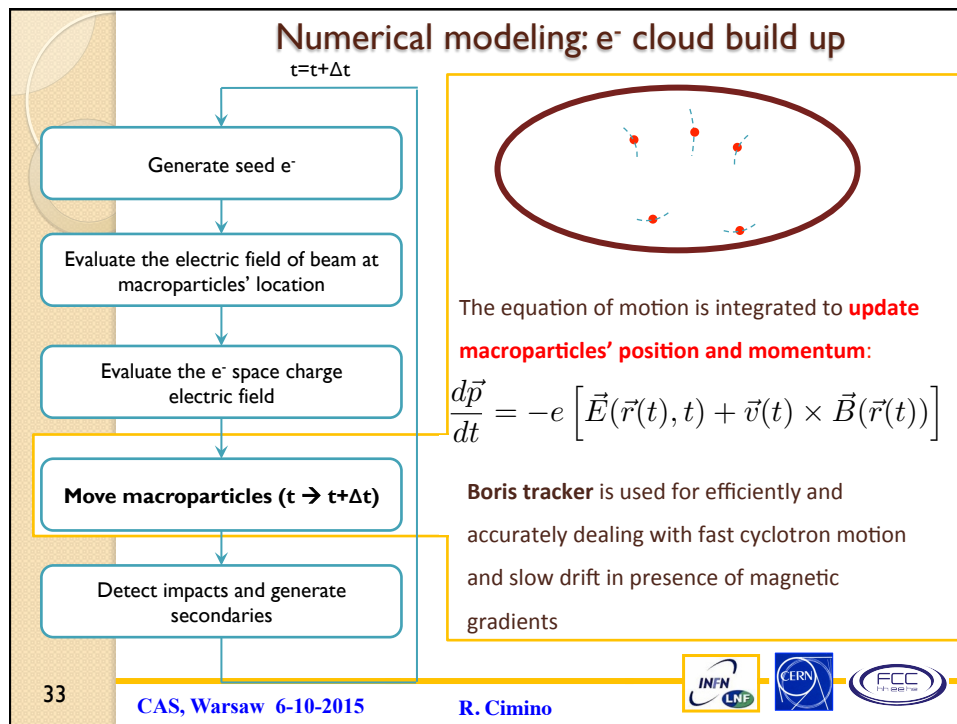
The **electric field**, given by:

$$\vec{E}(x, y) = -\nabla \phi(x, y)$$

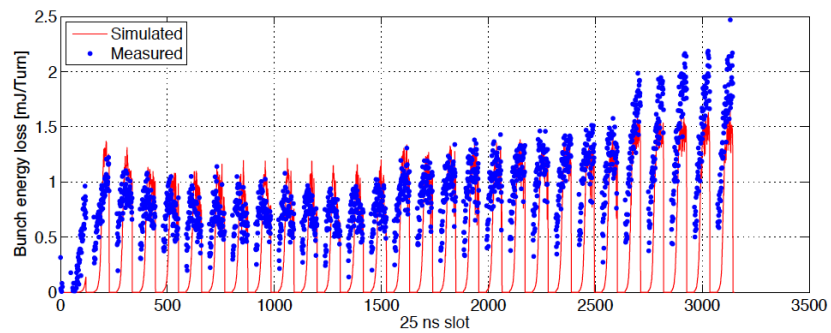
is calculated on the grid points and interpolated at the macroparticles' positions

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Numerical modeling: e⁻ cloud build up



- Example: determine the bunch-by-bunch phase shift and compare it with machine measurements

(see: G. Rumolo UPAS Lectures 2015)

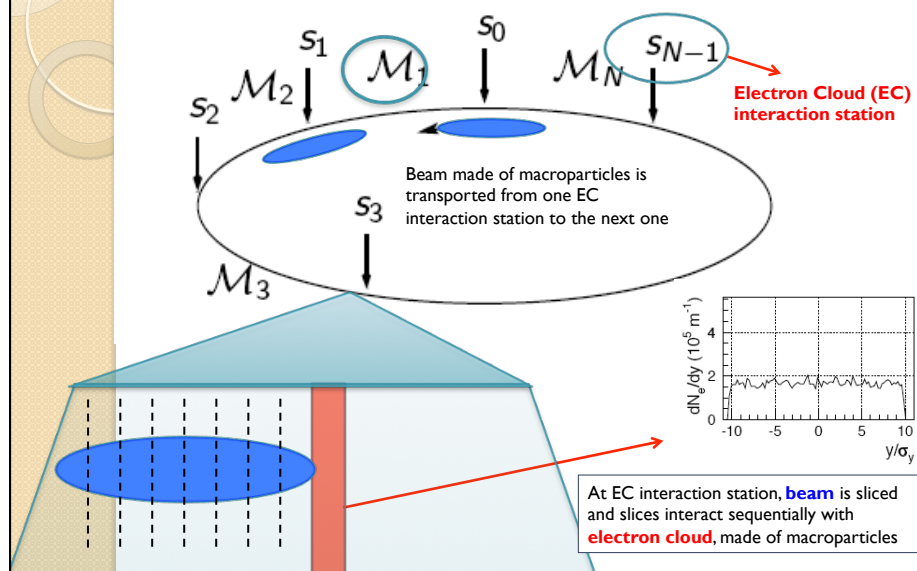
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Numerical modeling: electron cloud instability



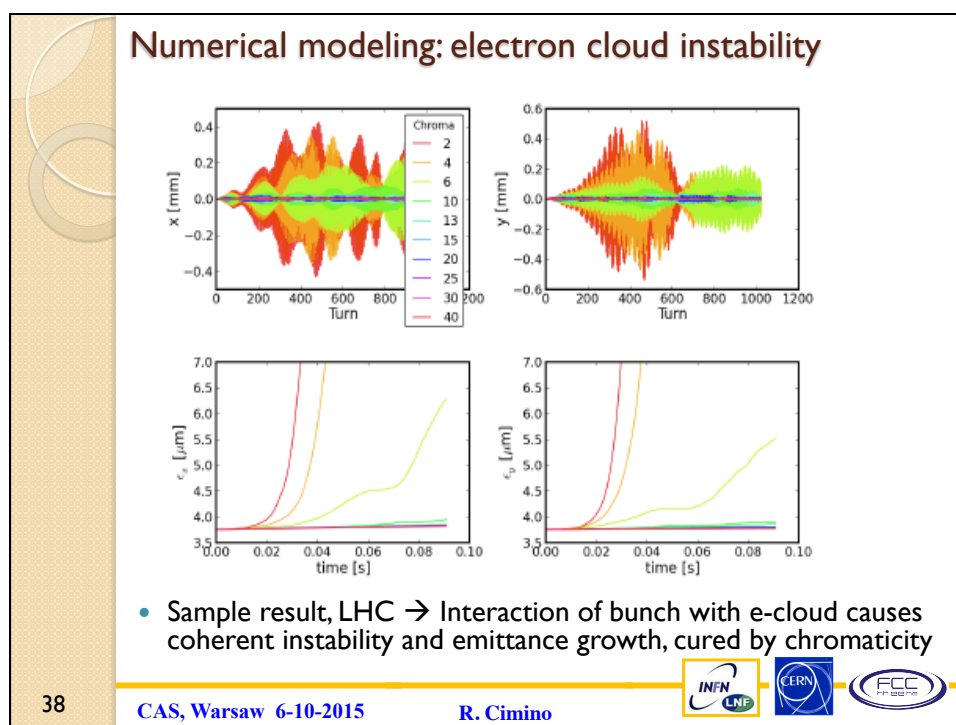
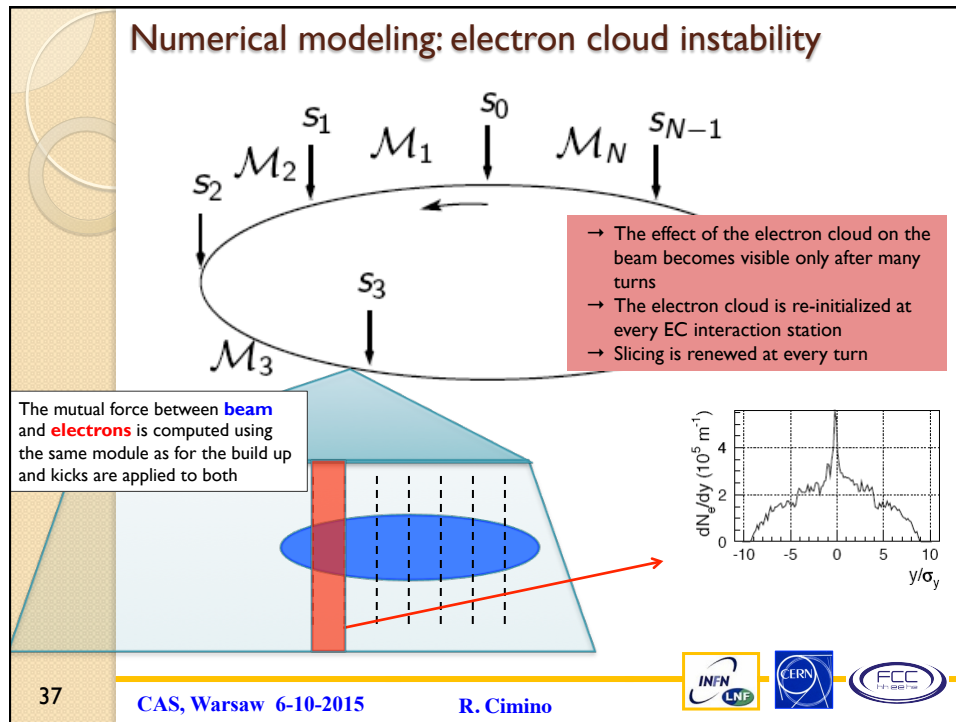
(see: G. Rumolo UPAS Lectures 2015)

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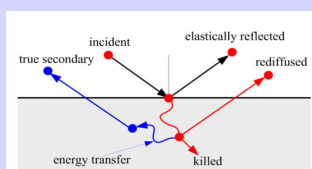
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Secondary Electron Yield (SEY)



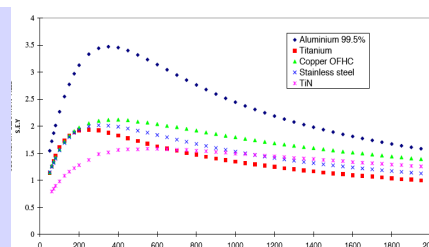
secondary electron emission

three-step process:

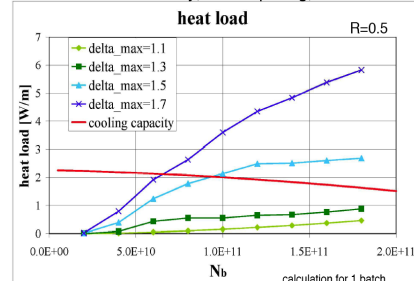
- production of SEs at a depth z
- transport of the SE toward the surface
- emission of SE across the surface barrier

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).



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



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

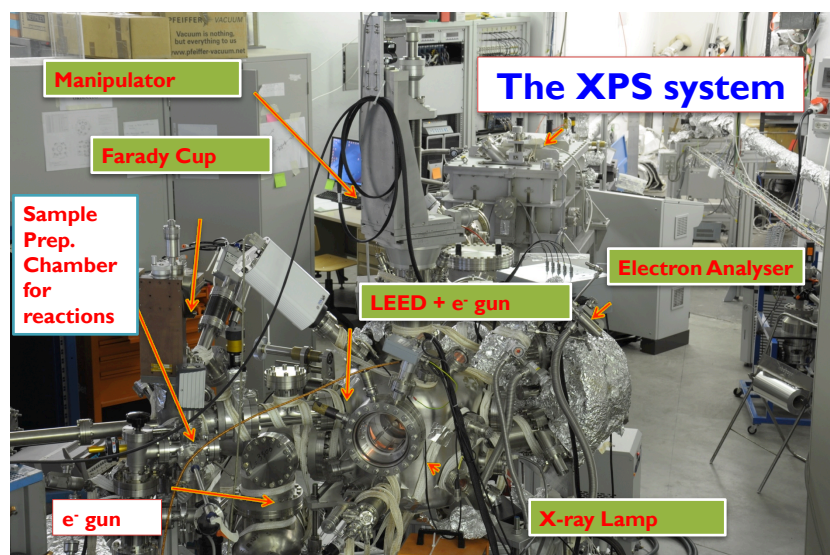
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Need of "state of the art" Surface Science systems to study SEY



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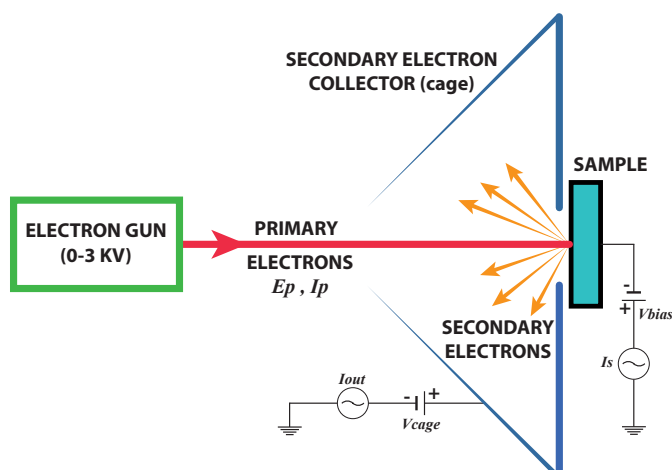
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Measure of Secondary e⁻ Yield: 2 methods

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



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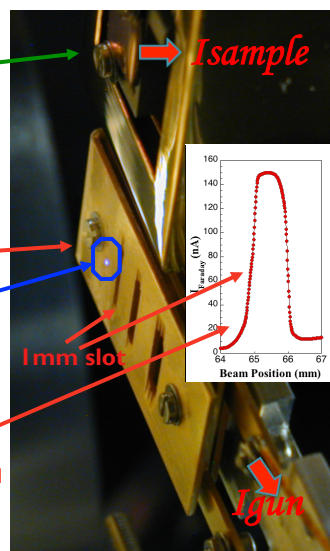


2nd method: Measure of Secondary e⁻ Yield

- 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 μ A ($20\mu\text{C/h/mm}^2$ - 20mC/h/mm^2)
- Intense spot ($\phi < 0.5$ mm) with low background

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



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Measure of Secondary e⁻ Yield: 2 methods

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

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

I_{sample} and I_{in}

Advantages:

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

Disadvantages

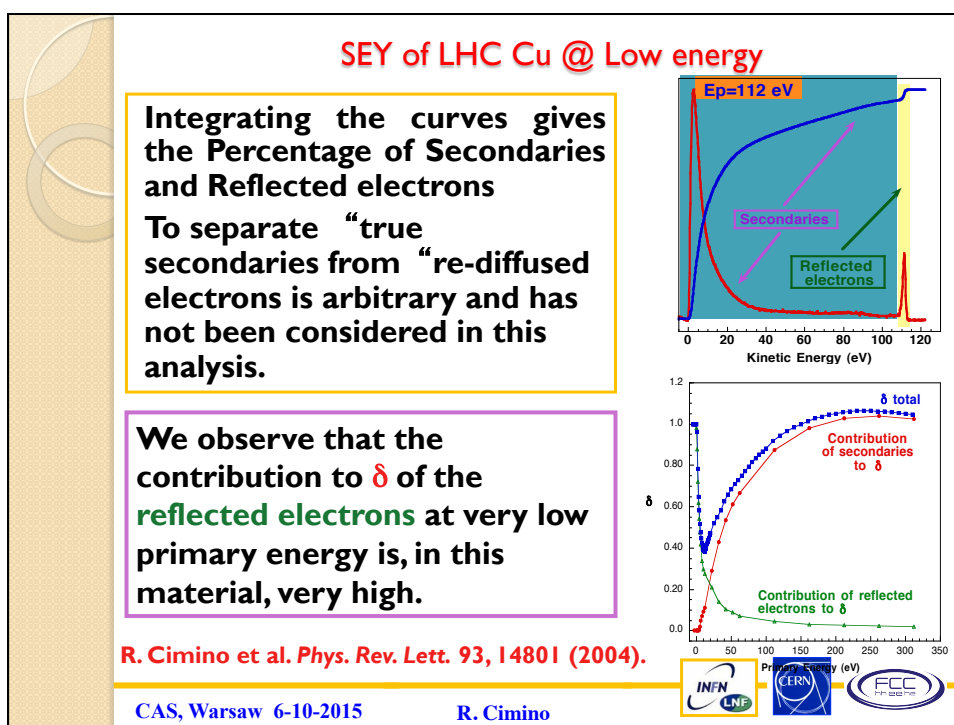
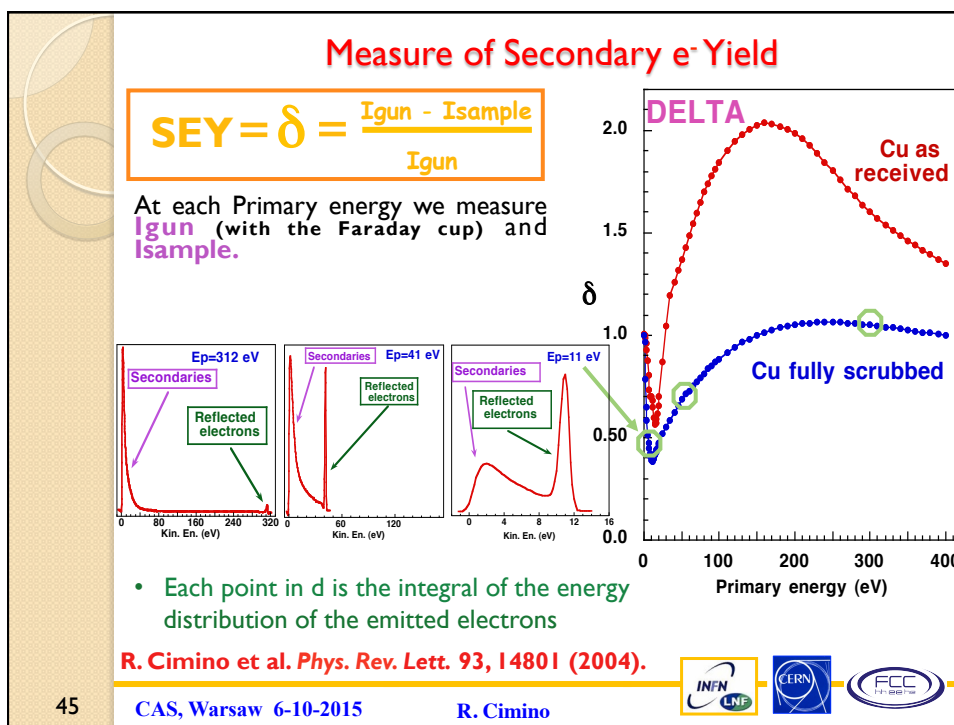
- Gun need to be very stable (takes time)
- More work (2 separate runs)

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Recently A. N. Andronov, A. S. Smirnov, I. D. Kaganovich, E. A. Startsev, Y. Raitsev, and V. I. Demidov, (in Proceedings of ECLOUD'12 (2013), CERN-2013-002, p. 161) questioned this result based on the fact that: **Long (forgotten) history of secondary electron emission studies suggests otherwise.**

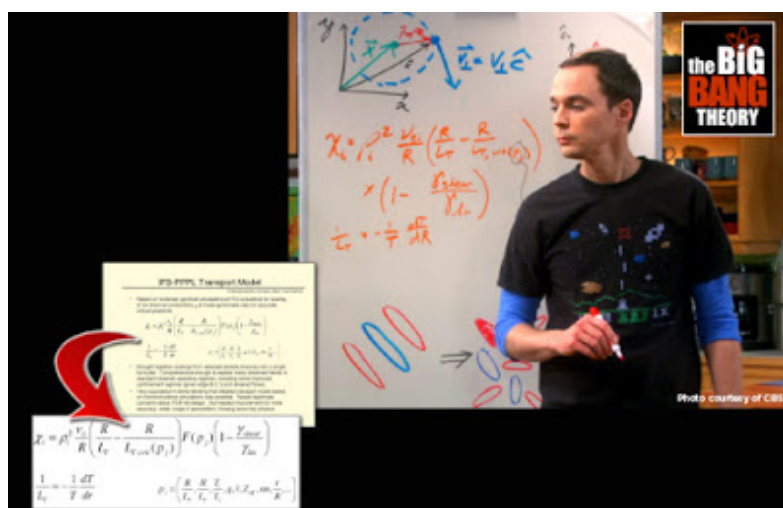
- Theoretical
 - Quantum diffraction from potential barrier
- Experimental
 - Difficulties of measurements at low incident electron energy
 - Previous careful measurements showing contrary observation
 - Probe measurements in plasma will not work

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While I will leave the theoretical aspects to others....



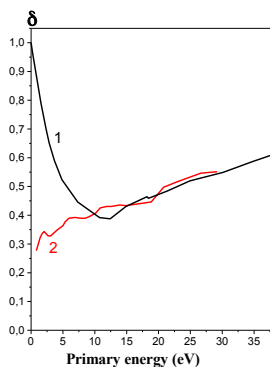
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Previous careful measurements showing contrary observation

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 ELOUD'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. Gorbatiy, Russian Physics Journal, **13** 1477 (1970).

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Previous careful measurements showing contrary observation

Total secondary electron yield of Mo as a function of incident electron energy after degassing by prolong heating of target.

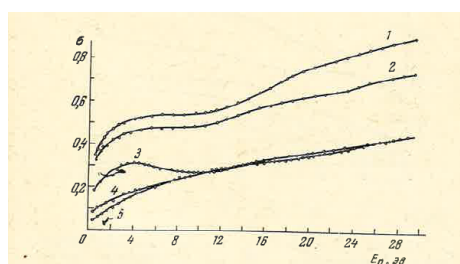


Рис. 2.9. Вторично-эмиссионные характеристики молибдена [596].
 1 — мишень не обжарена; 2 — мишень накалилась 1 мин при $t = 1000^\circ\text{C}$;
 3 — 30 мин при $t \approx 1800^\circ\text{C}$; 4 — 4 час при $t \approx 2000^\circ\text{C}$; 5 — 8 час при $t \approx 2500^\circ\text{C}$.

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

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Total secondary electron yield of Ge.

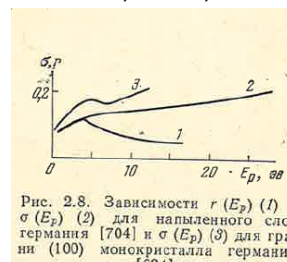


Рис. 2.8. Зависимости $\delta(E_p)$ (1) и $\sigma(E_p)$ (2) для напыленного слоя германия [704] и $\sigma(E_p)$ (3) для грани (100) монокристалла германия [634].

I. M Bronshtein, B. S Fraiman. Secondary Electron Emission. Moscow, Russia: Atomizdat, p. 60 (1969).



Thanks to this contribution we decided to address in details the capability of our setup to study LE-SEY.

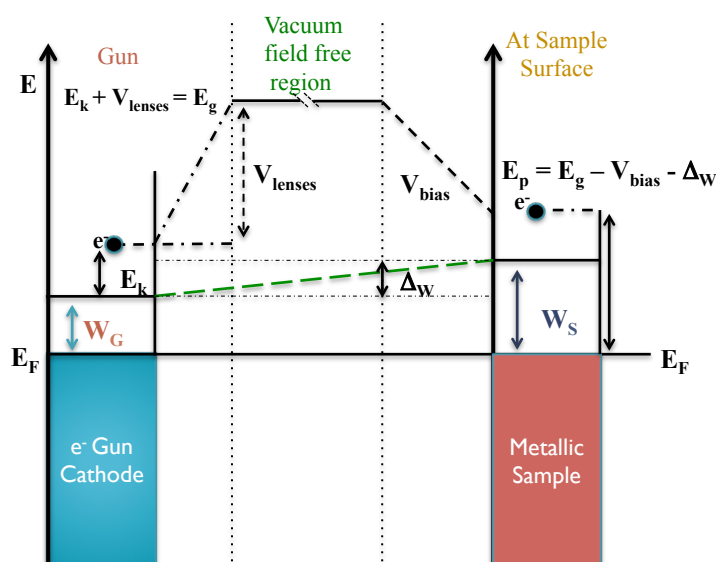
- Setting the energy scale.
- Expected Setup limitations at Low energy
- Study in identical conditions (same geometry etc.) atomically clean (XPS) Cu obtained by cycles of Ar^+ sputtering of the “as received” Cu.
- Compare it to “as received” Cu samples.
- Warning: “As received” is NOT a well defined chemical state!

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Setting the energy scale for metals



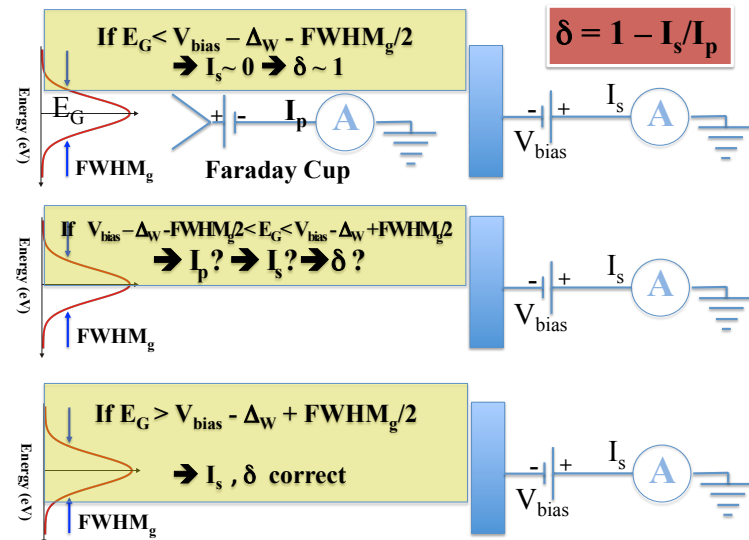
R. Cimino et al. PR ST (2015)

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Expected Setup limitations @ low energy



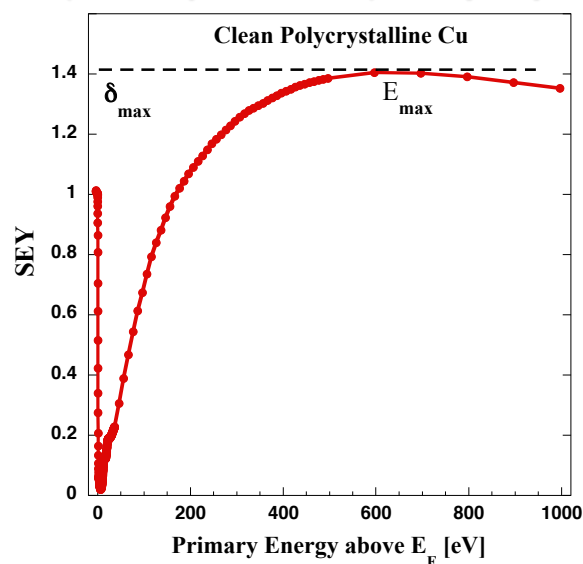
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Clean (Ar⁺ Sputtered) Polycrystalline Cu



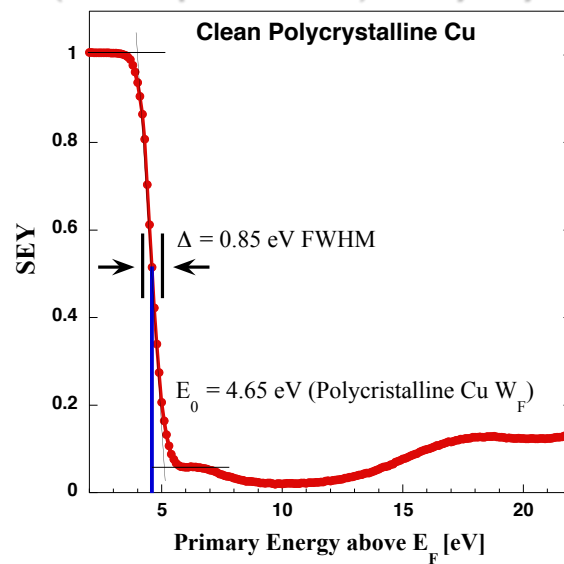
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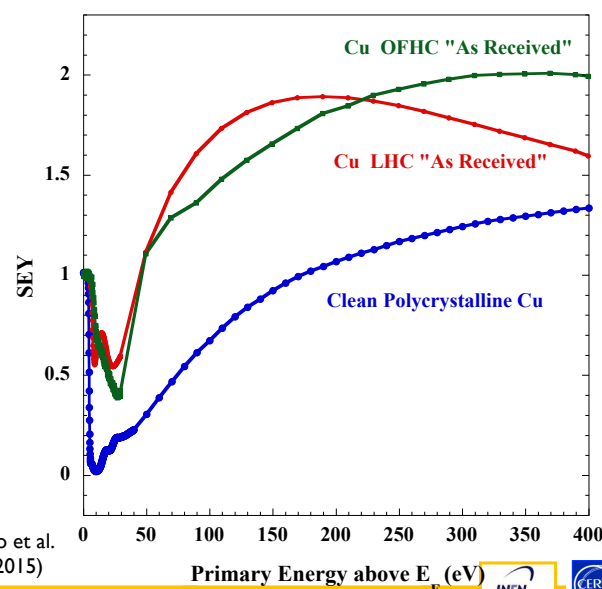
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"As received" vs. Clean Cu

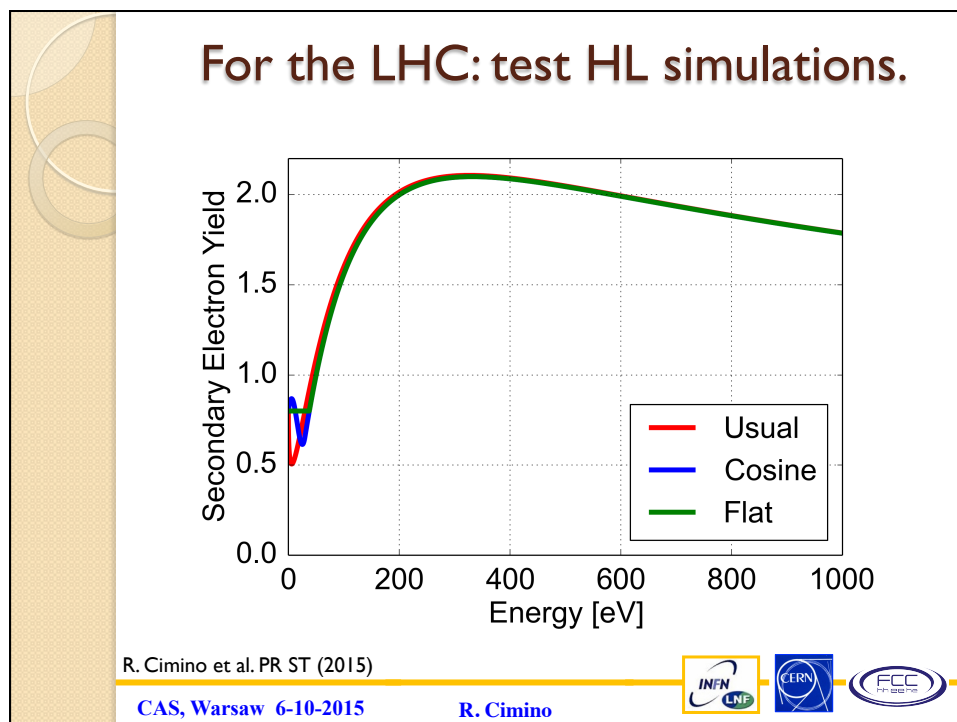
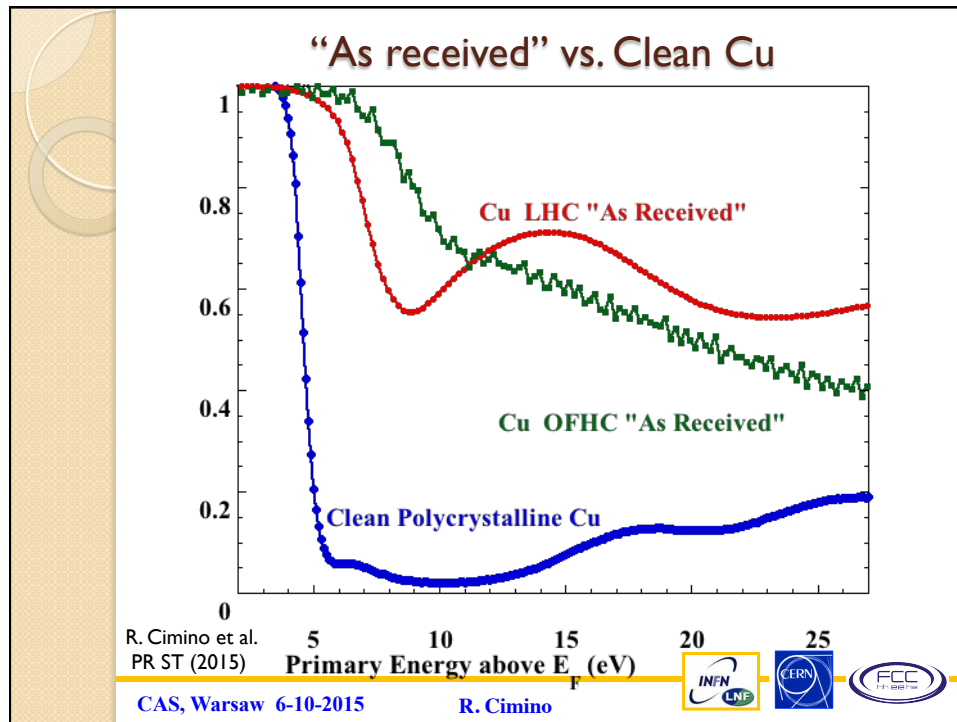


R. Cimino et al.
PR ST (2015)

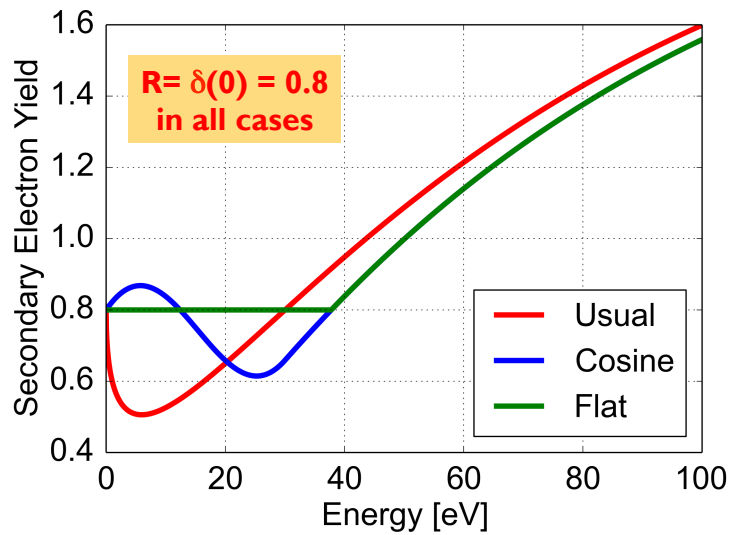
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For the LHC: test HL simulations.



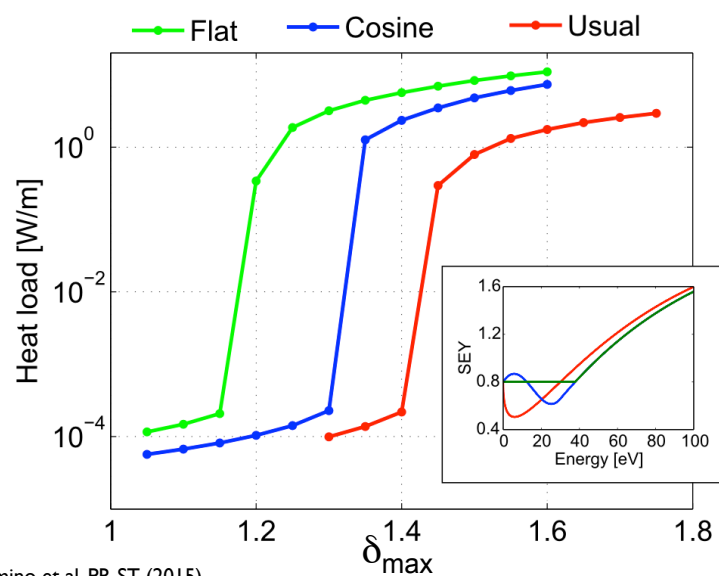
R. Cimino et al. PR ST (2015)

CAS, Warsaw 6-10-2015

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For the LHC: test HL simulations.



R. Cimino et al. PR ST (2015)

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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)
I430023 (pag. 65).

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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)

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Proceedings of IPAC2014, Dresden, Germany

WEPME034

SOFT X-RAY REFLECTIVITY AND PHOTOELECTRON YIELD OF TECHNICAL MATERIALS: EXPERIMENTAL INPUT FOR INSTABILITY SIMULATIONS IN HIGH INTENSITY ACCELERATORS*

R. Cimino¹, LNF-INFN, Frascati, Italy and CERN, Geneva, Switzerland
F. Schäfers, Institute for Nanometre Optics and Technology, HZB BESSY-II, Berlin, Germany

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18**, 040704 (2015)

Measurements of x-ray scattering from accelerator vacuum chamber surfaces, and comparison with an analytical model

G. F. Dugan and K. G. Sonnad

CLASSE, Cornell University, Ithaca, New York 14853, USA

R. Cimino

INFN, Laboratori Nazionali di Frascati, P.O. Box 13, 00044 Frascati, Italy

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F. Schäfers

Helmholtz-Zentrum Berlin (HZB), Berlin, Germany
(Received 6 September 2014; published 30 April 2015)

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- **Photon energy:**
20-1600 eV
- a low grating (150 l/mm)
- is used for 20-150 eV
- a high grating (1228.1 l/mm) is used for 130-1600 eV
- **Samples:** aluminum, copper, and stainless steel
- **Spot size:**
- 0.25 mm in vertical,
- 1.1 mm in horizontal

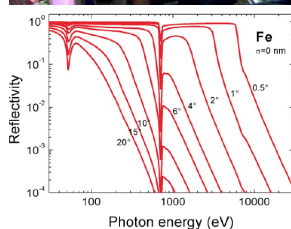
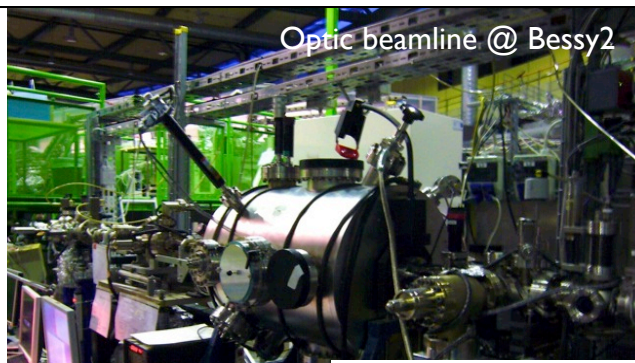


Figure 3: Fresnel-reflectivity of a smooth Fe surface as function of photon energy for various incidence angles.

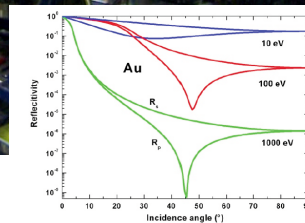


Figure 2: Reflectivity R_s and R_p of a perfect Au-coating as function of incidence angle in the UV and soft x-ray range.

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Reflectometer at BESSY II

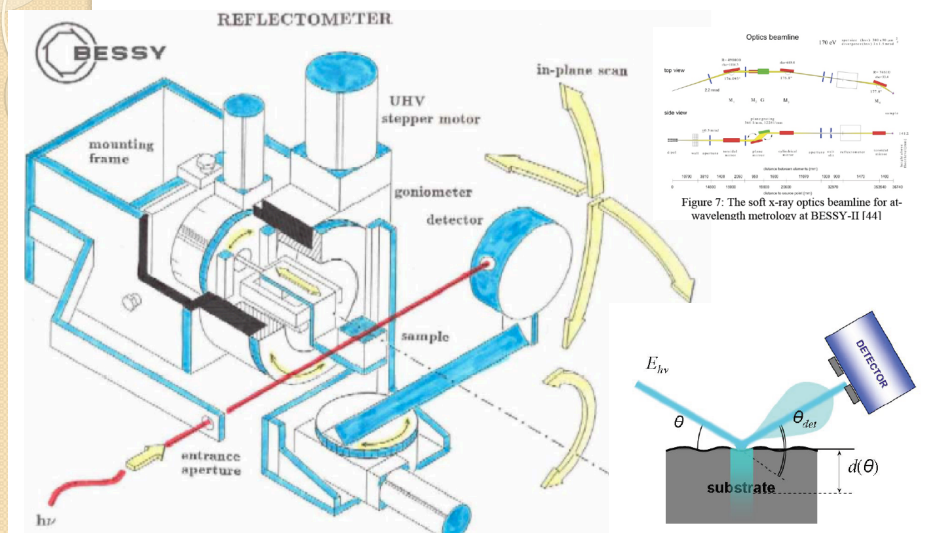


Figure 9: Geometry in reflectometry experiments.

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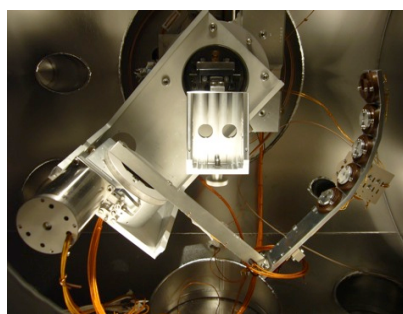
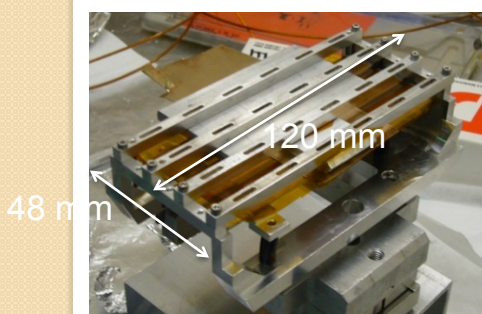
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Samples and Sample holder

- During the preliminary beam period, we measured different samples:
 - as example here we show CU from LHC beam screen
- The samples are isolated from the sample holder by Kapton to also measure the photo yield.



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Reflectivity from LHC Cu

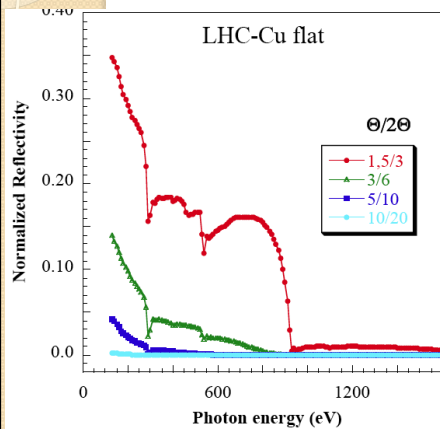


Figure 10: Reflectivity of LHC-Cu sample representative of the flat part of the beam screen, as function of photon energy for various incidence angles Θ and emission angle 2Θ .

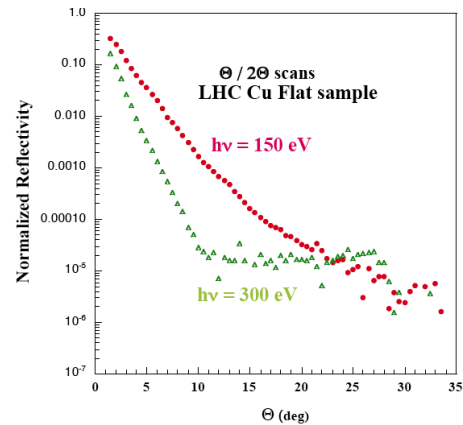


Figure 14: Normalized Reflectivity of LHC- Cu Flat sample as function of incidence angles Θ and emission angle 2Θ , for two photon energies of 150 and 300 eV, respectively.

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Roughness produce scatter light

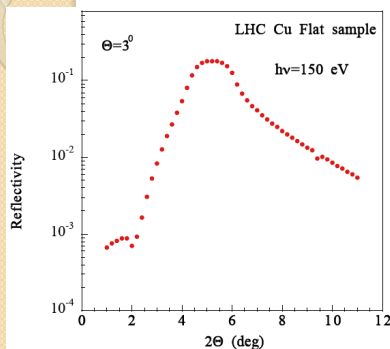


Figure 11: Normalized reflectivity of LHC- Cu Flat sample as function of emission angle 2Θ , for a given photon energy $h\nu = 150$ eV and incidence angle of $\Theta = 3^\circ$.

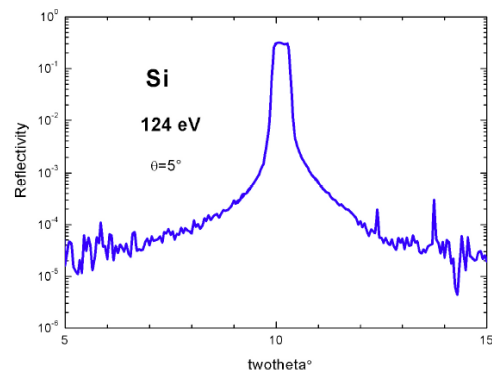


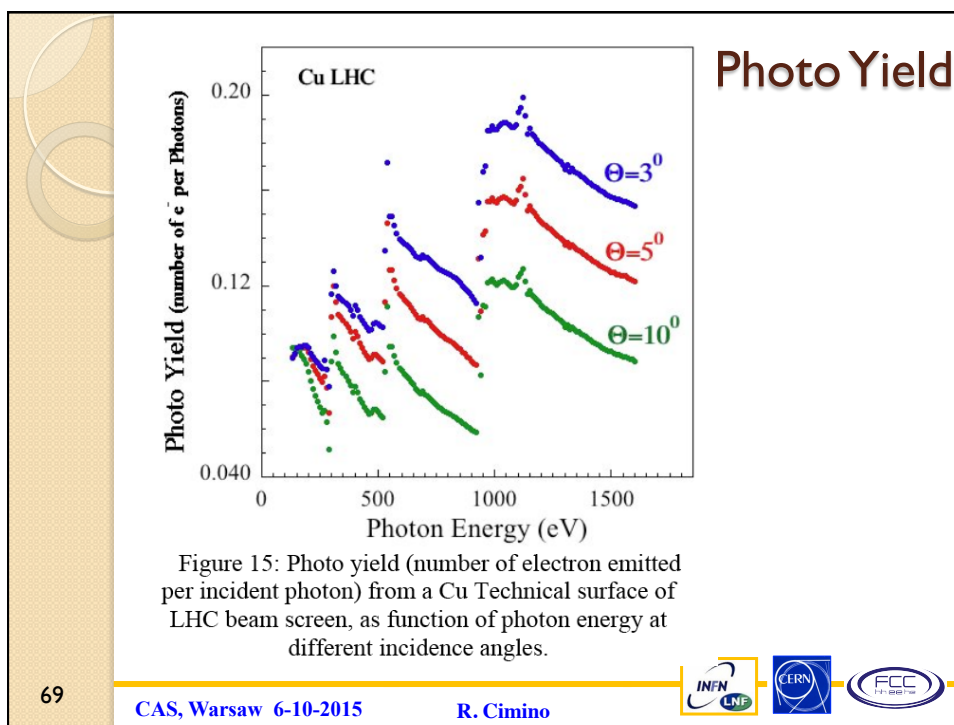
Figure 12: Scattering from a quasi-perfect Si mirror surface taken at 5° incidence angle and at 124 eV (10 nm). Data taken with a 4x4mm photodiode.

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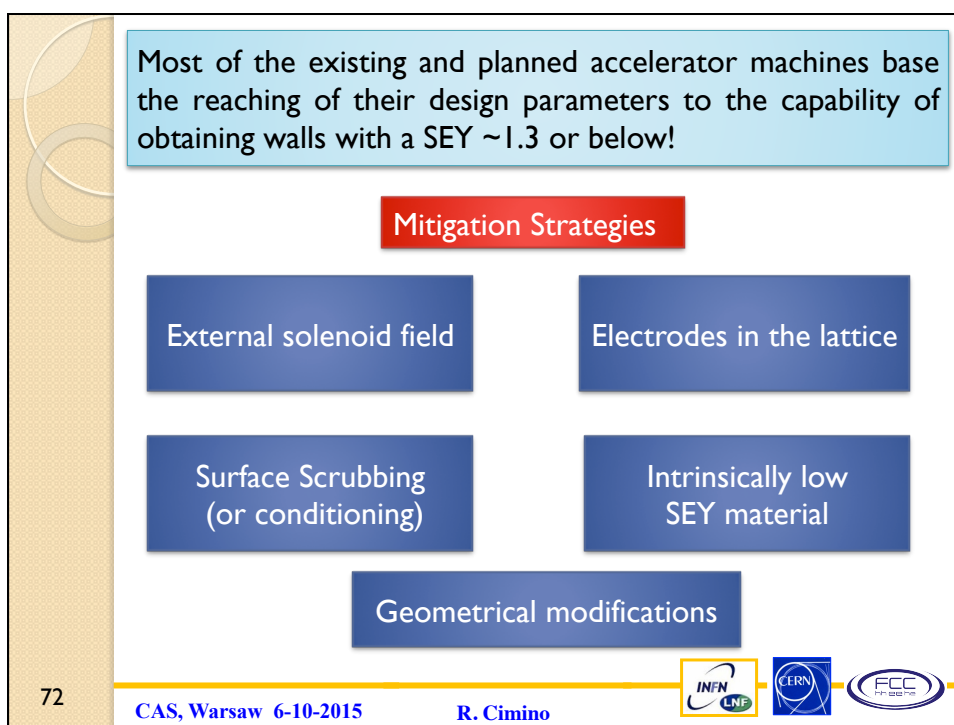
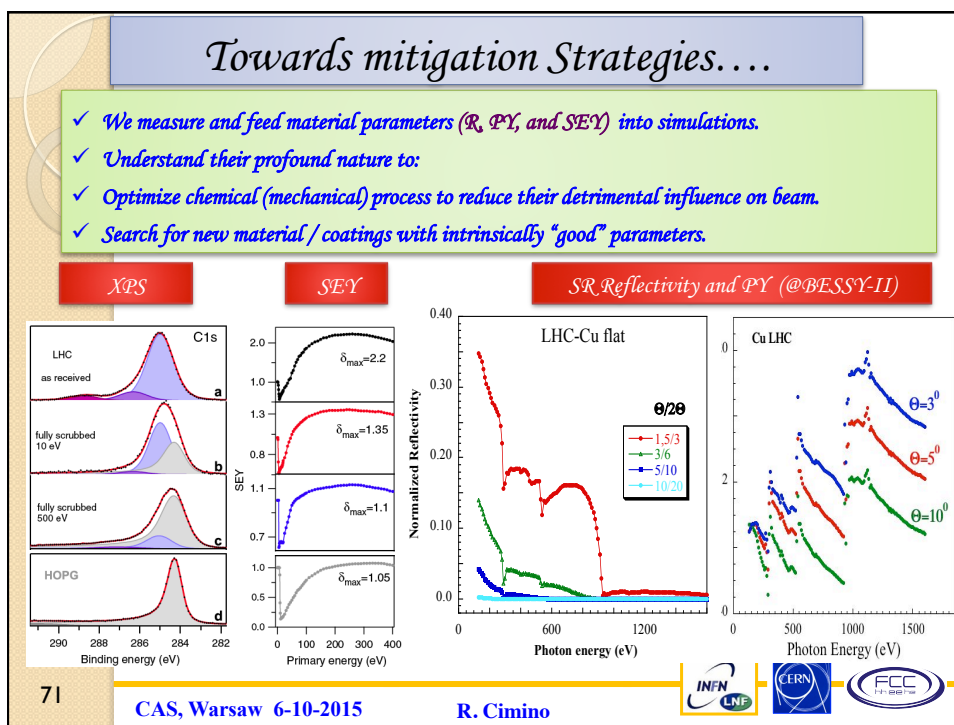


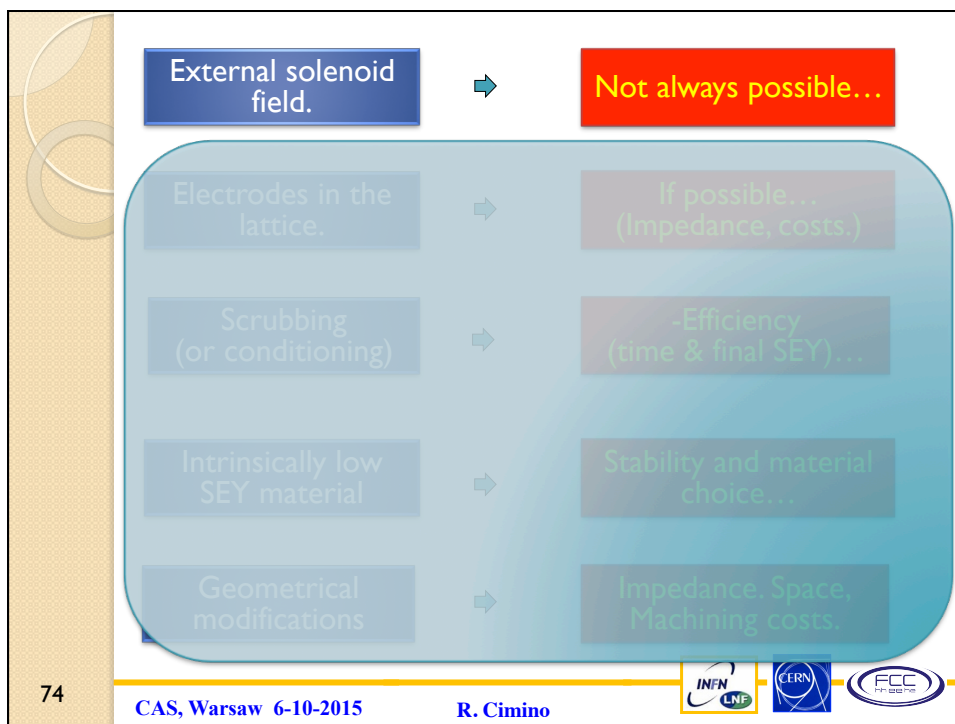
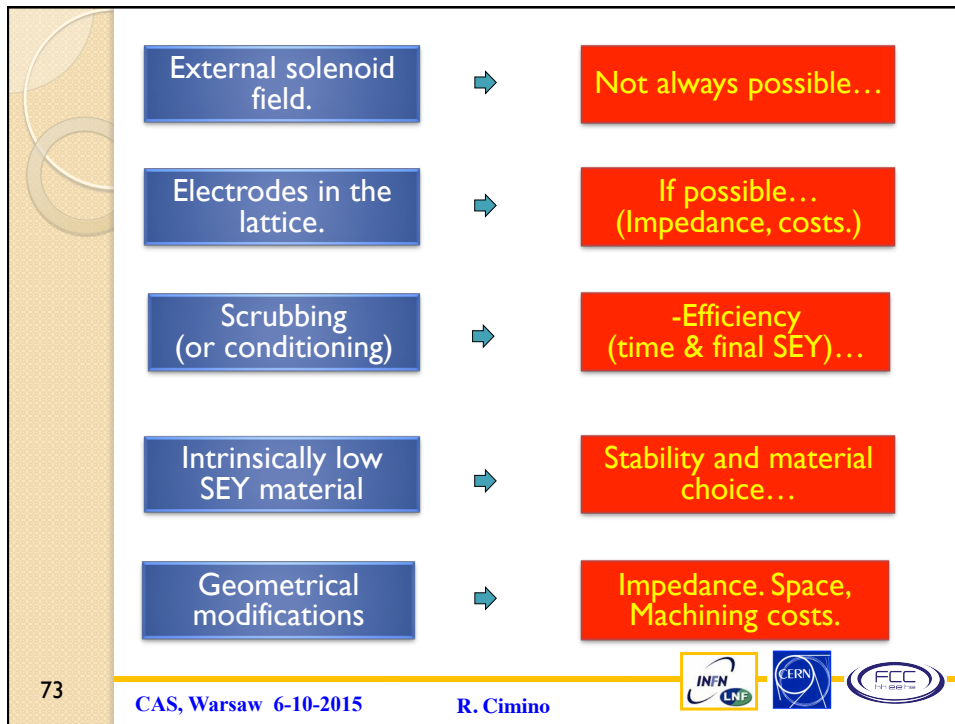
Electron cloud in accelerators

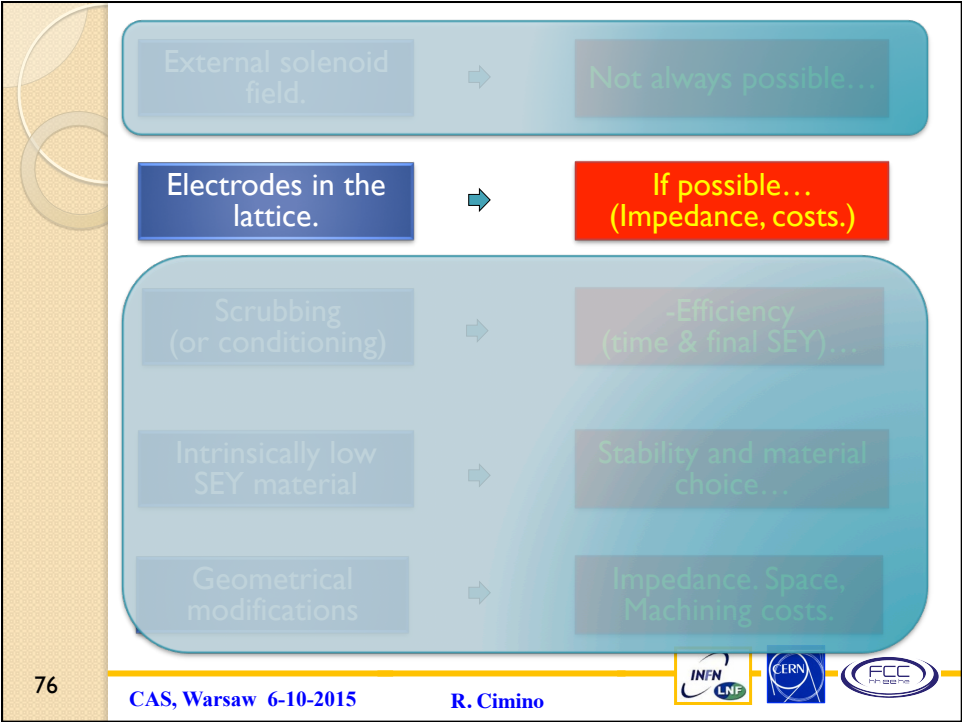
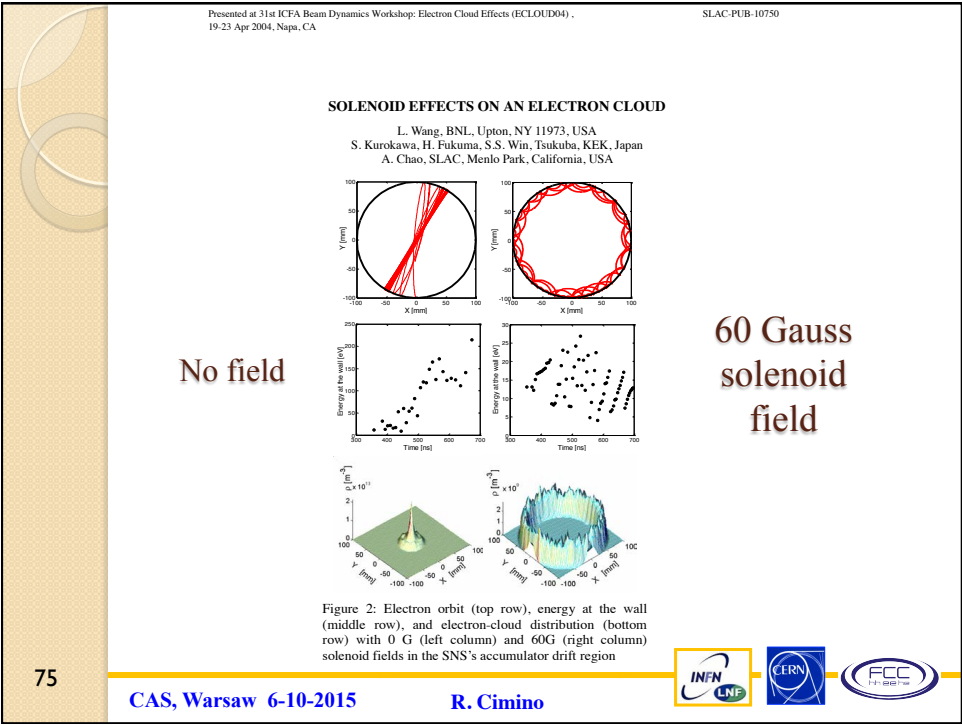
- Phenomenology:
What happens to the Vacuum beam pipe in presence of the beam? (LHC Example)
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 I430023 (pag. 65).

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Electrodes at DAΦNE



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

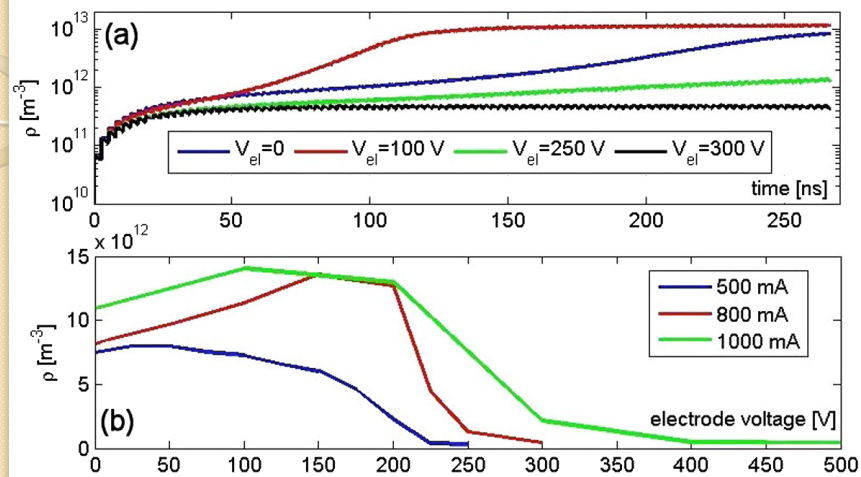
77

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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.

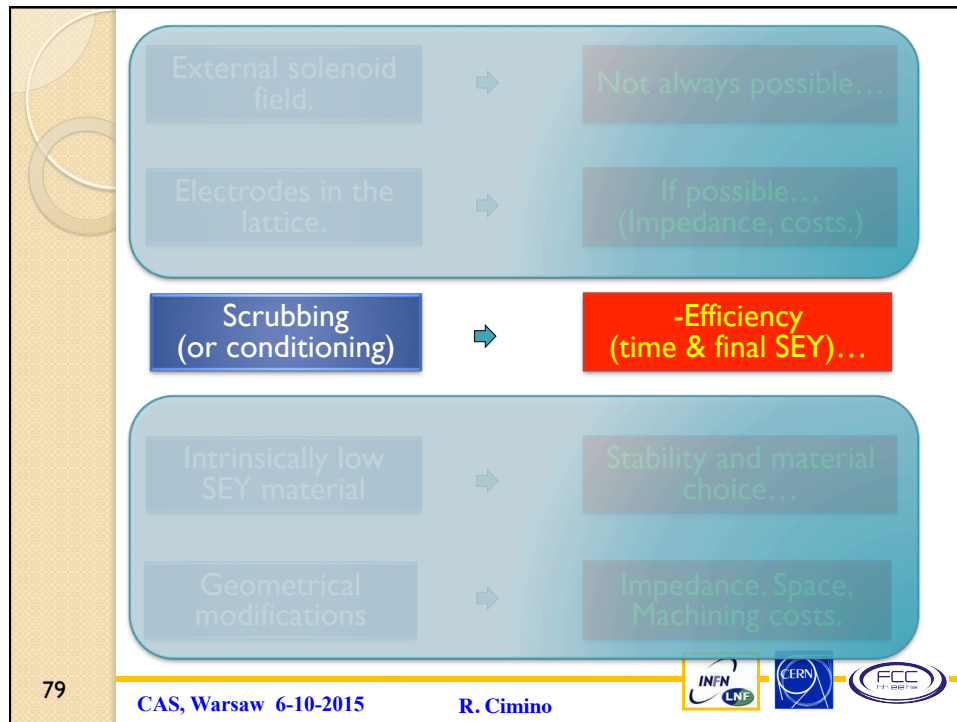
D. Alesini et al. *Phys. Rev. Lett.* **110**, 124801 (2013)

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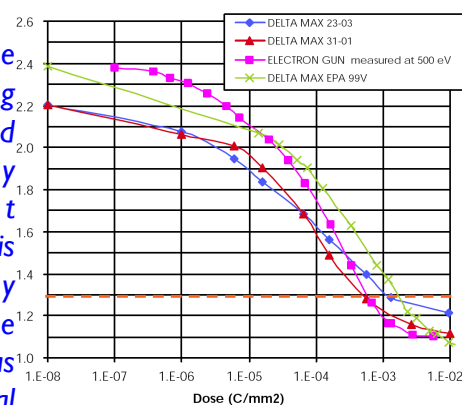




The Beam “scrubbing” effect is the ability of a surface to reduce its SEY after e⁻ bombardment.

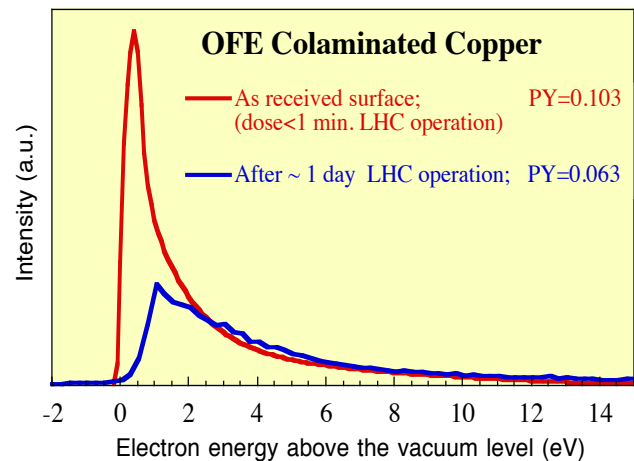
from LHC PR 472 (Aug. 2001):

“... 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.

Beam scrubbing effect with photon



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

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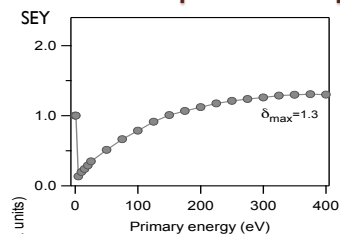
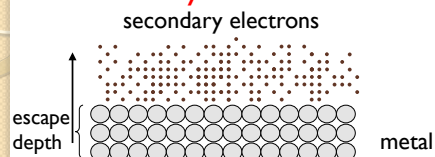
CAS, Warsaw 6-10-2015

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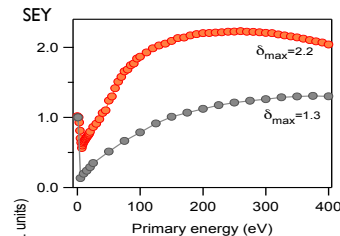
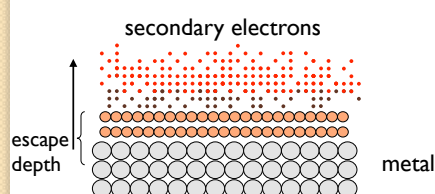
Study the Chemistry governing the SEY reduction (scrubbing) with X ray photoelectron spectroscopy

Atomically clean surface



➤ the effective SEY of the metal is strongly modified by the surface contamination

"As received" surface



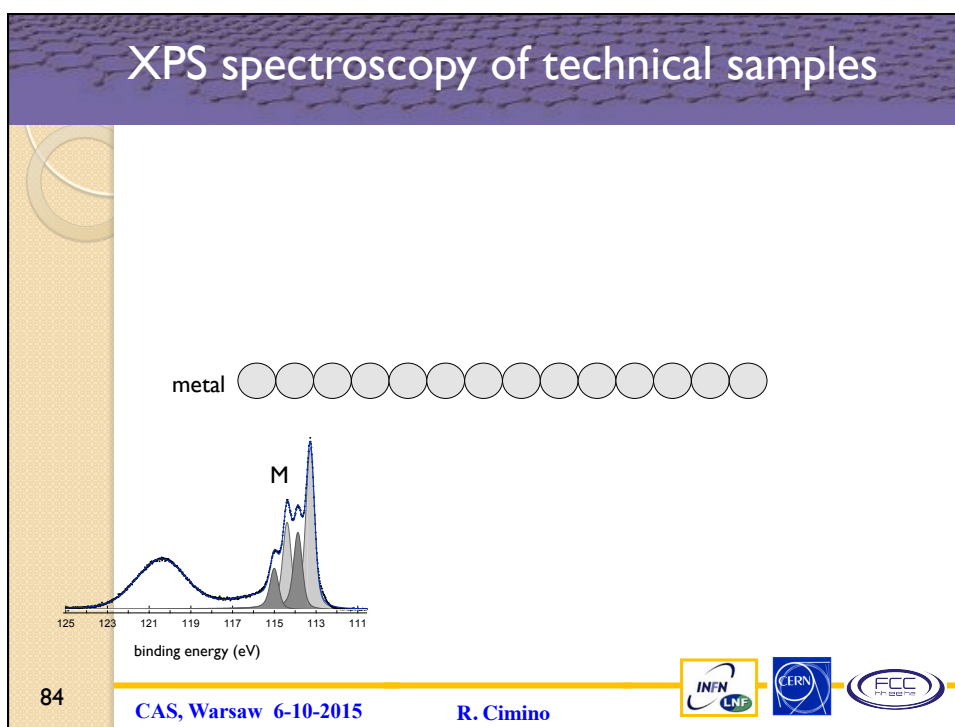
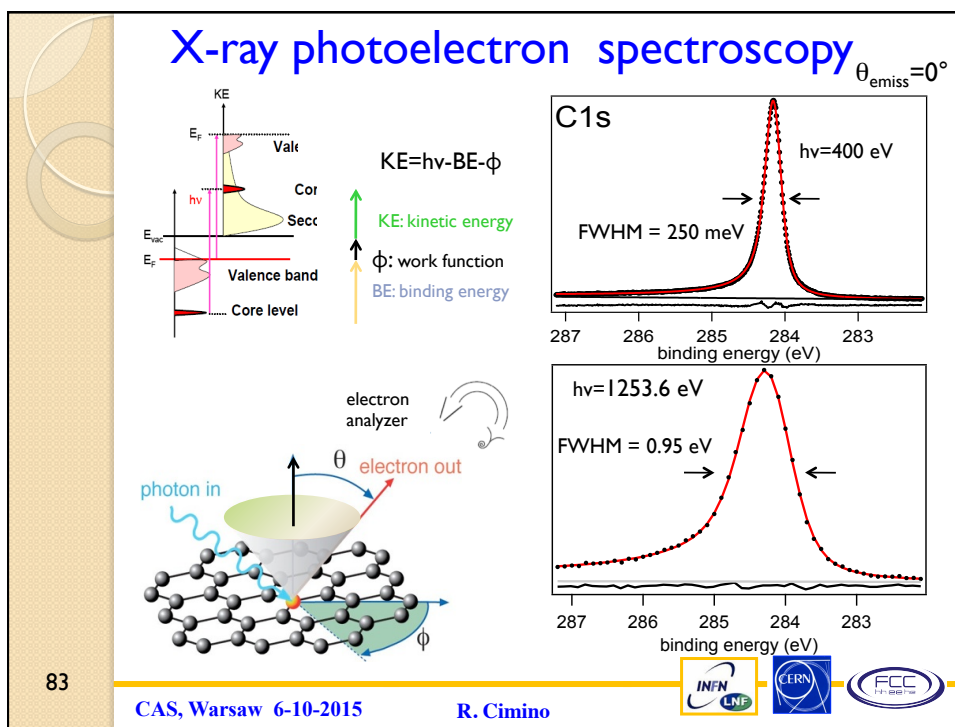
➤ SEY is very Surface sensitive and XPS is a powerful tool to study its chemistry dependence

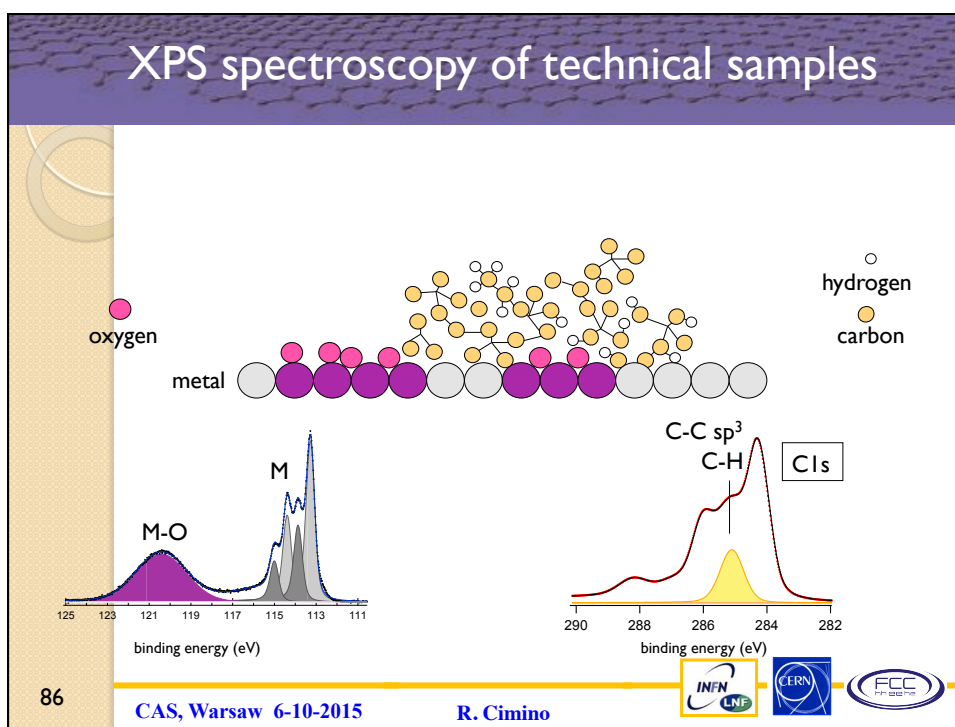
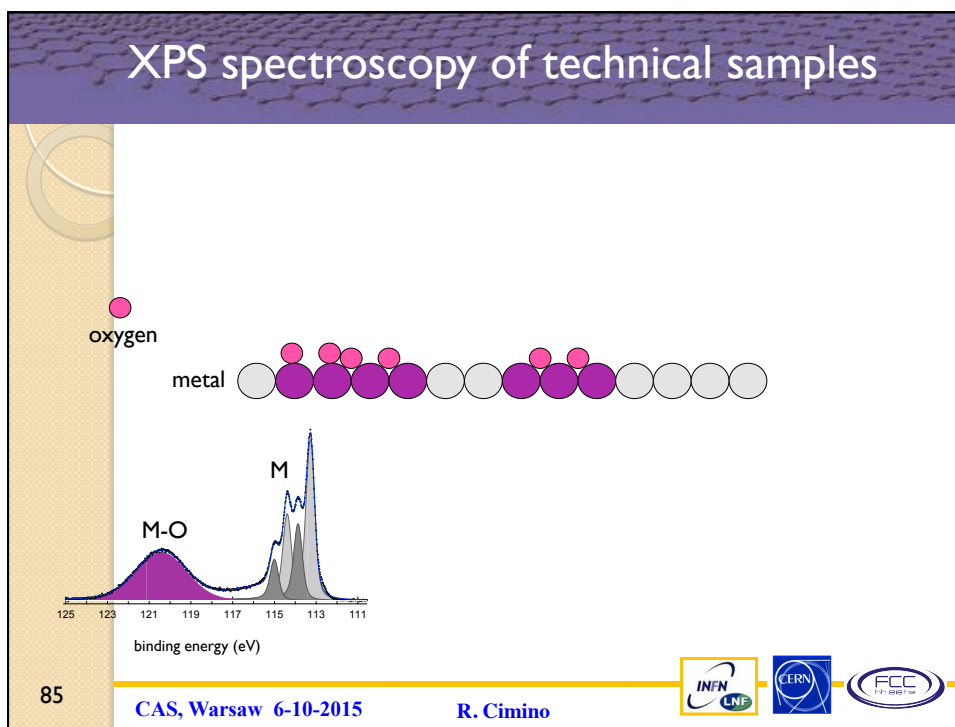
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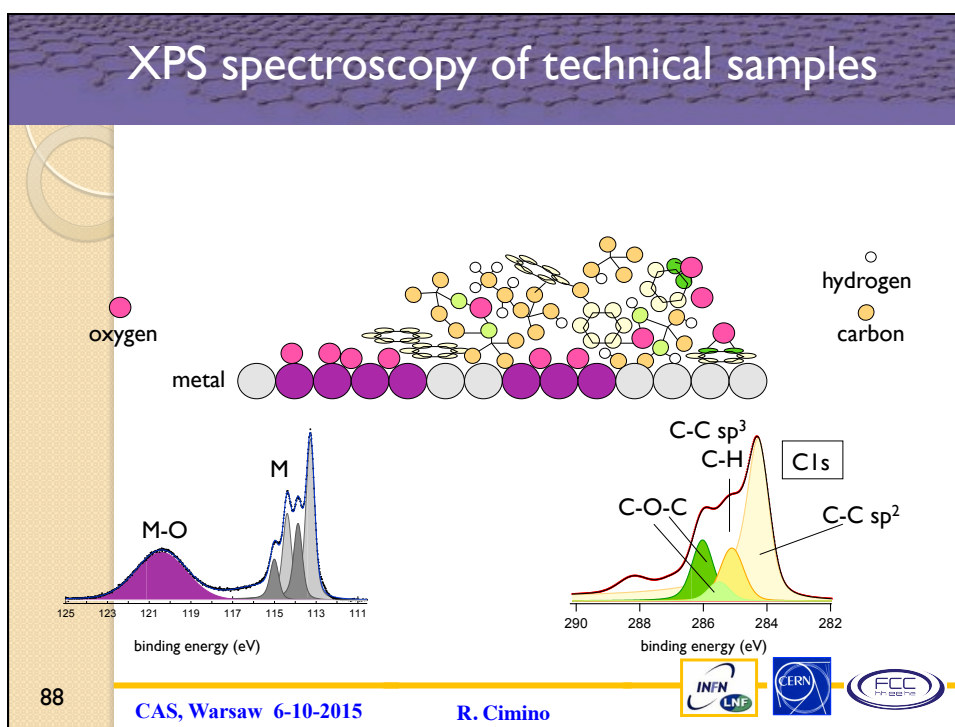
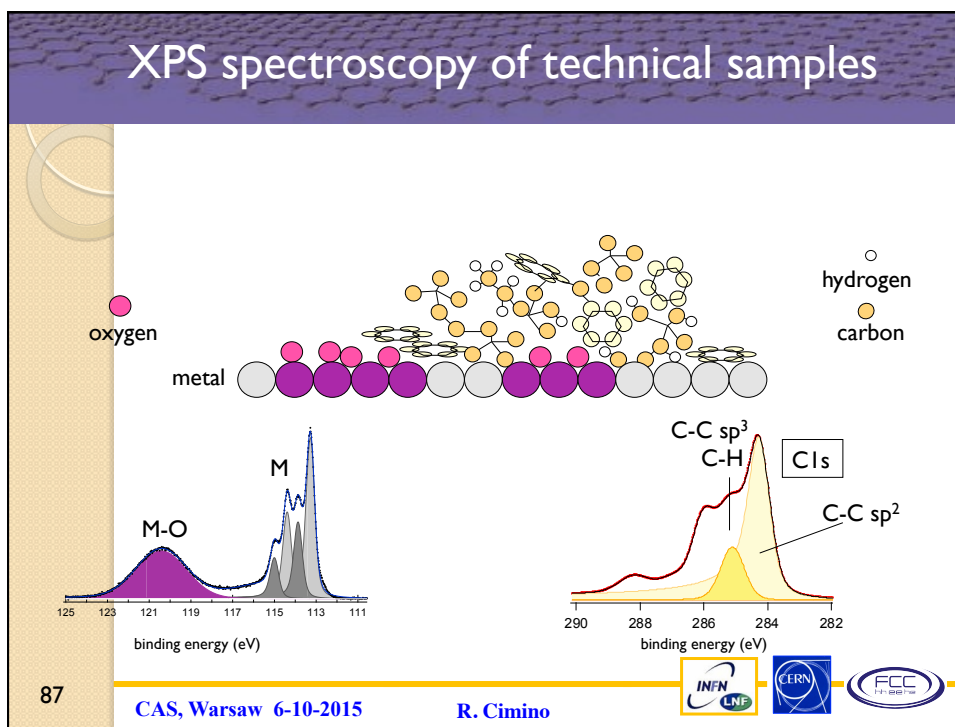
CAS, Warsaw 6-10-2015

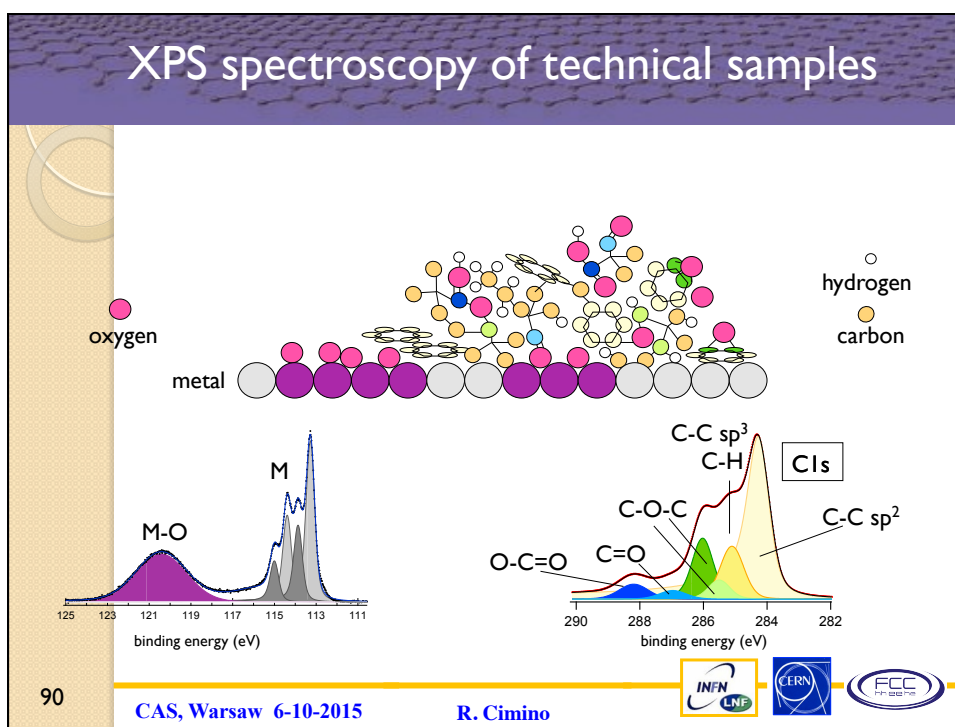
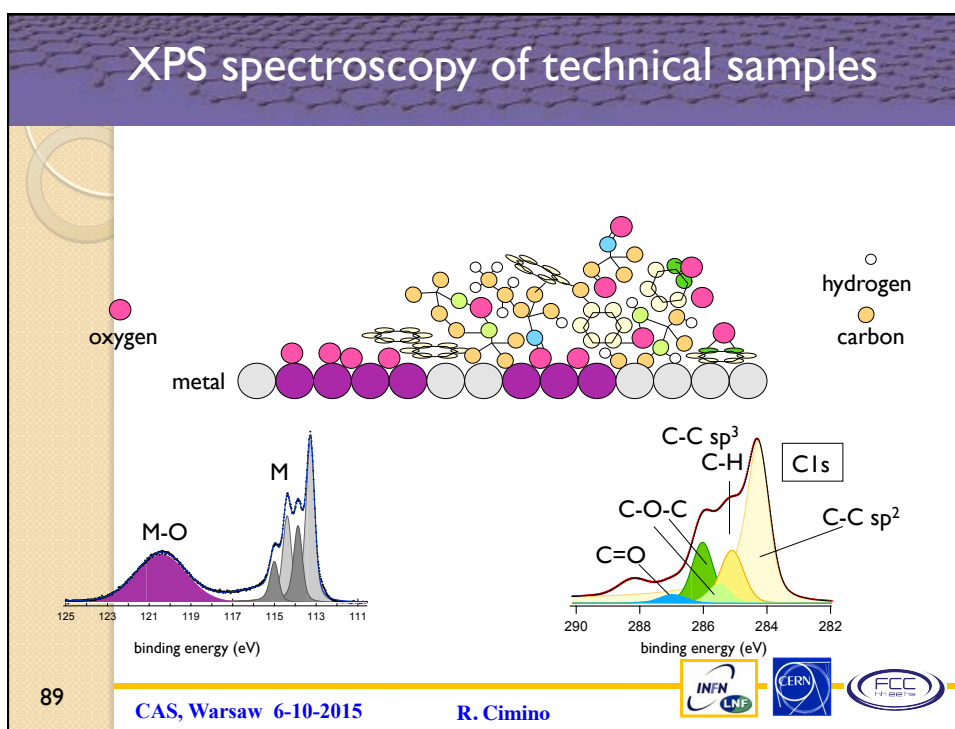
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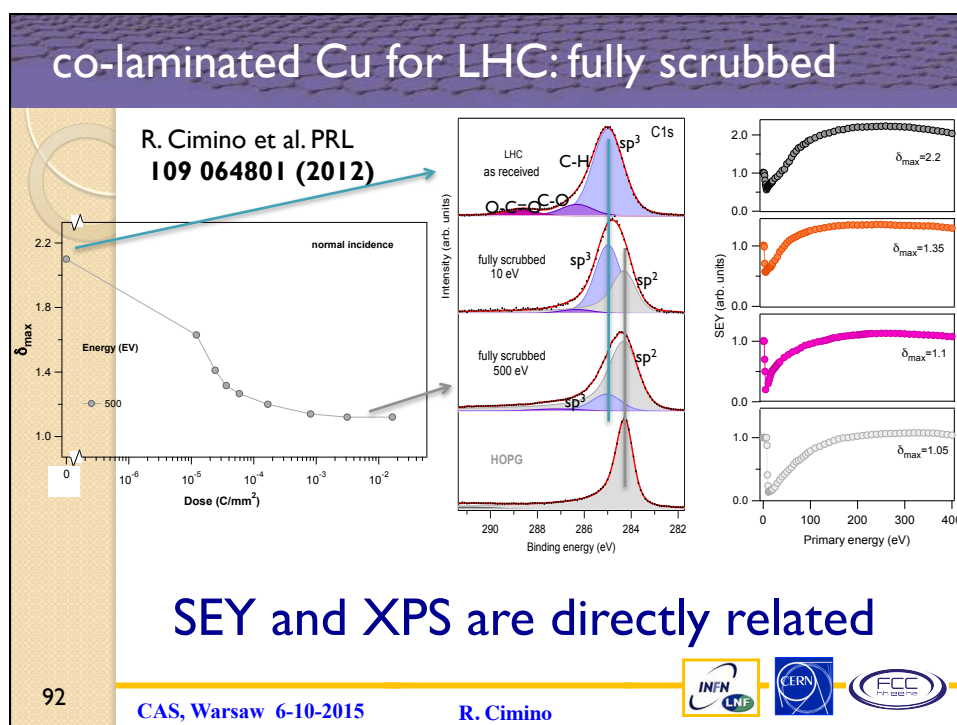
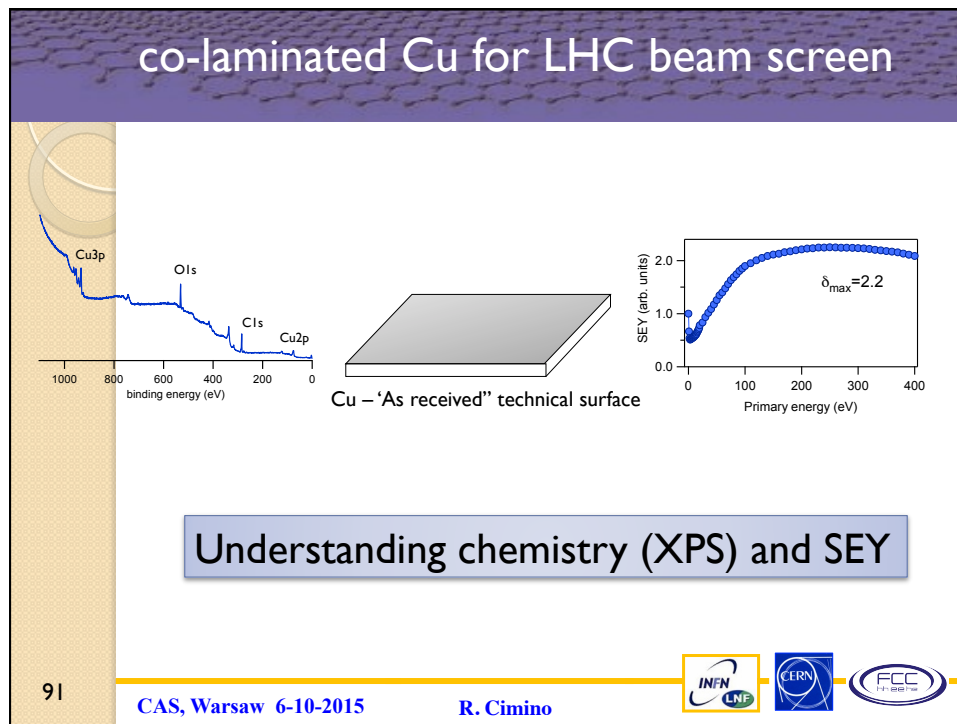






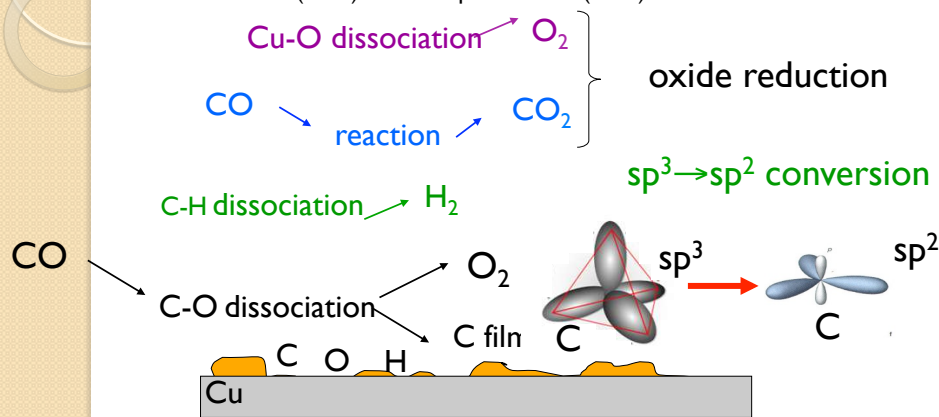






e⁻ beam induced surface reactions

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

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- The chemical origin of the scrubbing is now clear: it is due to **Electron induced surface graphitization!**
- It occurs (with small differences) for many technical surface like Cu, SS, TiN etc. (noticeably not for Al)
- **BUT: it is a phenomenon which intrinsically need energy to occur: do all electrons induce it?**

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PRL 109, 064801 (2012)

PHYSICAL REVIEW LETTERS

week ending
10 AUGUST 2012

Nature of the Decrease of the Secondary-Electron Yield by Electron Bombardment and its Energy Dependence

R. Cimino,¹ M. Commisso,¹ D. R. Grosso,¹ T. Demma,² V. Baglin,³ R. Flammini,^{1,4} and R. Larciprete^{1,5}

¹LNF-INFN, Via E. Fermi 40, 00044 Frascati (Roma), Italy
²Laboratoire de l'Accélérateur Linéaire, CNRS-IN2P3, Université Paris-Sud 11, Orsay, France
³CERN, Geneva, Switzerland
⁴CNR-IMIP Istituto Metodologie Inorganiche e Plasmi, Via Salaria Km. 29.300, 00019 Monterotondo Scalo (RM), Italy
⁵CNR-ISC Istituto dei Sistemi Complessi, Via Fosso del Cavaliere 100, 00133 Roma, Italy

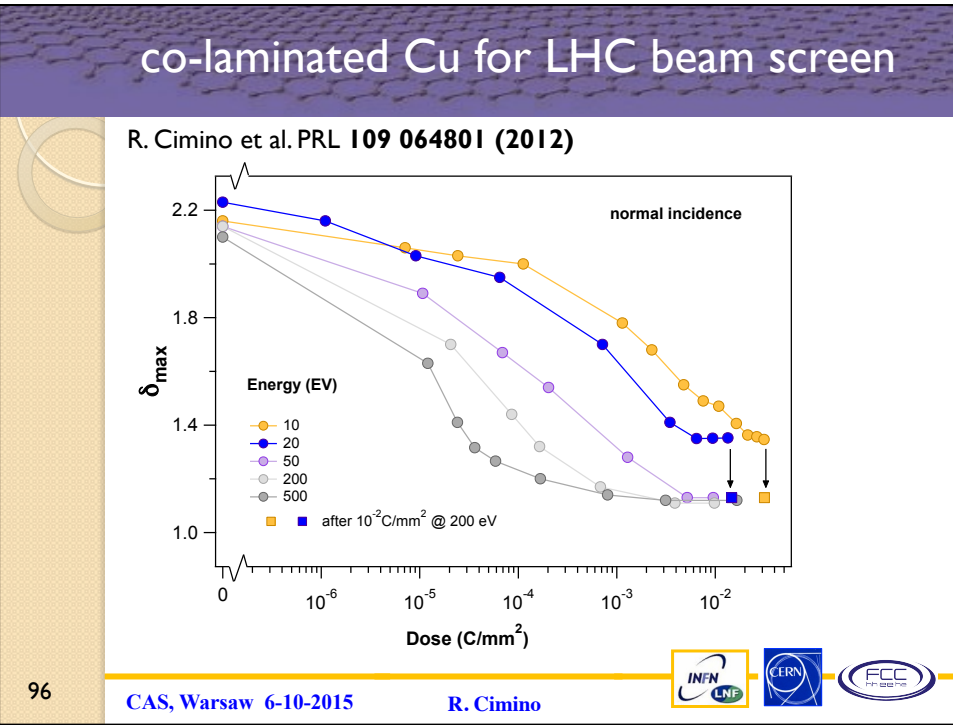
(Received 26 April 2012; published 10 August 2012)

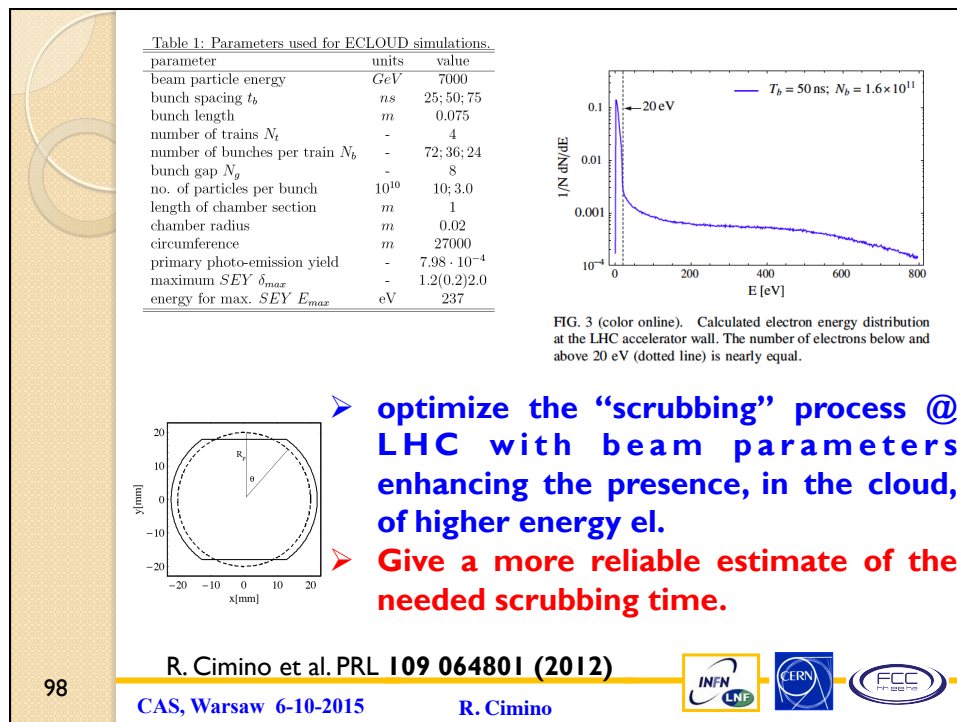
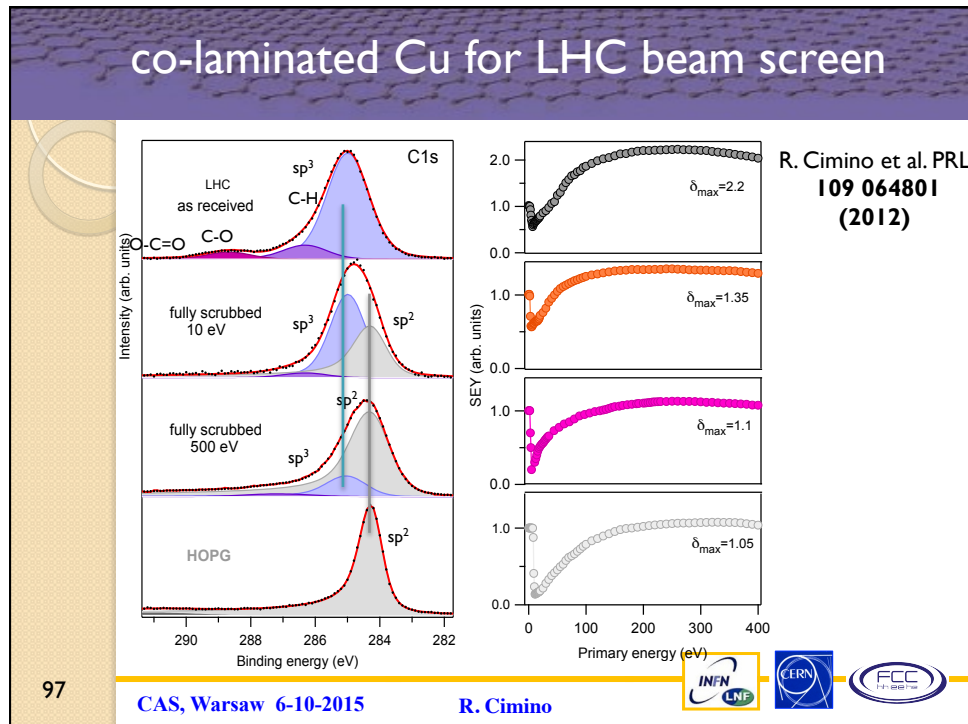
We performed a combined secondary electron yield (SEY) and x-ray photoelectron spectroscopy study as a function of the electron dose and energy on a Cu technical surface representative of the LHC accelerator walls. The electron bombardment is accompanied by a clear chemical modification, indicating an increased graphitization as the SEY decreases. The decrease in the SEY is also found to depend significantly on the kinetic energy of the primary electrons. When low-energy primary electrons are employed ($E \leq 20$ eV), the reduction of the SEY is slower and smaller in magnitude than when higher-energy electrons are used. Consequences of this observation are discussed mainly for their relevance on the commissioning scenario for the LHC in operation at CERN (Geneva), but are expected to be of interest for other research fields.

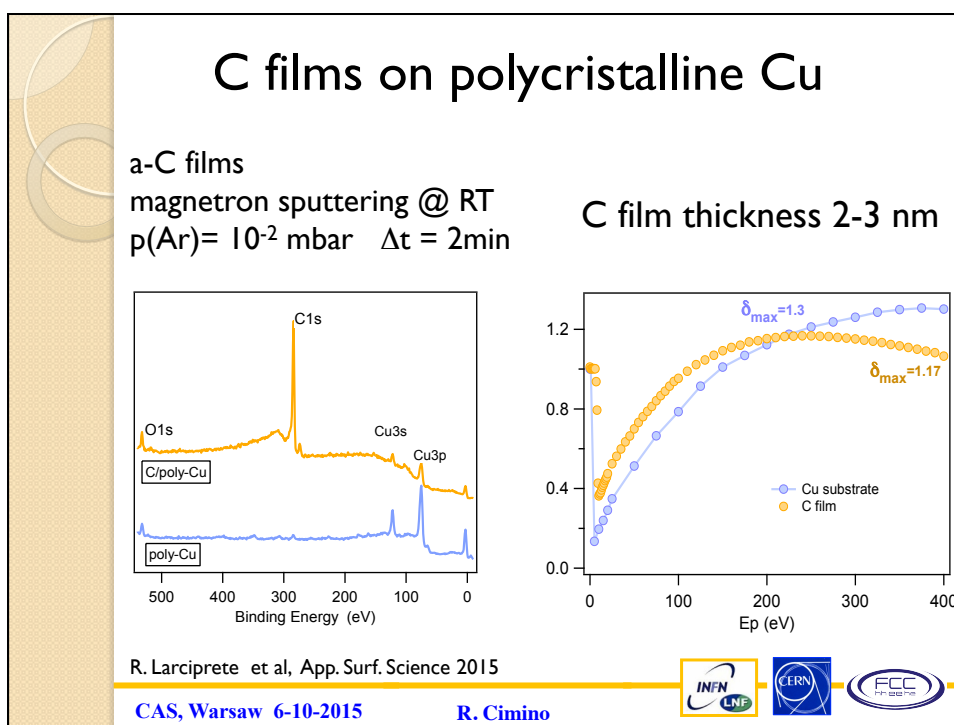
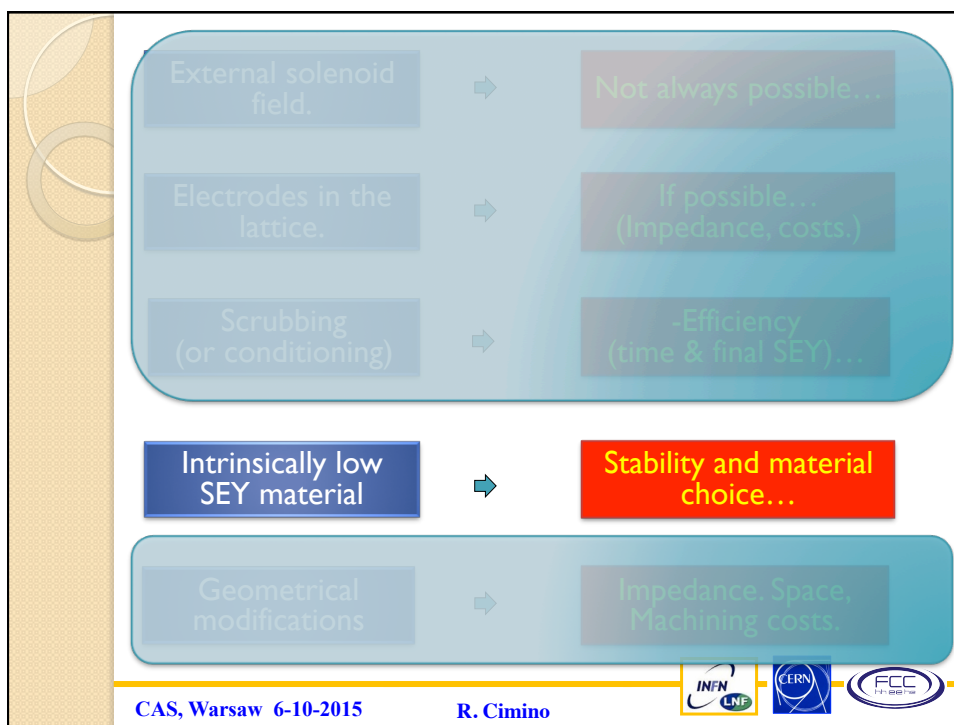
DOI: 10.1103/PhysRevLett.109.064801 PACS numbers: 29.20.-c, 79.20.Hx, 07.30.-t, 29.27.Bd

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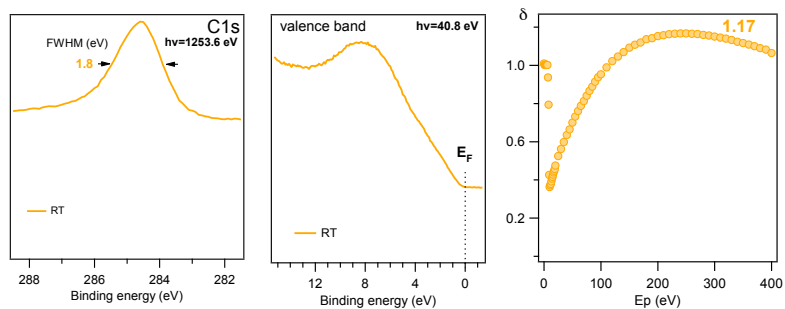
CAS, Warsaw 6-10-2015 R. Cimino







C films on polycrystalline Cu



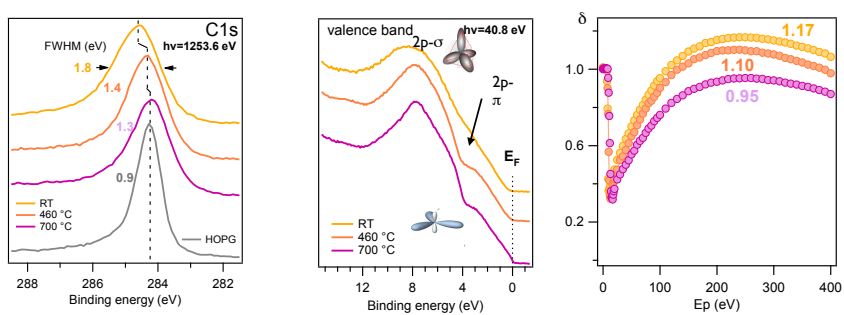
R. Larciprete et al, App. Surf. Science 2015

CAS, Warsaw 6-10-2015

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C films on polycrystalline Cu



the graphitization of the C films corresponds to a lower SEY

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

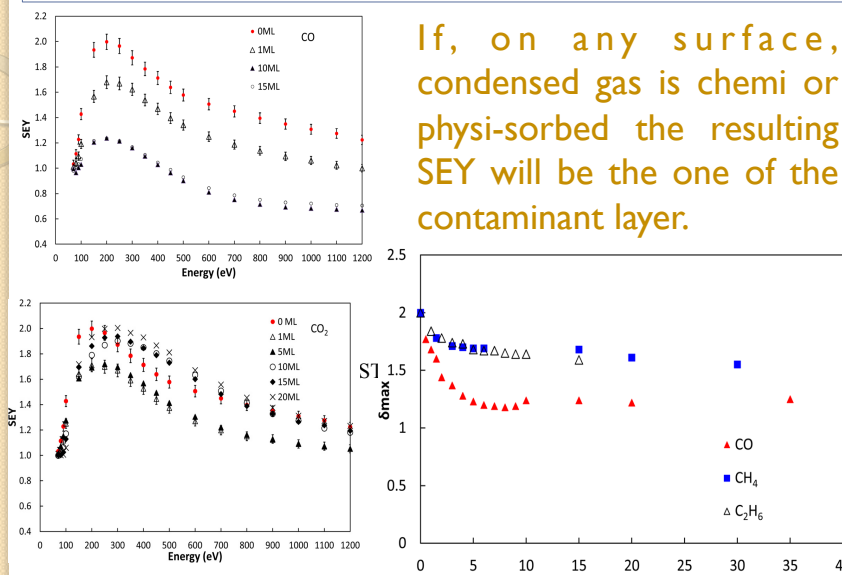
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a-C bases its stability on its low reactivity

If, on any surface, condensed gas is chemi or physi-sorbed the resulting SEY will be the one of the contaminant layer.



Kuzucan, et al JVSTA 30, 051401 (2012)

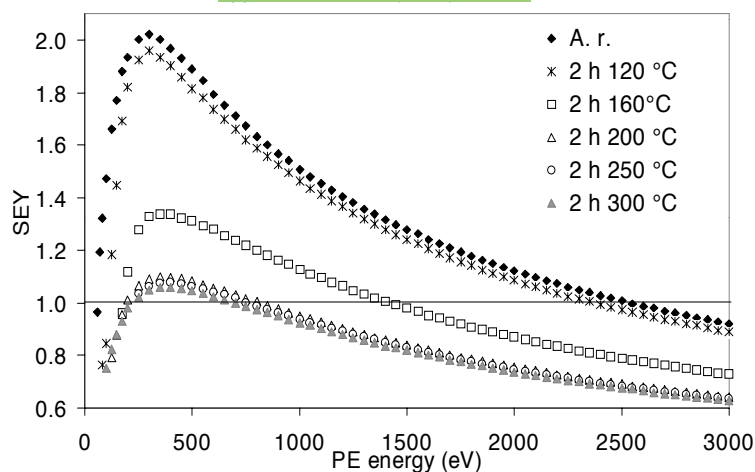
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If annealing (@ ~ 200 °C) is possible: TiZrV

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

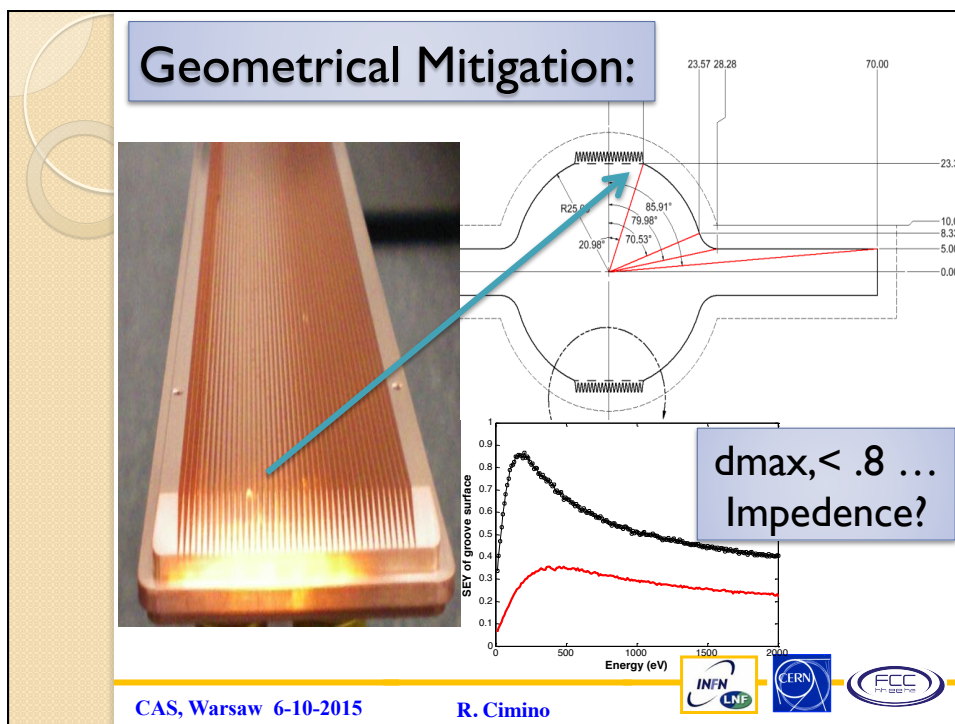
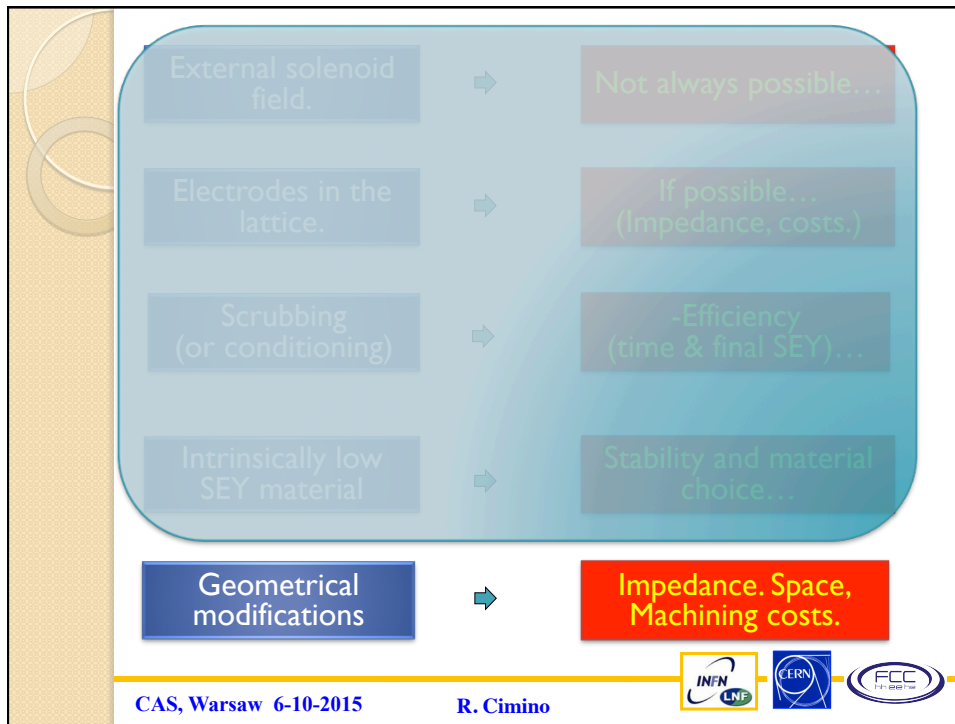


Activated NEG: it pumps, low SEY, stable: ideal mitigator

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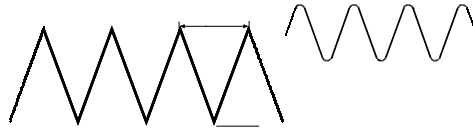




Impedance enhancement factor

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

$$\eta = \frac{Z_{\text{grooved surface}}}{Z_{\text{smooth surface}}} = \frac{\int H^2 ds}{H_0^2 W}$$



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

p=1.25mm (period)
d=2.5mm (depth)
t=0.125mm (thickness)

$$\eta = 1.64$$

p=1.25mm
d=2.5mm
t=0.25mm

$$\eta = 1.42$$

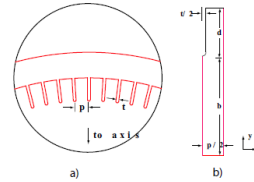


Figure 1: a) detail of the grooved vacuum chamber wall; dimensions shown are period p and fin thickness t ; b) detail of the grooved vacuum chamber wall; dimensions shown are period p and fin thickness t .

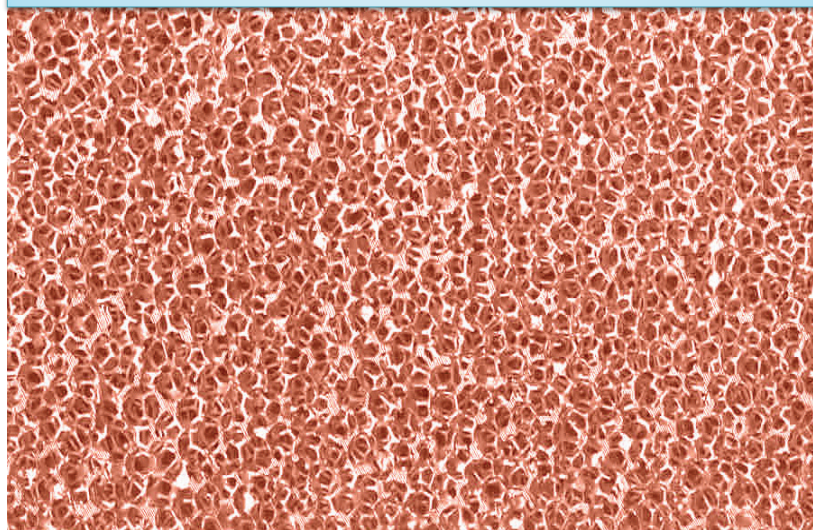
CAS, Warsaw 6-10-2015

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Sponge materials:

R. Cimino, A. Romano, S. Petracca, I. Masullo, M. Taborelli etc: (IPAC 2014)



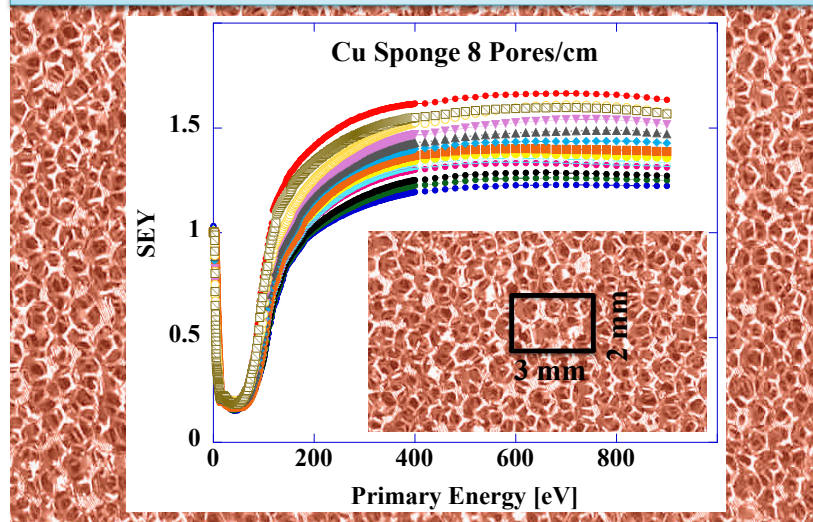
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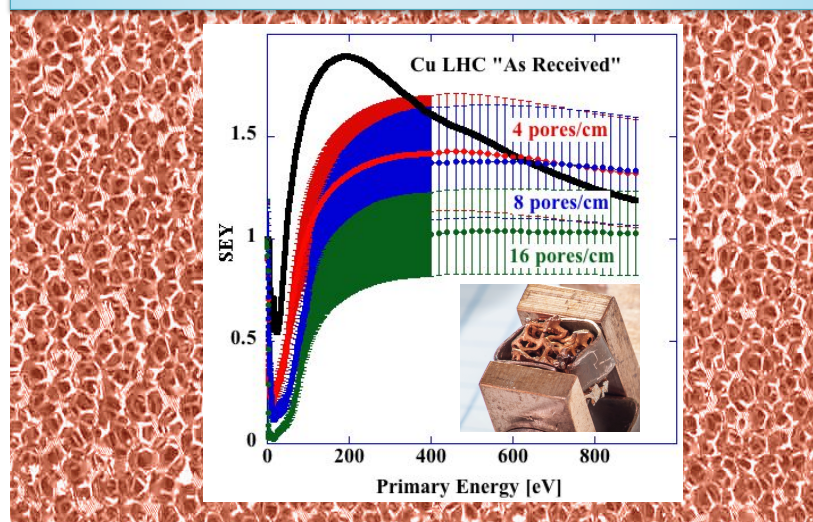
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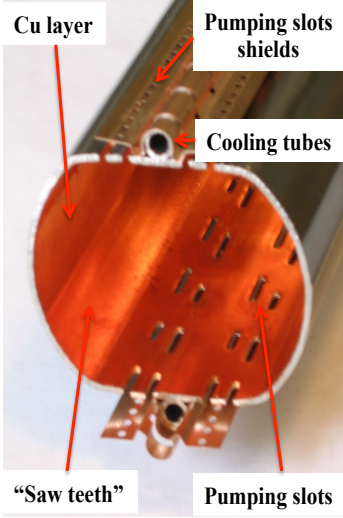
Sponge materials:
R. Cimino, A. Romano, S. Petracca, I. Masullo, M. Taborelli etc. (IPAC 2014)

Impedance, vacuum behaviour, desorption properties
are still under study
but seems very promising.

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Not only low SEY, PY and R



FUNCTION	PROCESS	DESIGN FEATURE
Reduce beam-induced cryogenic loads	Limit residual heat load to cold mass	Low-conduction supports
Increase development time of transverse resistive-wall instability	Intercept synchrotron radiation	High-conductivity copper plating
Resist eddy-current forces at magnet quench	Limit resistive wall impedance	Cooling at low temperature
Preserve field quality in magnet aperture	Structural material with high resistivity	Austenitic stainless steel structure
Maintain good beam vacuum	Low-permeability materials	Pumping slots
Limit development of electron cloud	Provide pumping from shielded cold surface	Avoid temperatures favoring desorption of common gas species
	Limit reflectivity and SEY of beam screen surface	Sawtooth absorber
		Beam scrubbing

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Conclusion

- **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.**

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Acknowledgements



Davide Remo Grosso, *INFN-LNF, Frascati (RM), Italy*
 Mario Commisso, *INFN-LNF, Frascati (RM), Italy*
 Dafne-L and Dafne Accelerator group.



Roberto Flammini, *CNR-IMIP, Montelibretti (RM), Italy*



Rosanna Larciprete and Antonio Di Trollo,
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