SEY measurements of coated surfaces with different coating thickness

E. Belli, P. Costa Pinto, M. Migliorati, G. Rumolo, T. Sinkovits, M. Taborelli

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Istituto Nazionale di Fisica Nucleare

ECLOUD'18

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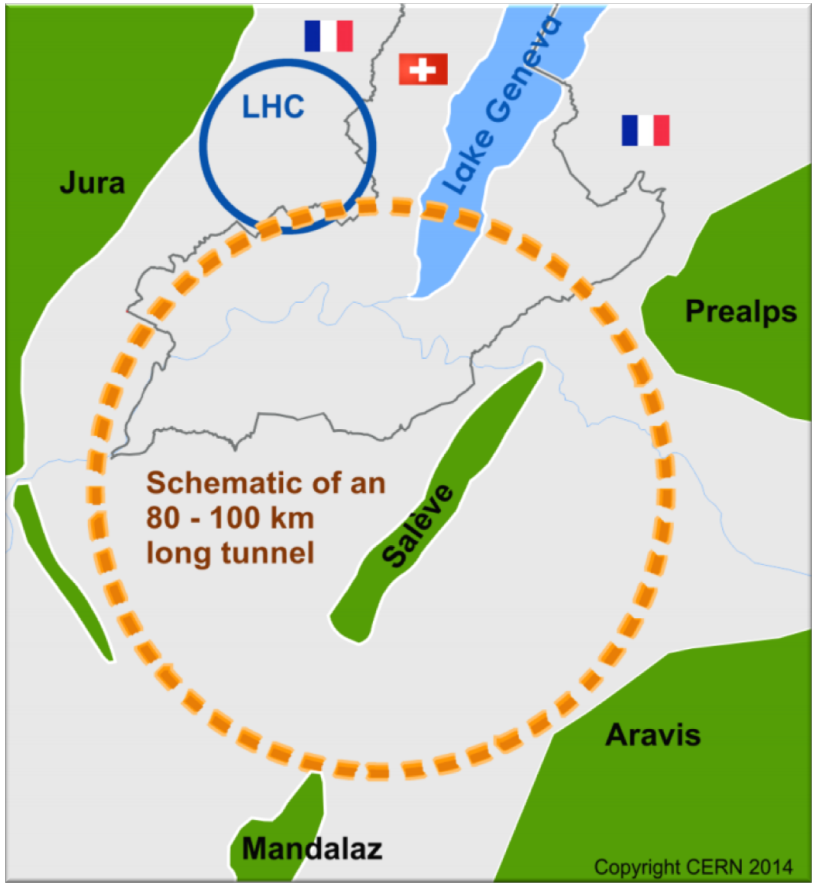
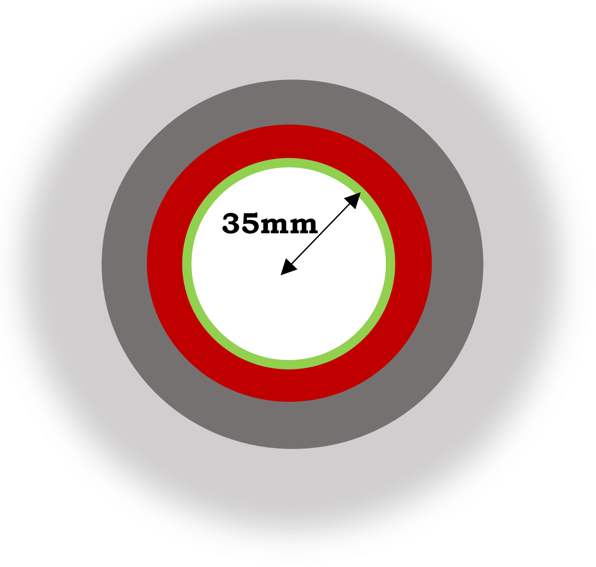
The FCC-ee project



High luminosity e^+e^- collider as ***potential first step*** towards the 100 TeV pp collider FCC-hh

	Z	W	H	tt	
Beam energy [GeV]	**45.6**	**80**	**120**	**175**	**182.5**
Circumference C [km]		97.75			
RF frequency f_{RF} [MHz]		400			
Arc cell	60°/60°	60°/60°	90°/90°	90°/90°	90°/90°
RF voltage V_{RF} [GV]	0.1	0.75	2.0	8.8	10.3
Momentum compaction α_c [10^{-5}]	1.48	1.48	0.73	0.73	0.73
Horizontal tune Q_x	269.14	389.124	389.13	389.108	389.108
Vertical tune Q_y	267.22	391.20	391.20	391.18	391.18
Synchrotron tune Q_s	0.025	0.0506	0.0358	0.0598	0.0622
SR energy loss/turn U_0 [GeV]	0.036	0.34	1.72	7.8	9.2
Longitudinal damping time τ_l [ms]	415	77	23	7.5	6.6
Beam current I [mA]	1390	147	29	6.4	5.4
Number of bunches/ring	16640	1300	328	40	33
Bunch population N [10^{11}]	1.7	2.3	1.8	3.2	3.35
Horizontal emittance ε_x [nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y [pm]	1	1.7	1.3	2.7	2.9
Energy spread - $\delta_{dp,SR}$ [%] - $\delta_{dp,BS}$ [%]	0.038 0.132	0.066 0.165	0.099 0165	0.144 0.196	0.150 0.2
Bunch length - $\sigma_{z,SR}$ [mm] - $\sigma_{z,BS}$ [mm]	3.5 12.1	3.0 7.5	3.15 5.3	2.75 3.82	2.76 3.78

The chamber model



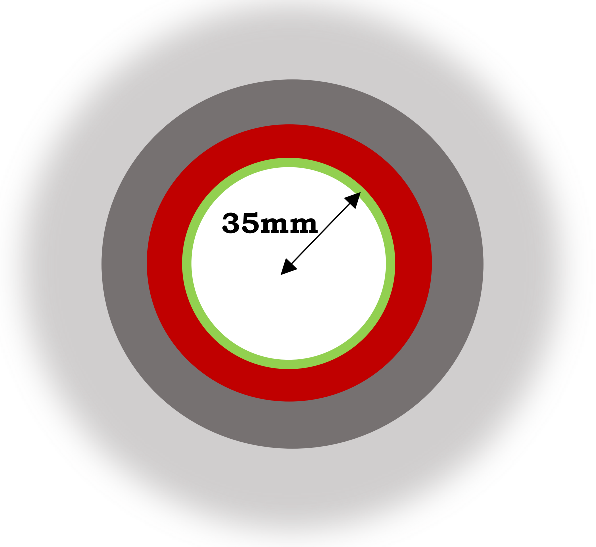
Iron
- $\Delta = \infty$
- $\rho = 6.89 \cdot 10^{-7}\ \Omega\text{m}$

Dielectric
- $\Delta = 6$ mm
- $\rho = 10^{15}\ \Omega\text{m}$

Copper
- $\Delta = 2$ mm
- $\rho = 1.66 \cdot 10^{-8}\ \Omega\text{m}$

Coating
- Pumping
- Electron cloud mitigation

The chamber model



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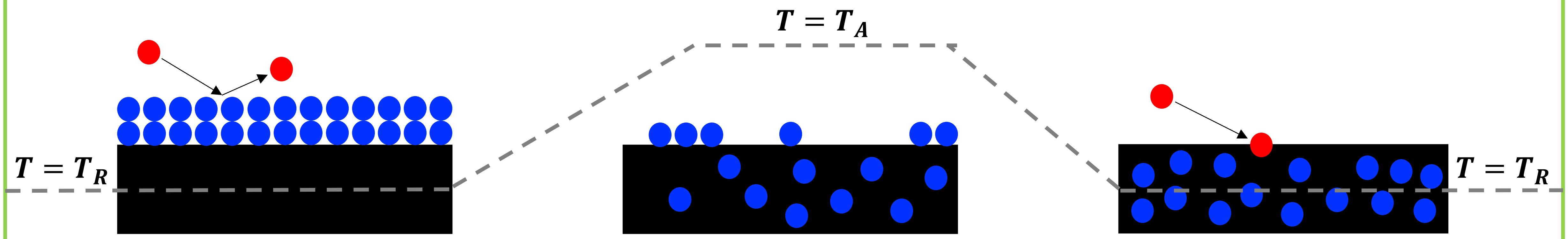
Coating
- Pumping
- Electron cloud mitigation

Non Evaporable Getters

- ❑ Getters can chemically absorb gas molecules if their surface is **clean**
- ❑ Clean surface obtained by diffusion of the oxide into the bulk (by heating in vacuum)



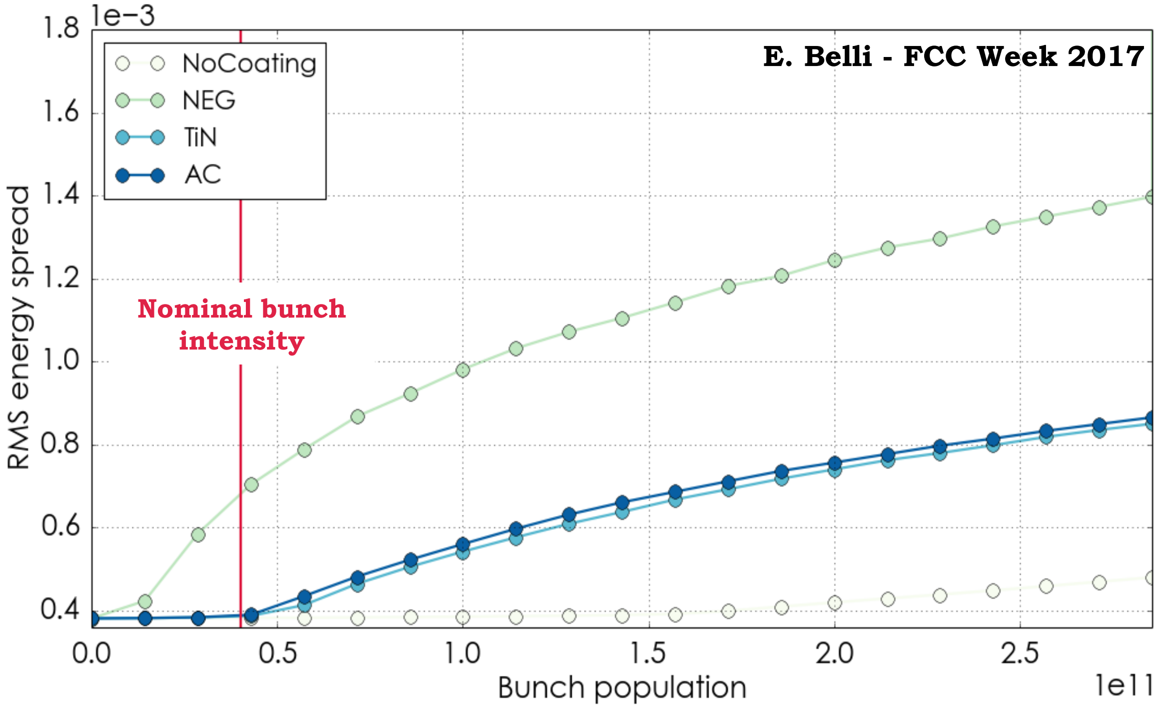
Oxide layer on the surface
➢ **No pumping**

Oxide diffusion into the bulk
➢ **Activation**

➢ **Pumping**

Motivation: resistive wall impedance

- The presence of the coating affects the resistive wall impedance
- Typical NEG thickness of $1\mu m$ makes the RW impedance responsible of quite low instability thresholds
  - Bunch unstable at nominal intensity



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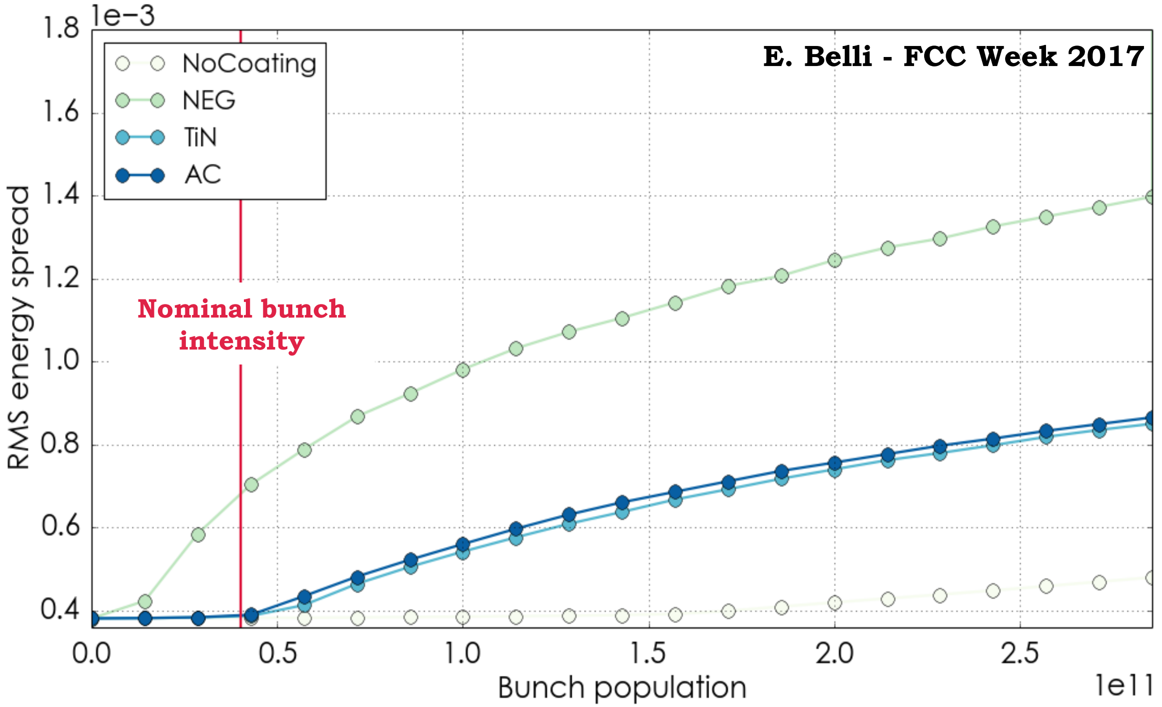
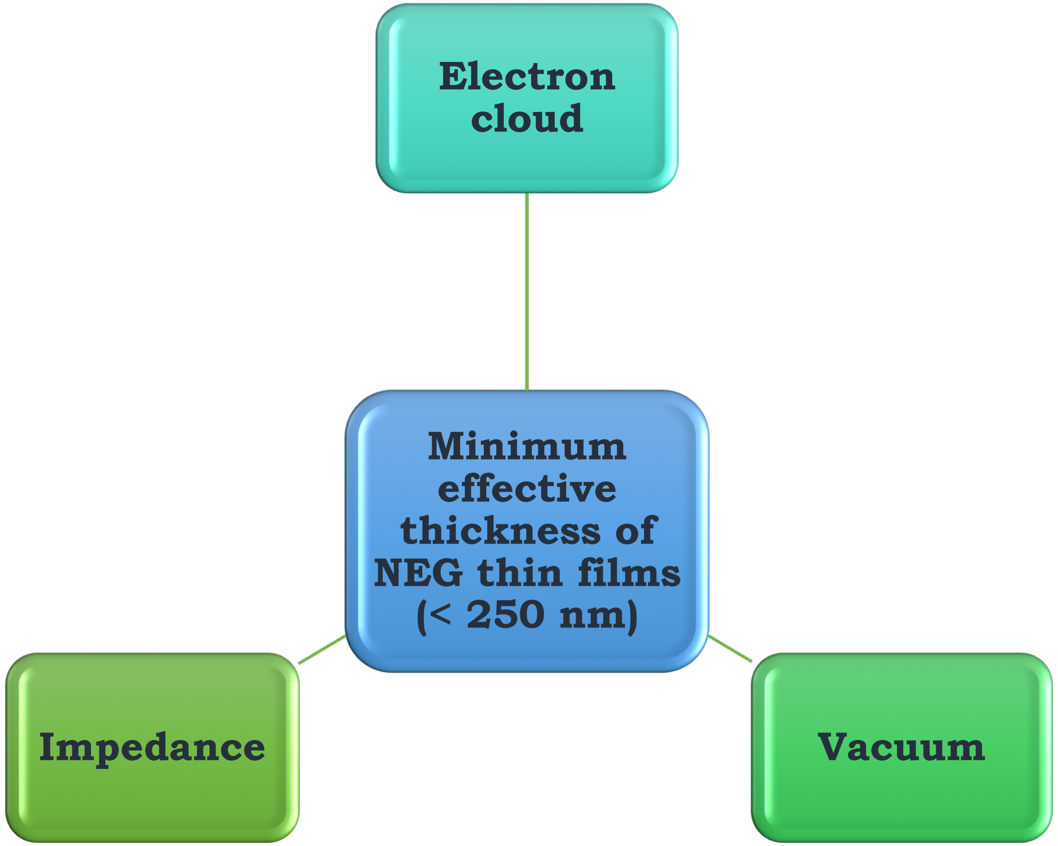
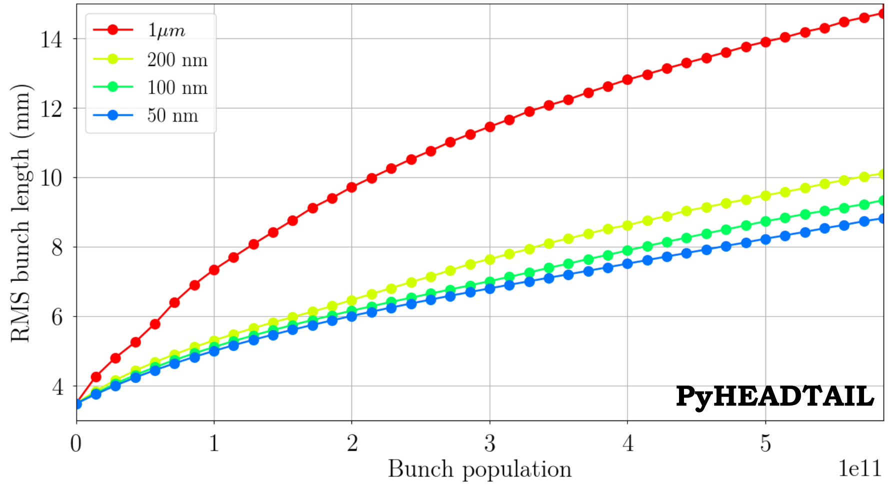


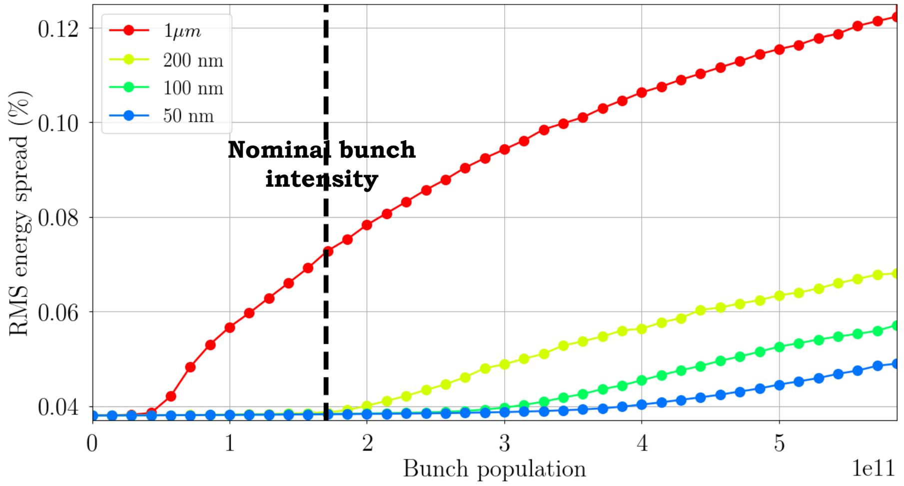


NEG thin films: single bunch beam dynamics

- NEG thin films with $1\mu m$, 200nm, 100nm, 50nm thicknesses

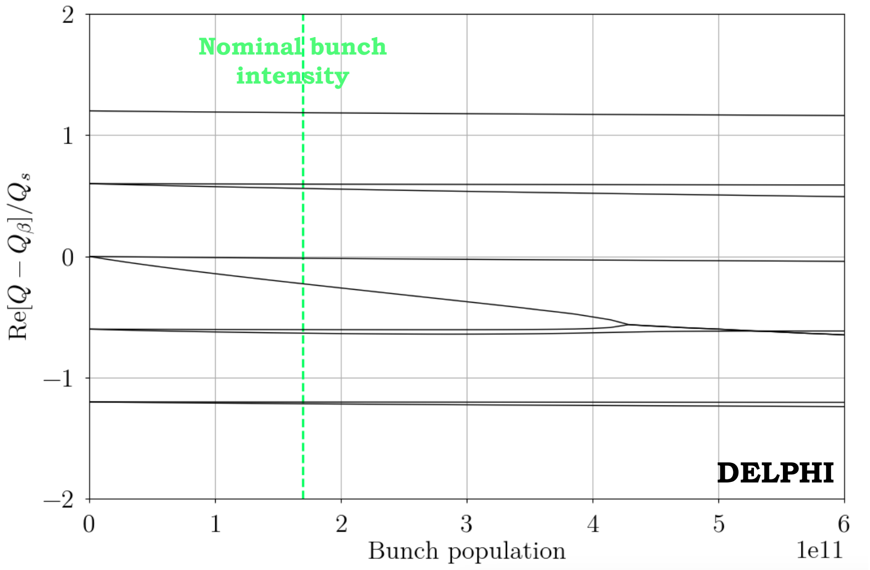
Microwave instability





- $1\mu m$ thickness makes the bunch unstable
- Thinner films allow to increase the MI threshold

Transverse Mode Coupling Instability



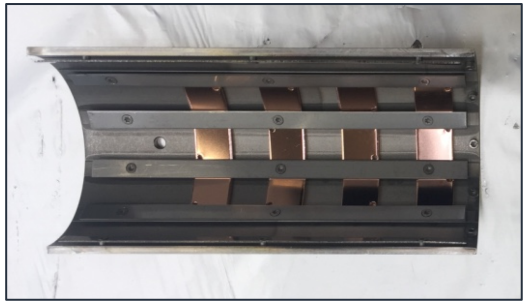
- Analytic simulations with DELPHI code including the bunch lengthening due to the longitudinal wake
- TMCI threshold affected to a lesser extent by the thickness

$$N_{th} = \frac{4\pi \frac{E}{e} \boldsymbol{\tau_b} Q_s}{e\beta\, Im\{Z_m^{eff}\}}$$

- For 100nm film, TMCI threshold ≈ 2.5x higher than nominal bunch population

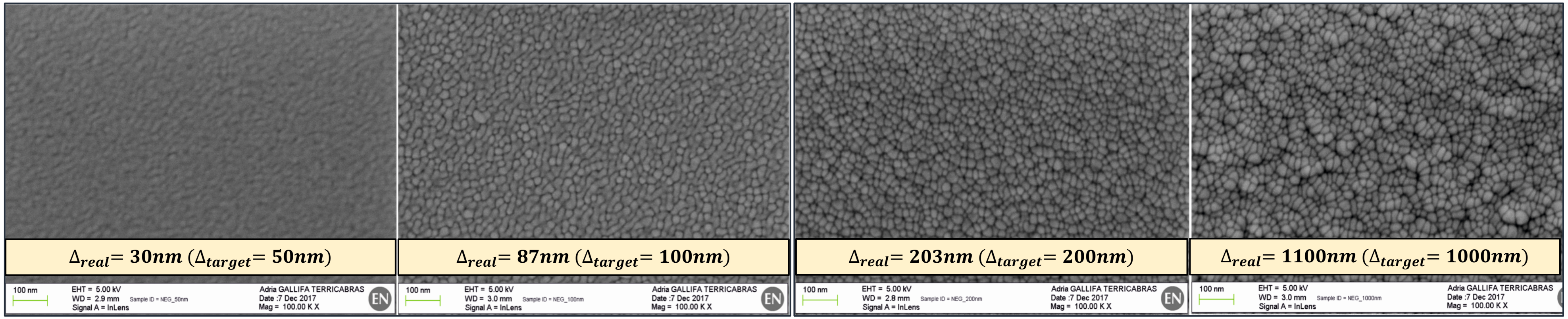
NEG deposition

- NEG deposition on chemically polished Cu samples via magnetron sputtering in a cylindrical system
- Kr as working gas
- Intertwisted 3mm diameter Ti-Zr-V wires as cathode
- Stainless steel vacuum chamber positioned in the centre of a solenoid providing a 200G magnetic field
- Samples at 46mm from the cathode
- Movable mask to allow coating in only one run
- 25% Ti, 40% Zr, 35% V film composition



Surface morphology and thickness

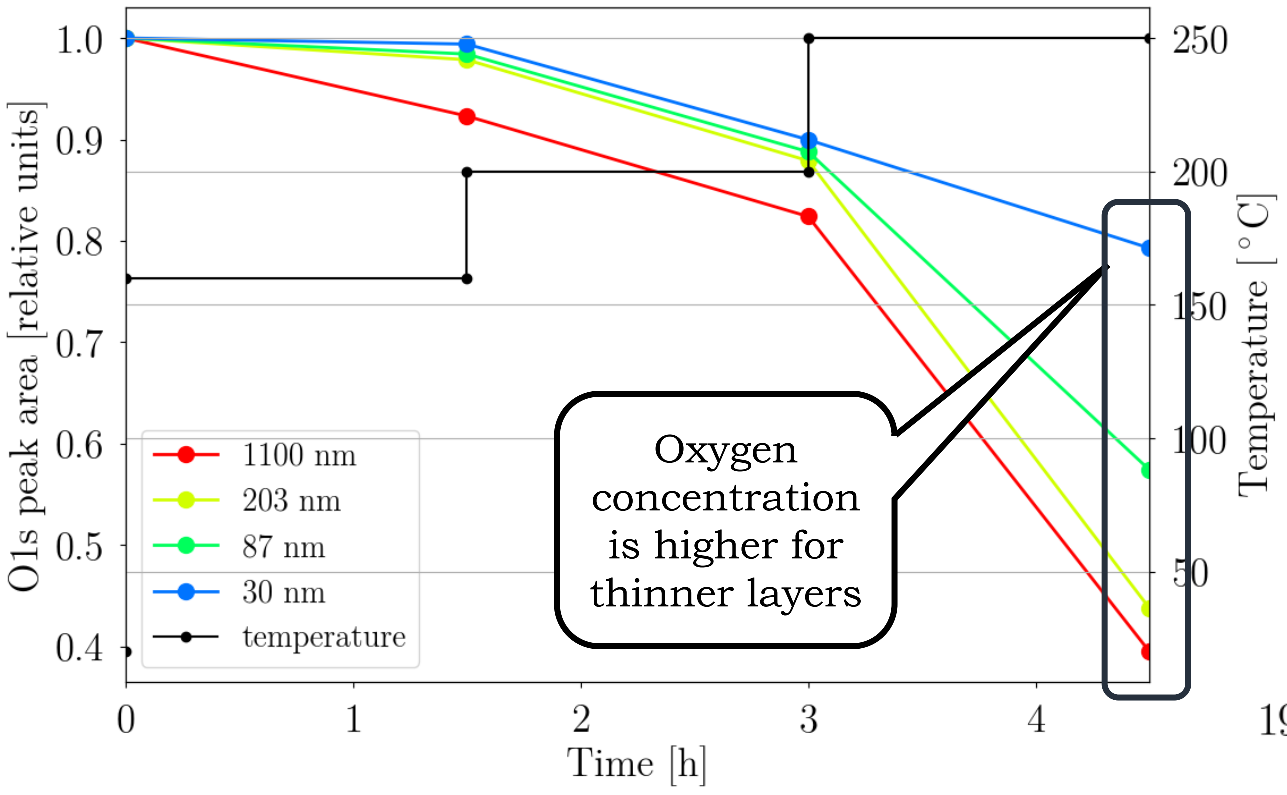
- Real thickness determined by scanning electron microscopy (SEM)

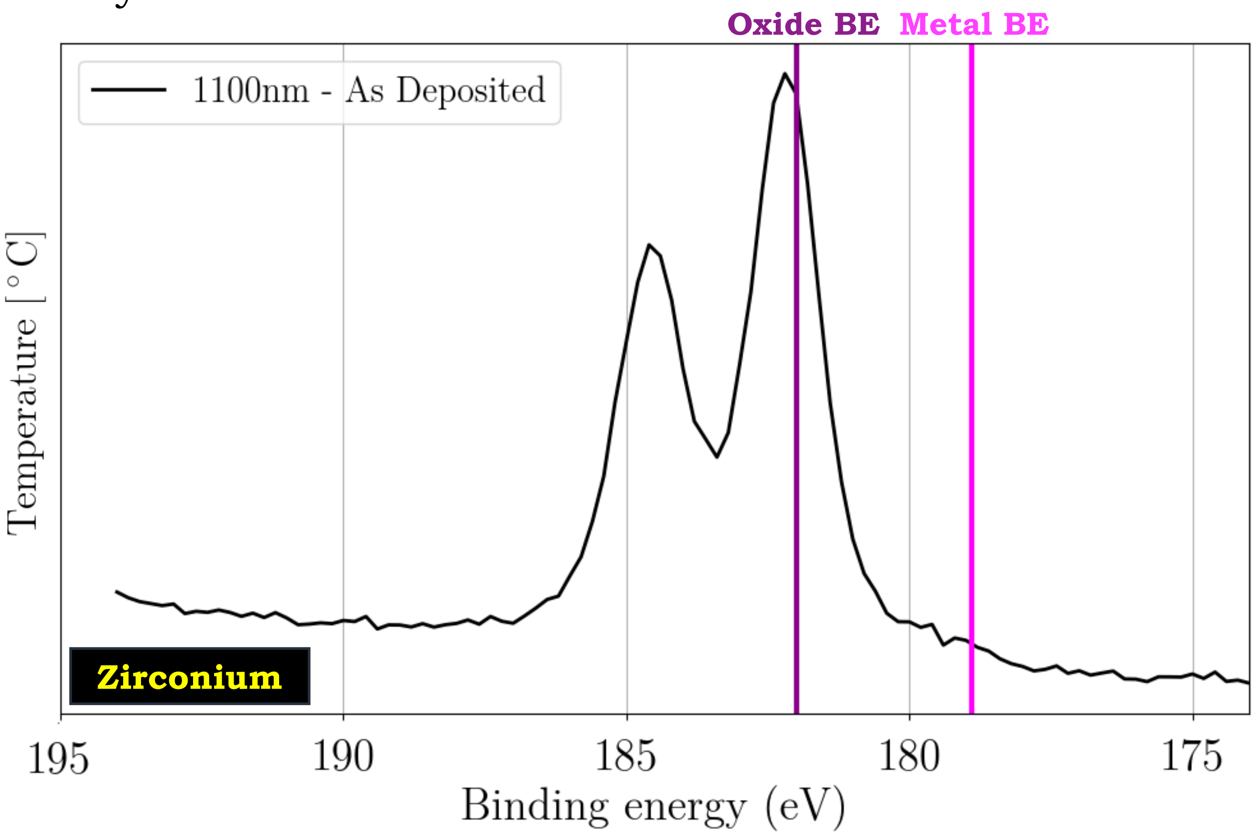


- Full surface coverage
- Uniform thickness
- Changes in the coating roughness with increased thickness

Activation performance

- Surface composition and activation performance measured by X-ray Photoemission Spectroscopy (XPS)
- Multiplex spectra taken:
  - At room temperature
  - After 1h heating at 160°C
  - After 1h heating at 200°C
  - After 1h heating at 250°C
- 4 activation cycles with air exposure between two consecutive cycles





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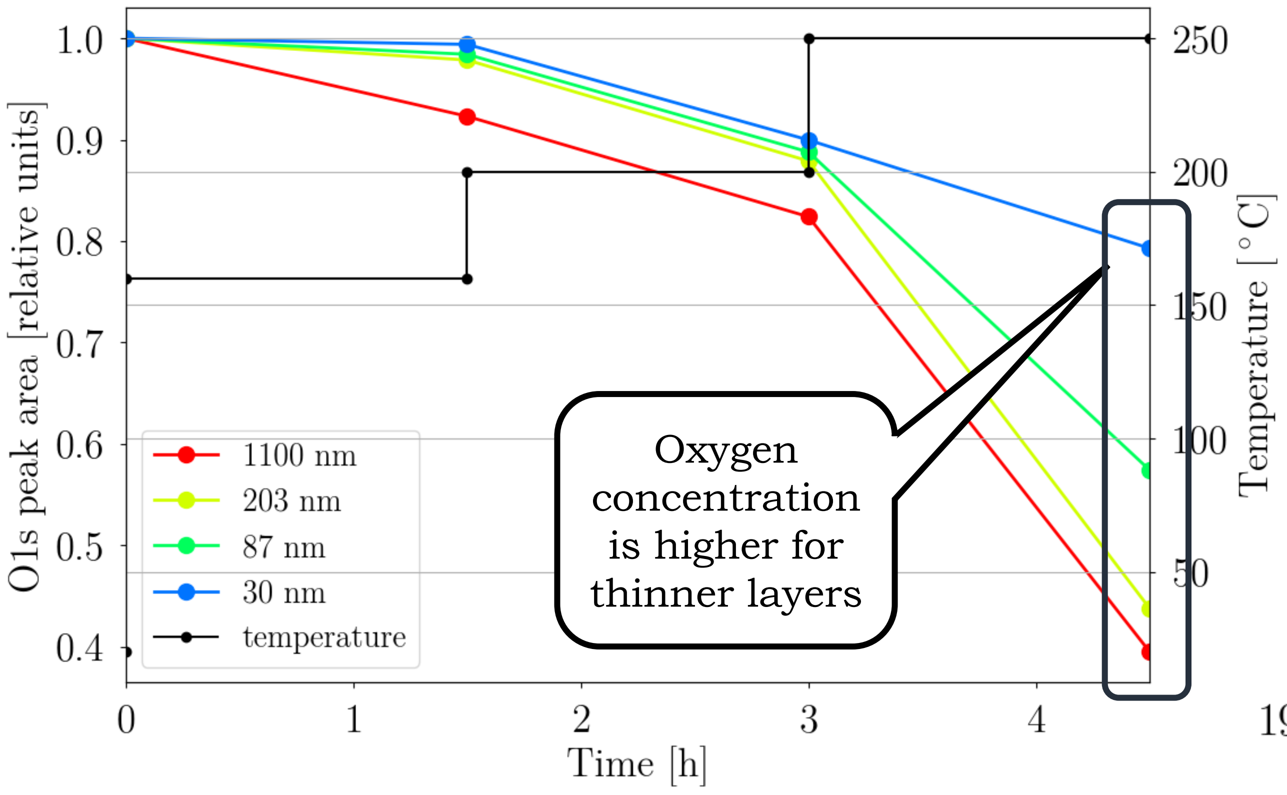

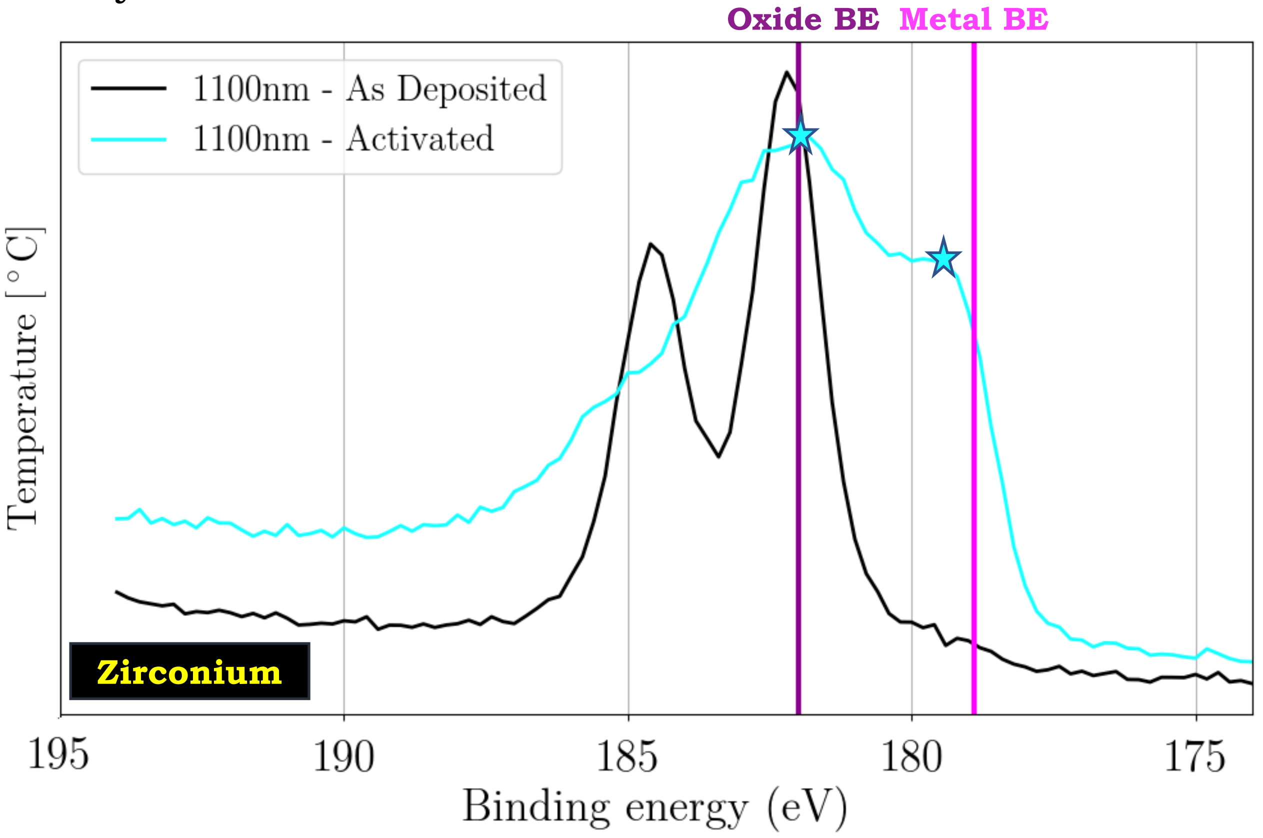

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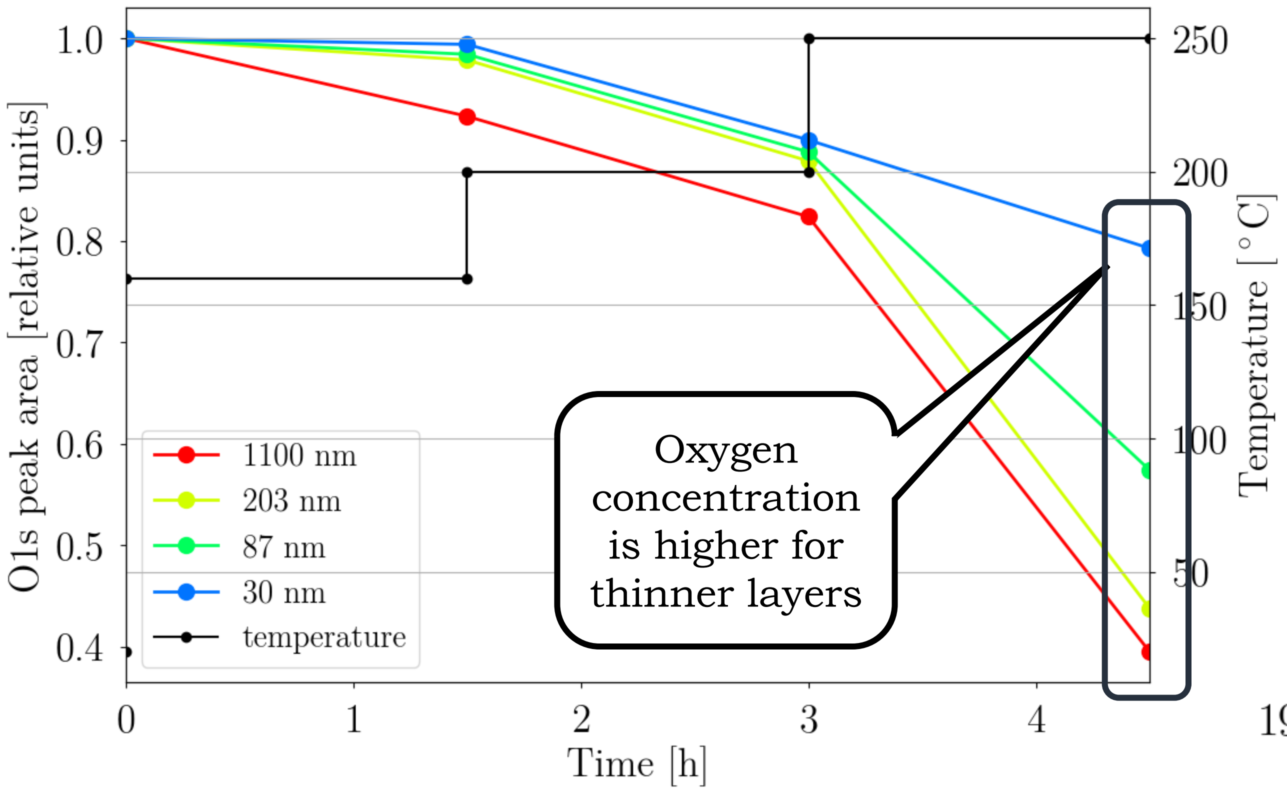

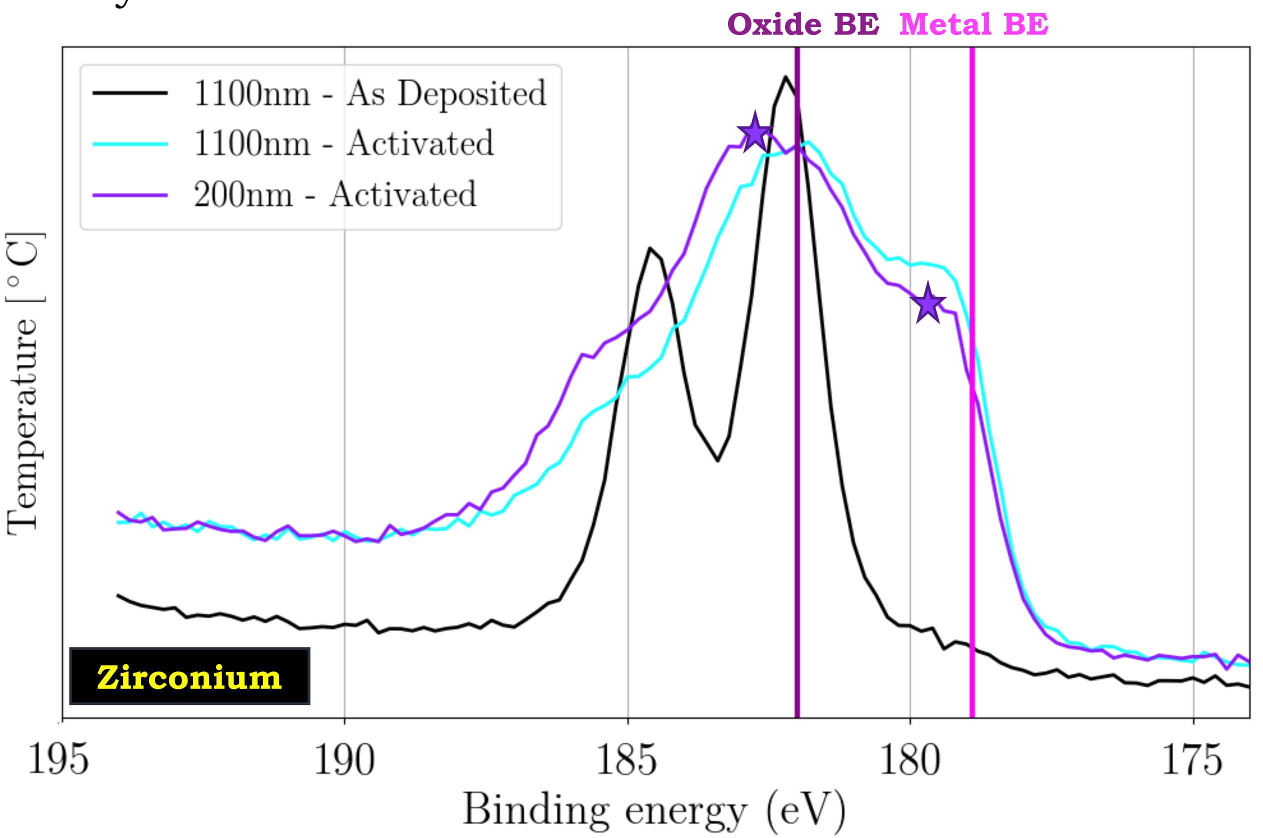

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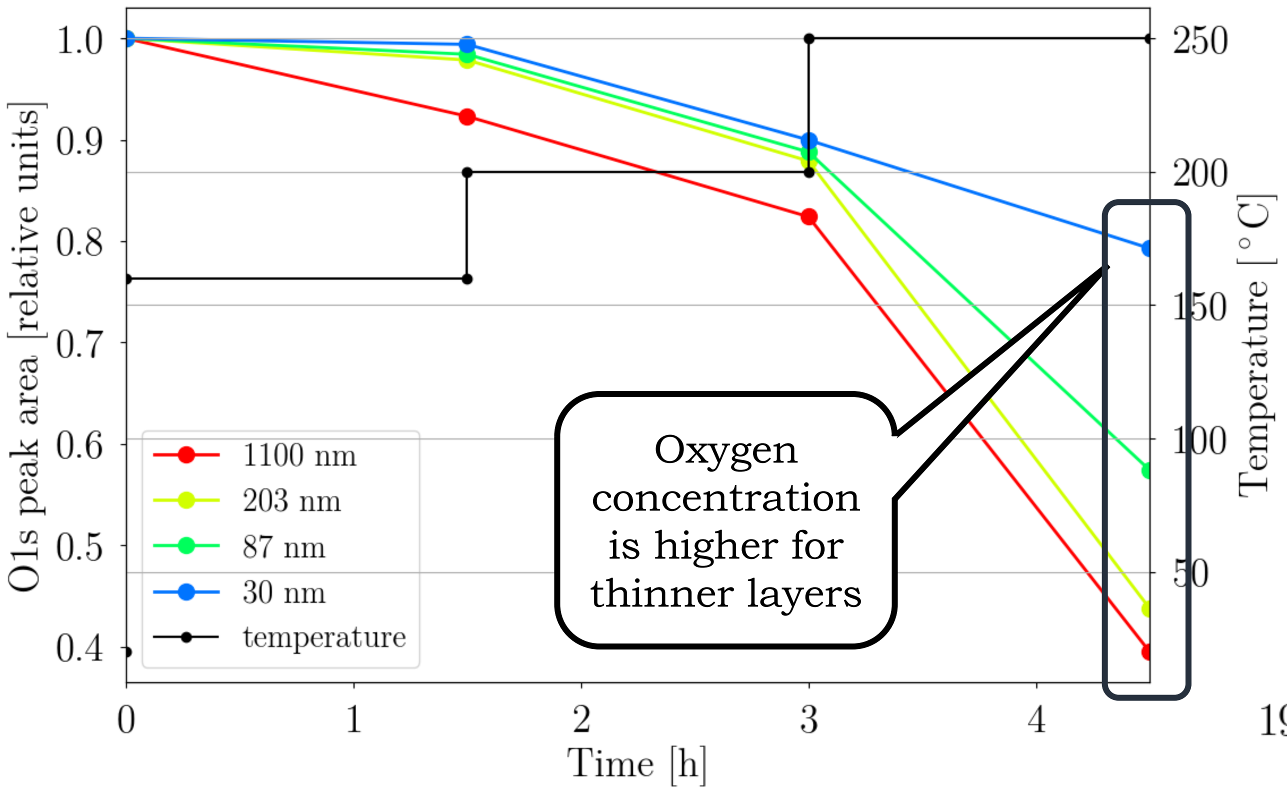

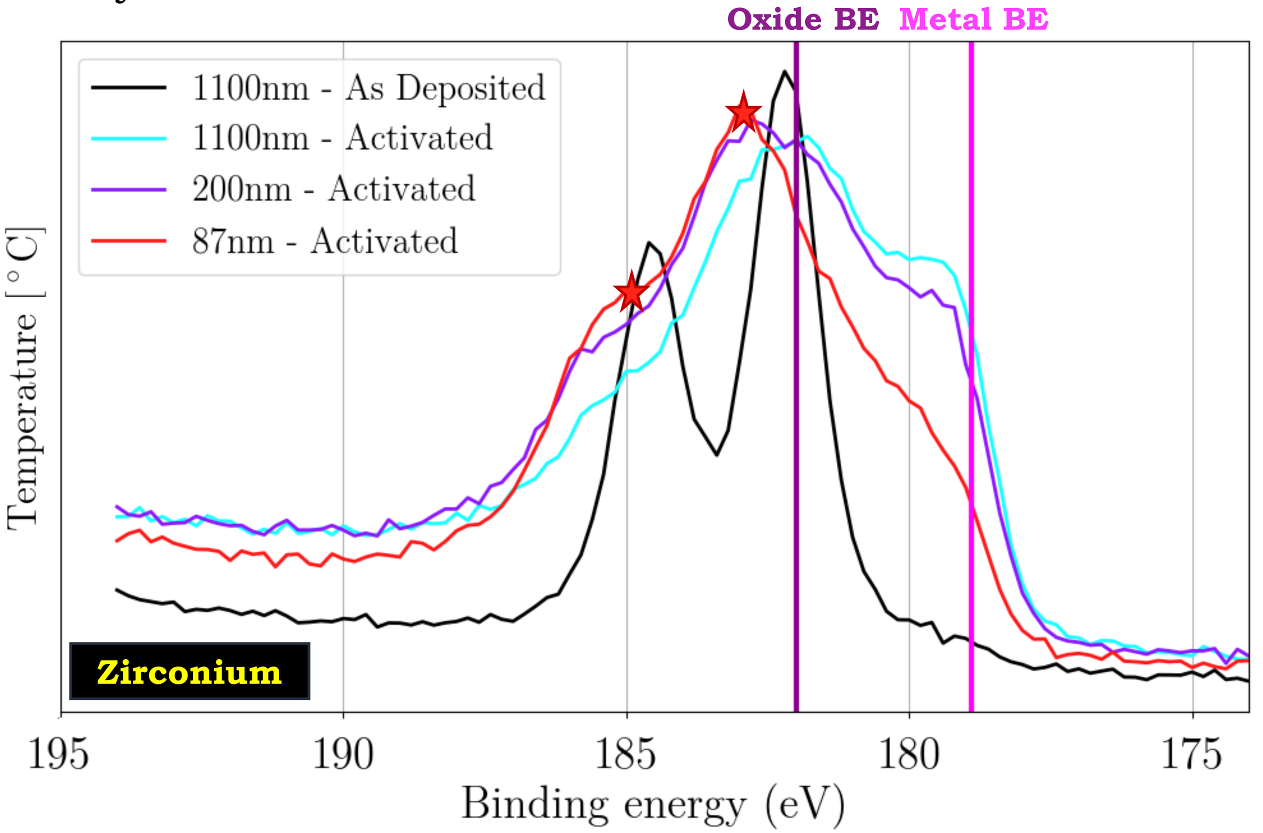

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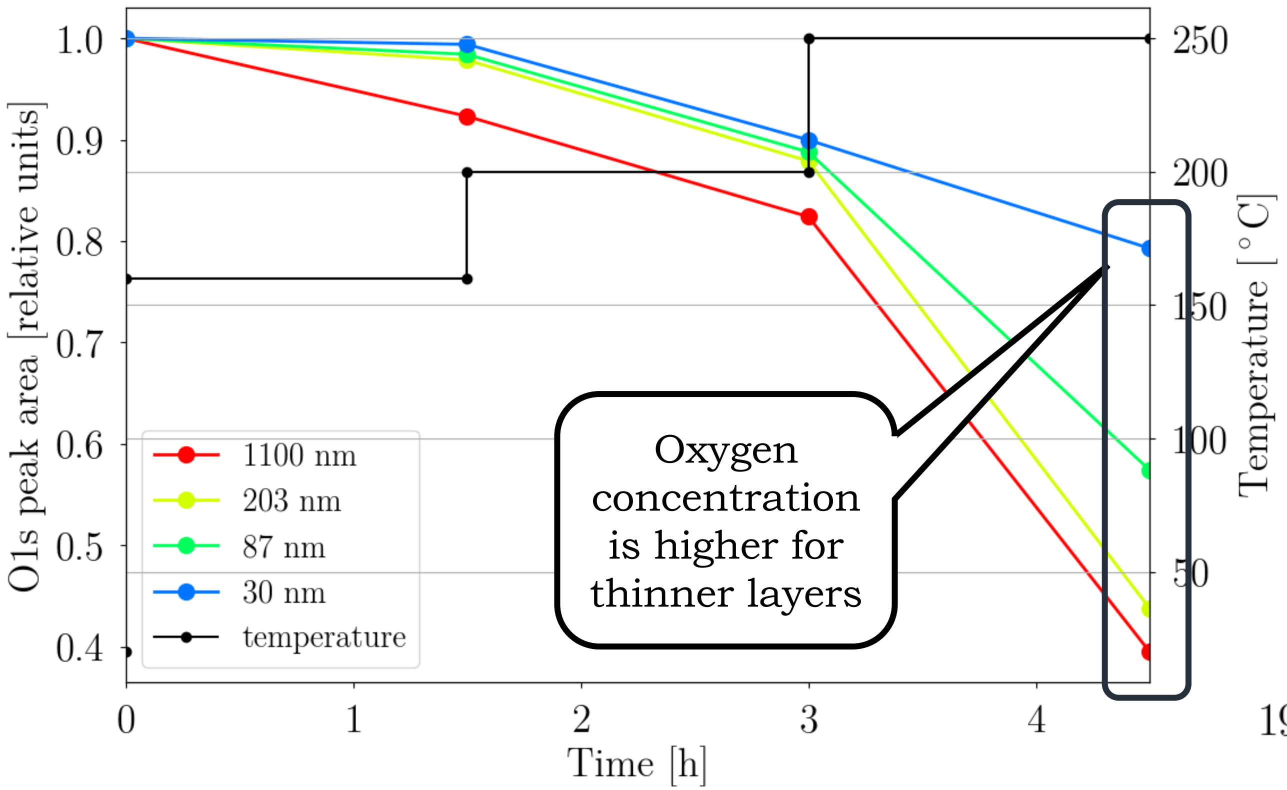
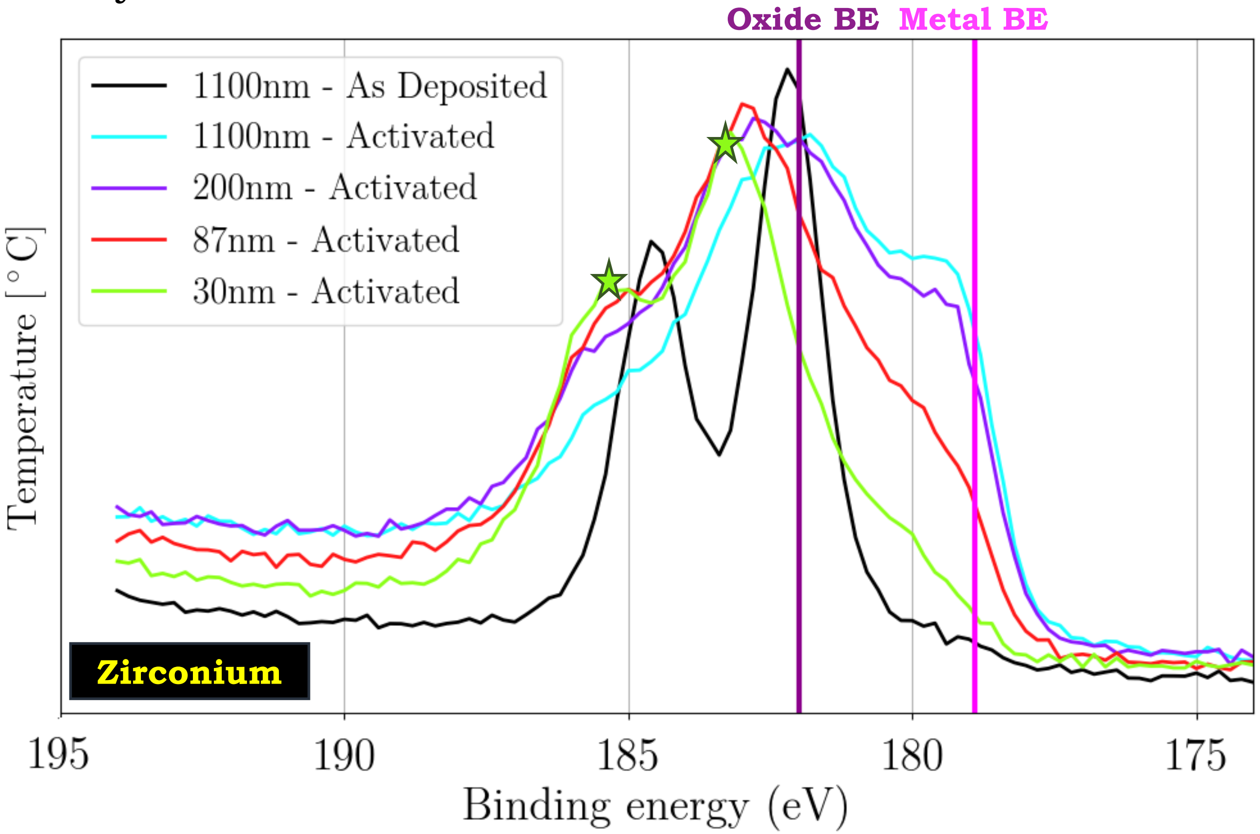
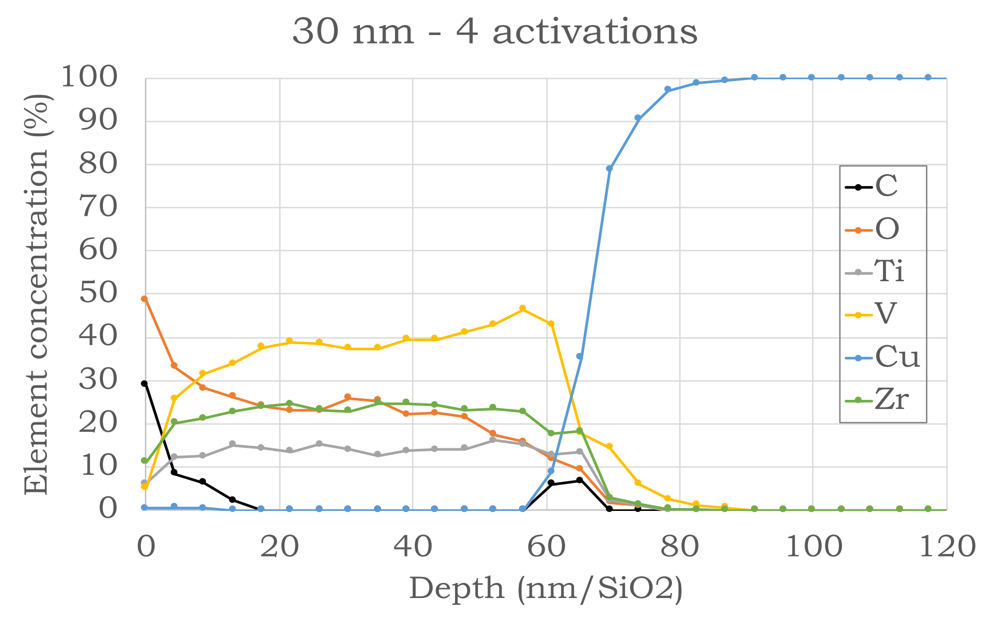
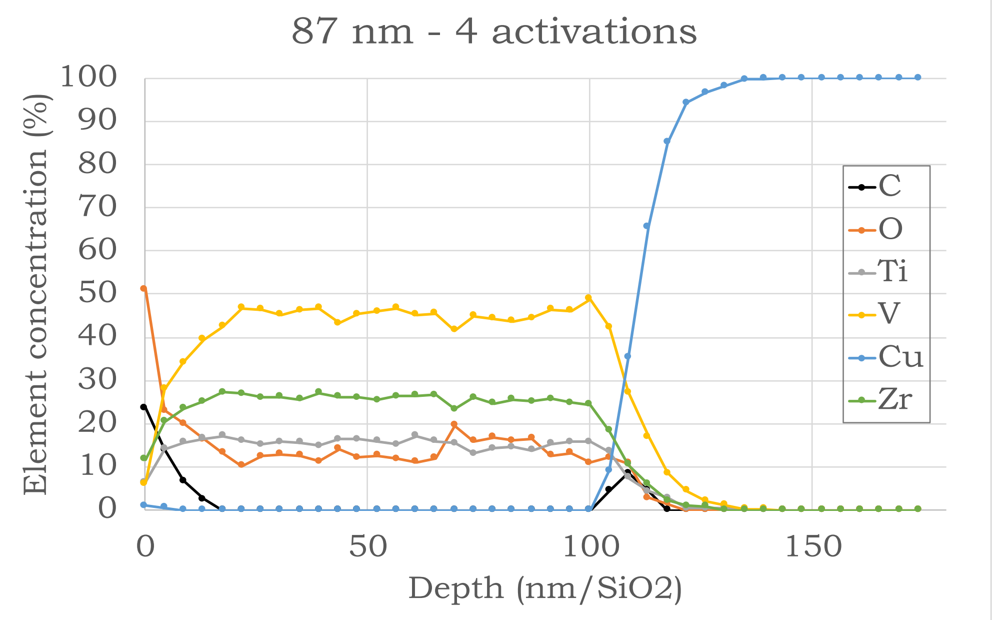
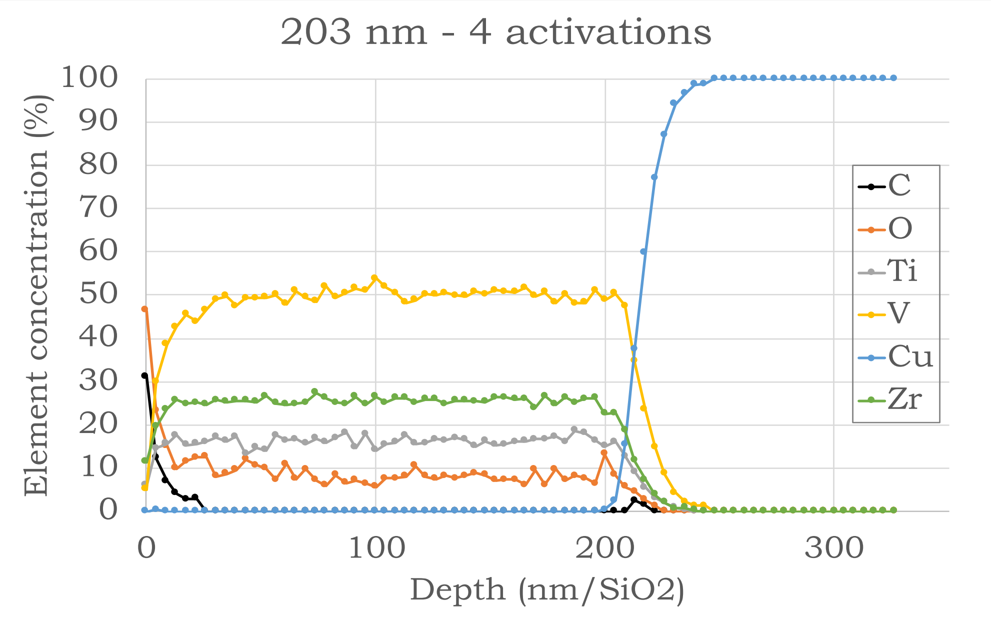


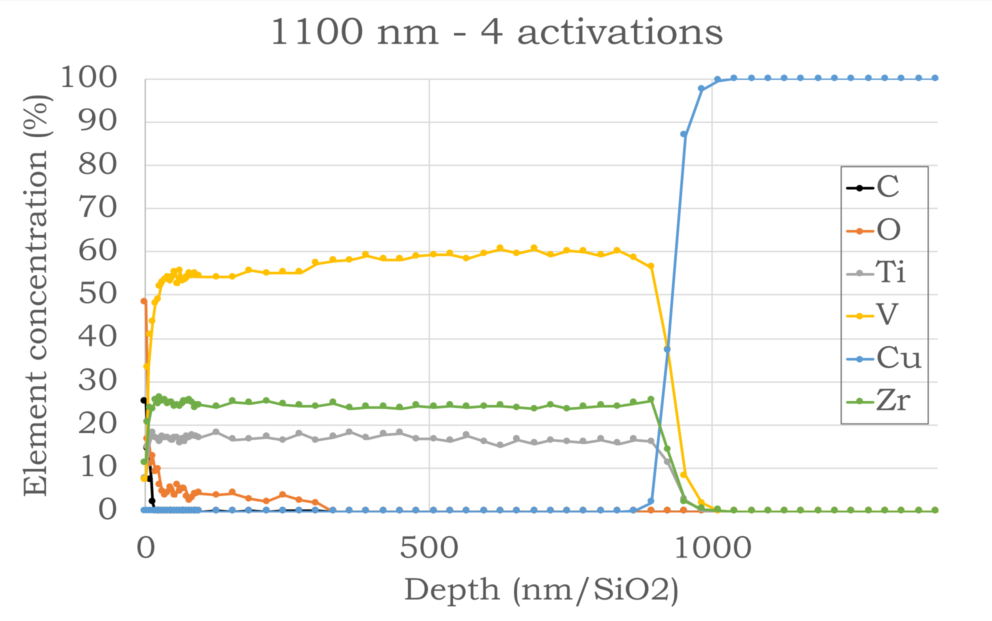


Depth profile after 4 activation cycles



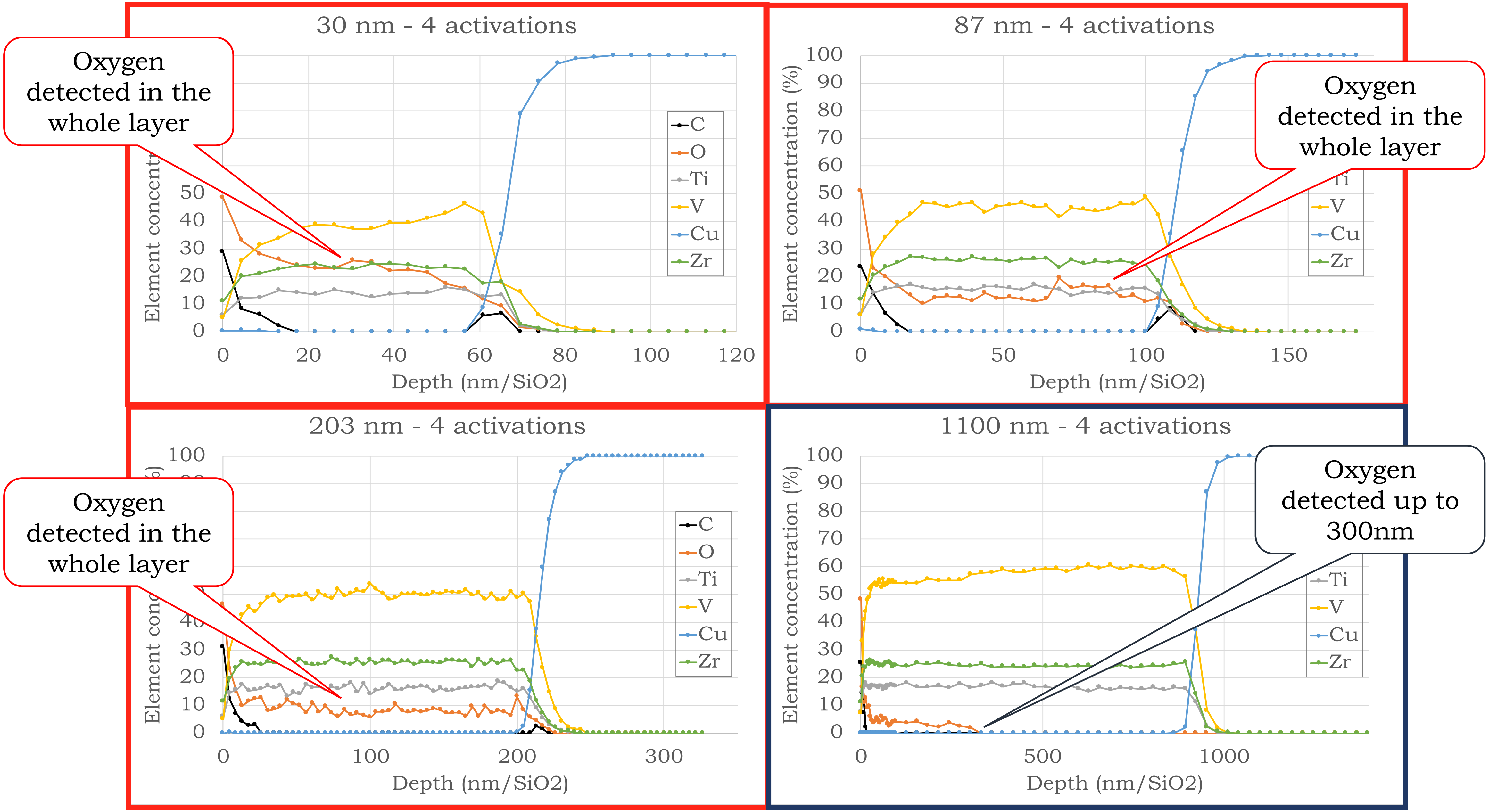






E. Belli - SEY measurements of coated surfaces with different coating thickness

Depth profile after 4 activation cycles



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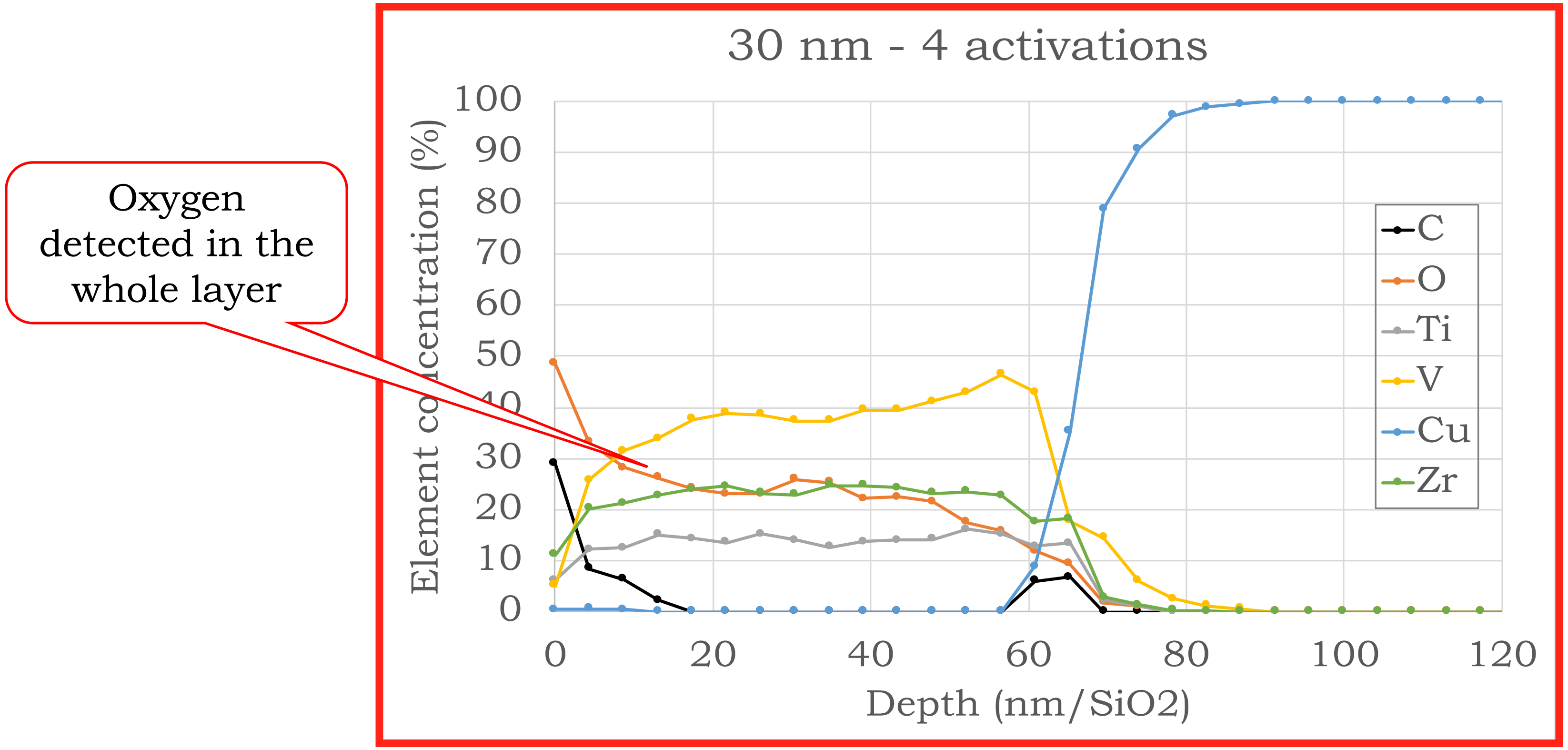
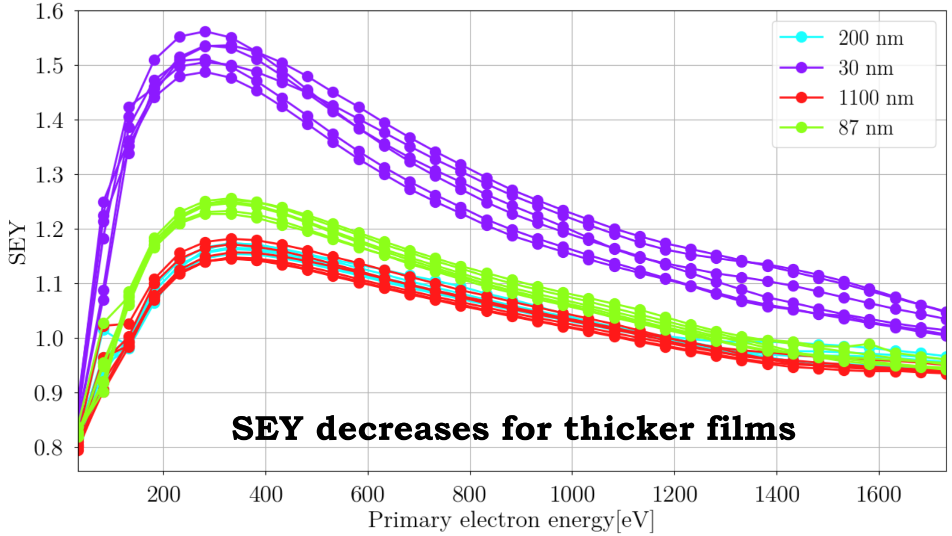
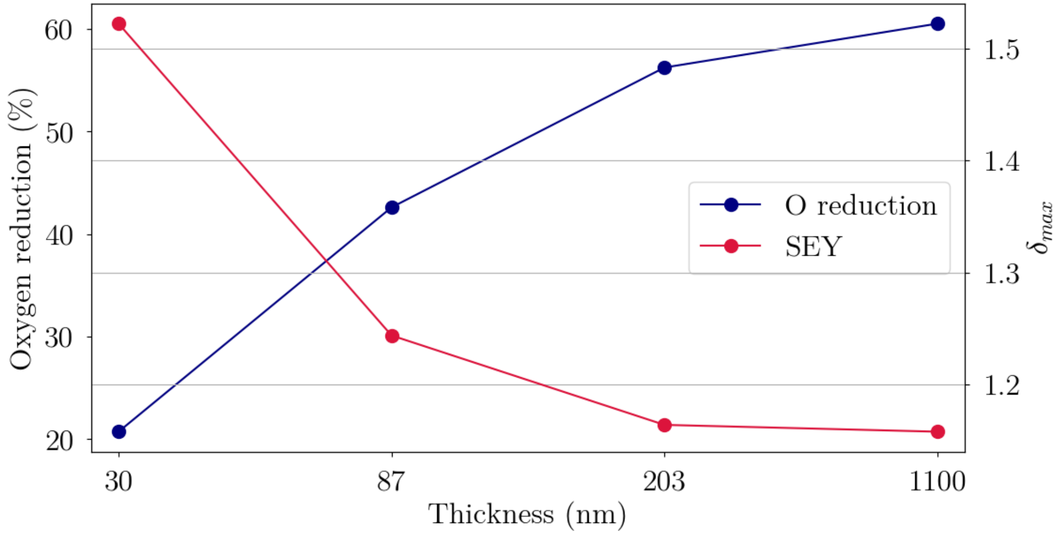


- ➢ The presence of oxygen deep inside the layer will affect the activation performance and the SEY
- ➢ NEG activation is a **diffusion limited** process
  - ❑ Temperature & Time
  - ❑ Material Structure
  - ❑ Gradient of concentration
    - ✓ At the given activation temperature and time, **diffusion (→ activation) will be slower** for the thinnest film due to the presence of oxygen deep inside the layer (loss of gradient)

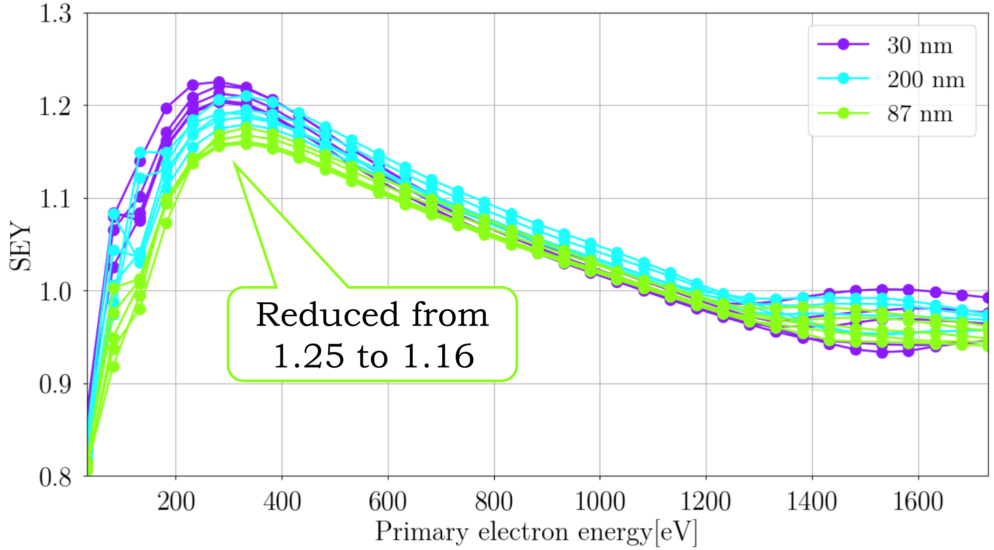
SEY measurements

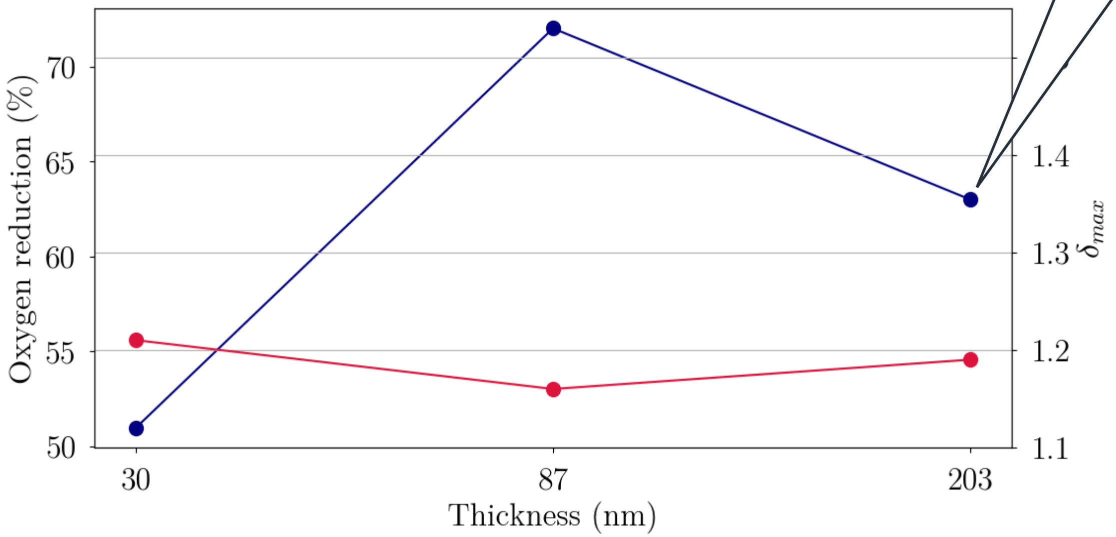
- Electron gun + collector + samples → $\delta = \dfrac{I_{coll}}{I_{coll} + I_{sample}}$
- After the 4th activation cycle of 4h





- After the 4th activation cycle of 24h



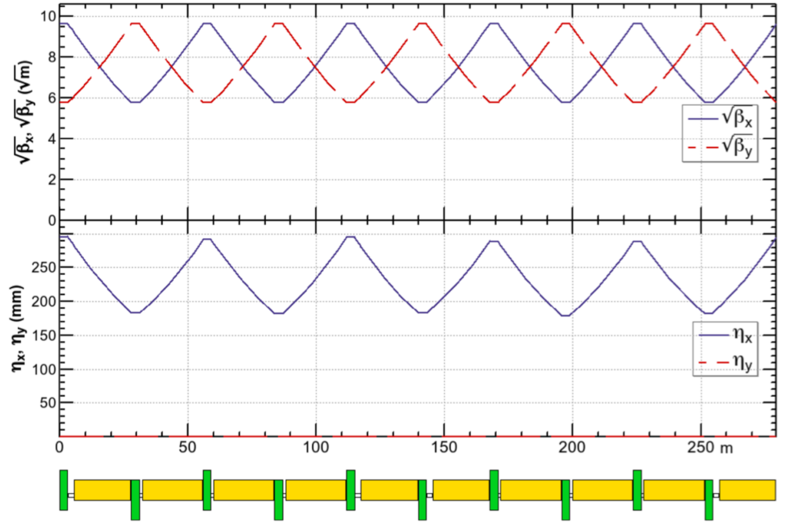


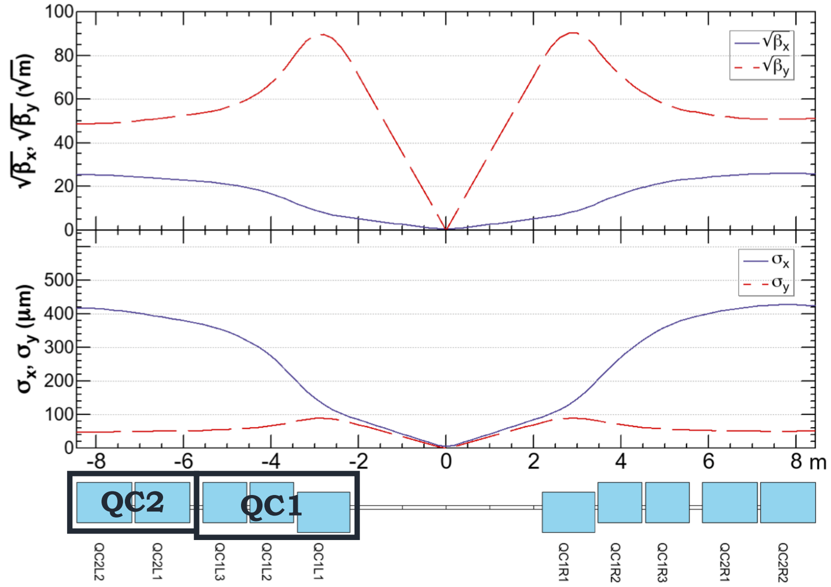
The presence of oxygen on the surface is responsible for higher SEY

EC simulation studies at 45.6 GeV

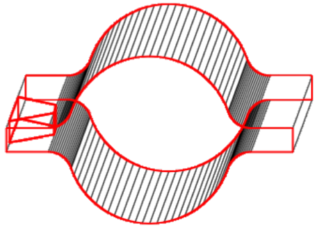
K. Oide

Element	L[m]	Magnetic field
Arc dipole	23.44	0.014 T
Arc quad	3.1	±5.65 T/m
Arc drift	-	-
QC1L1	1.2	-96.3 T/m
QC1L2	1	50.3 T/m
QC1L3	1	9.8 T/m
QC2L1	1.25	6.7 T/m
QC2L2	1.25	3.2 T/m





- ➢ Realistic shape of the vacuum chamber in the arcs (35 mm radius)
- ➢ Round chamber of 15 mm (20 mm) radius in Q1 (Q2)
- ➢ Electron cloud build-up in the arcs and IR magnets
  - ❑ Initial uniform distribution 10^9 e^-/m
  - ❑ SEY scan
  - ❑ Bunch spacing scan: 2.5 ns, 5 ns, 15 ns
  - ❑ Filling pattern: 80b + 25e
  - ❑ Nominal bunch intensity

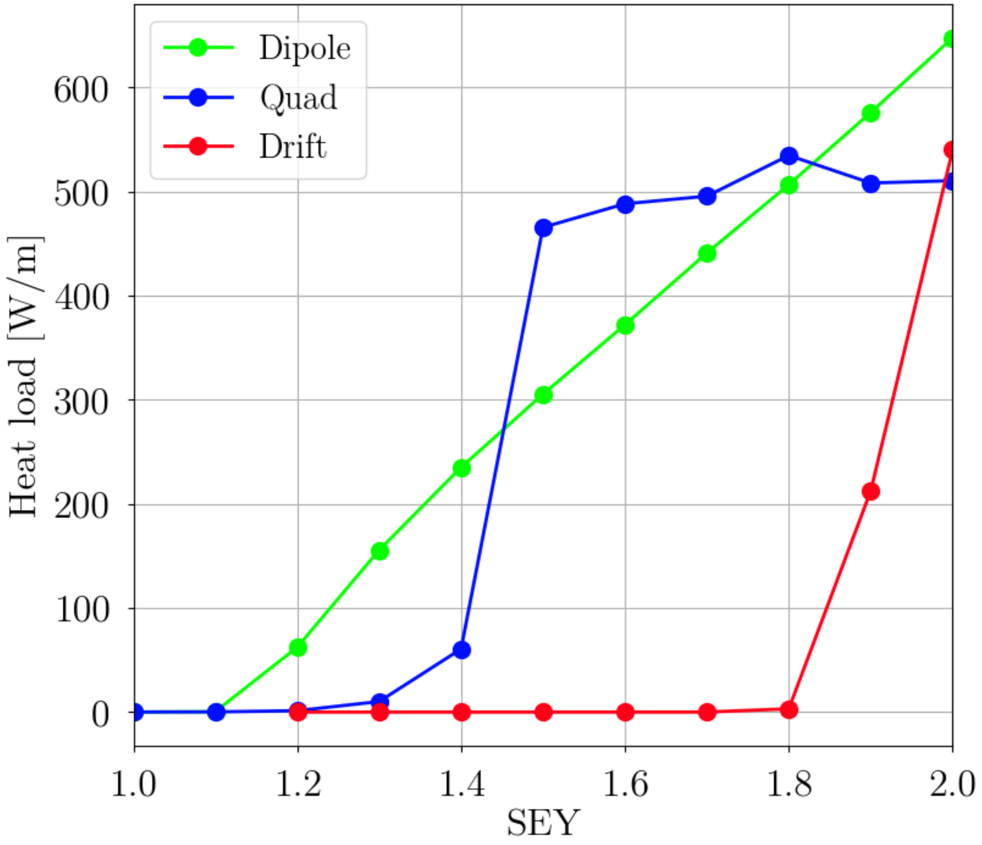


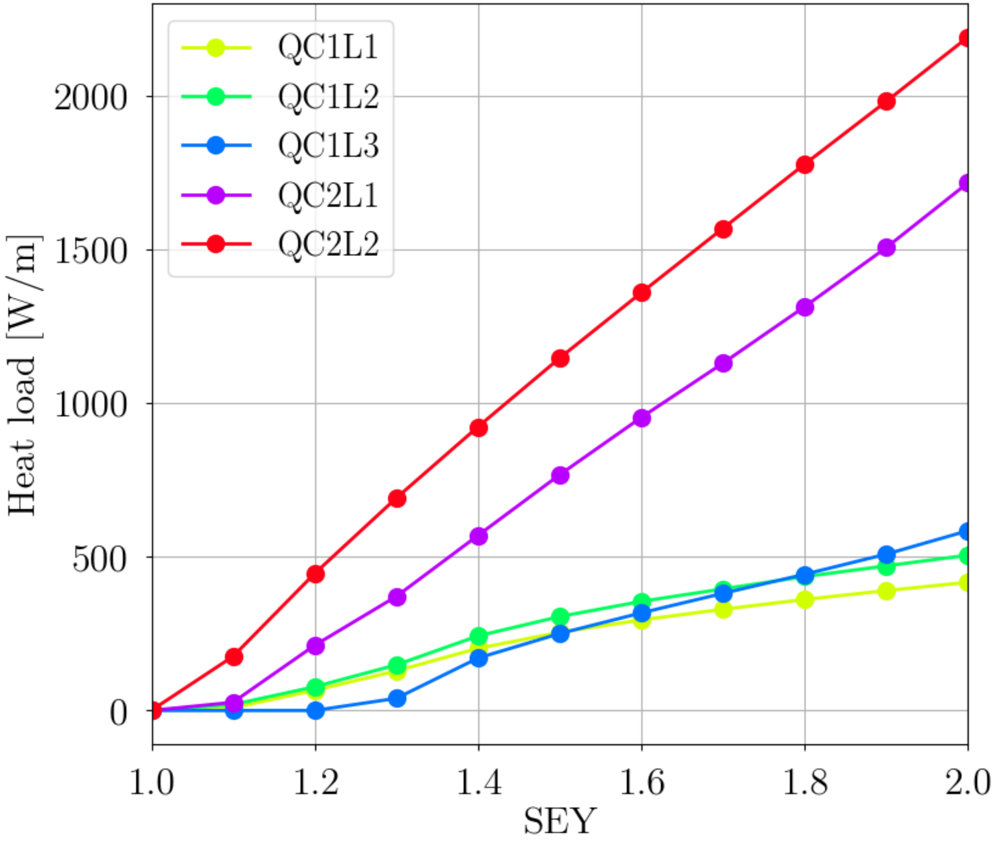
From RF calculations:
- ❖ 10 ns and 17.5 ns not acceptable for the present cavity geometry
- ❖ At least 100 RF buckets between 1st bunches of consecutive trains

2.5 ns beam

	Arc dipole	Arc quad	Arc drift	QC1L1	QC1L2	QC1L3	QC2L1	QC2L1
Multipacting threshold*	1.1	1.2	1.8	1.0	1.0	1.2	1.0	1.0

*highest SEY without EC build up

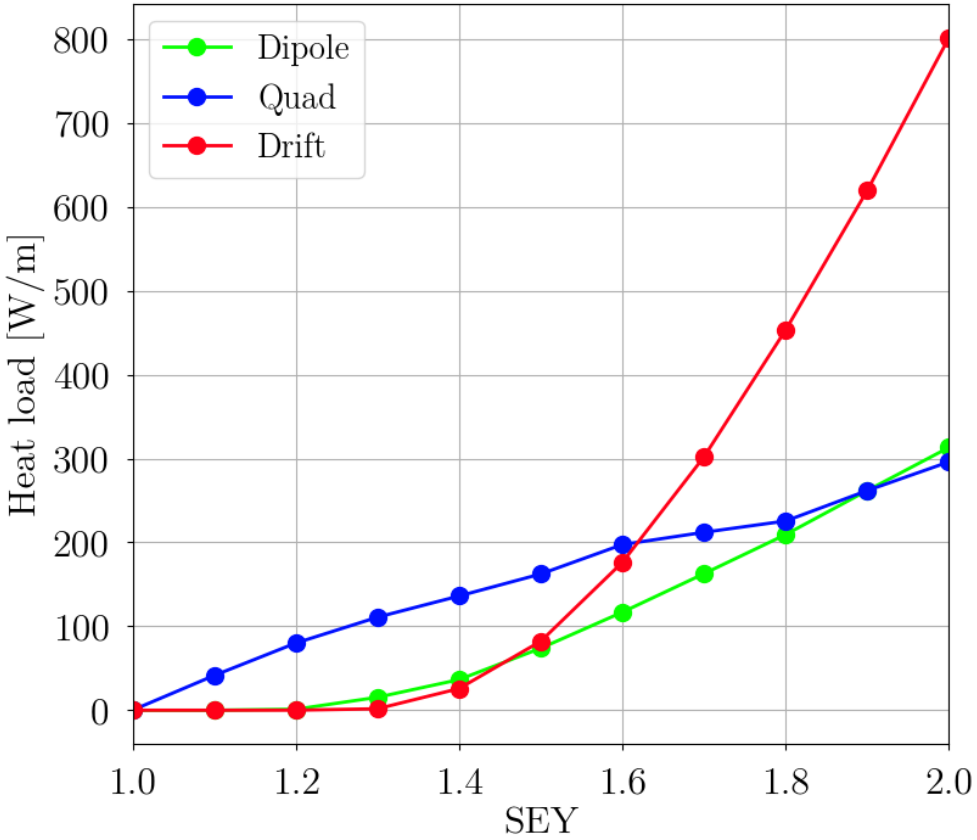


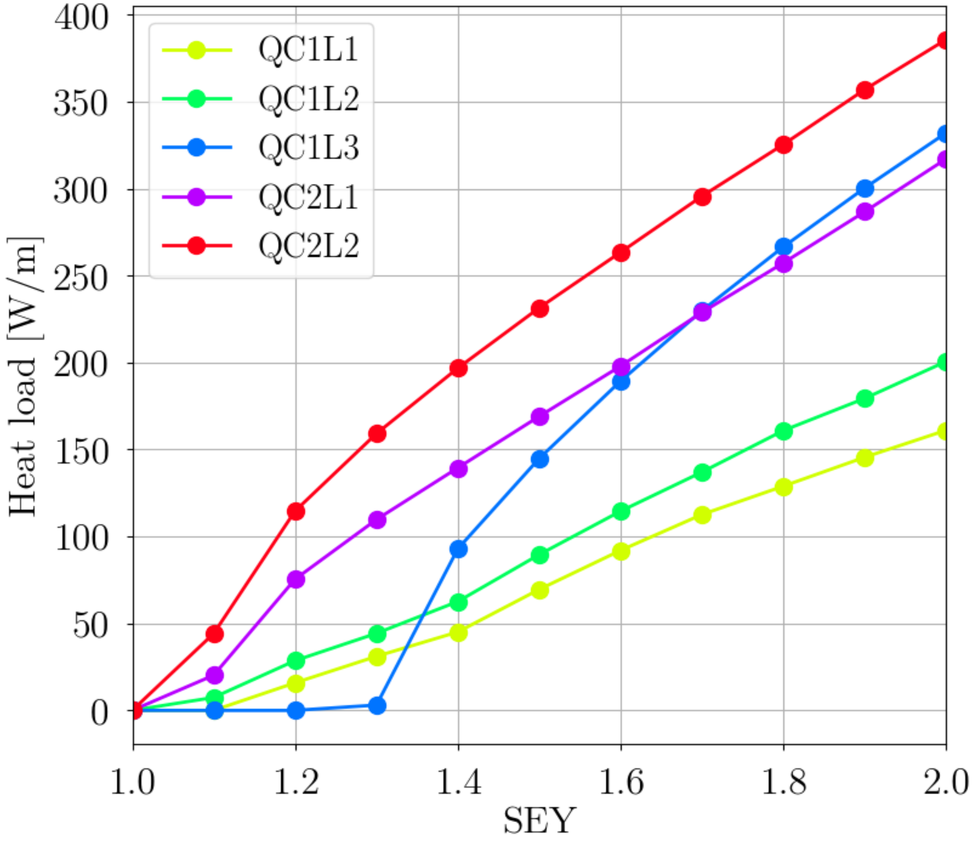


➢ Above threshold, very high heat load for 2.5 ns beam

5 ns beam

	Arc dipole	Arc quad	Arc drift	QC1L1	QC1L2	QC1L3	QC2L1	QC2L1
Multipacting threshold*	1.1	1.0	1.3	1.1	1.0	1.3	1.0	1.0

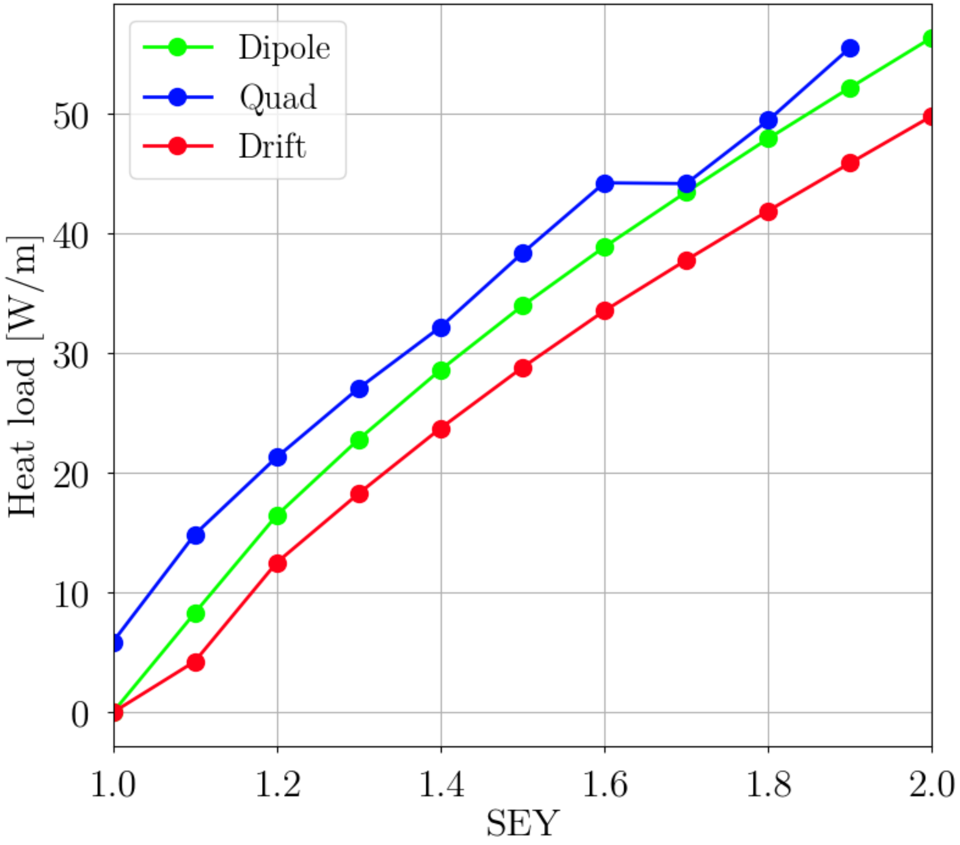


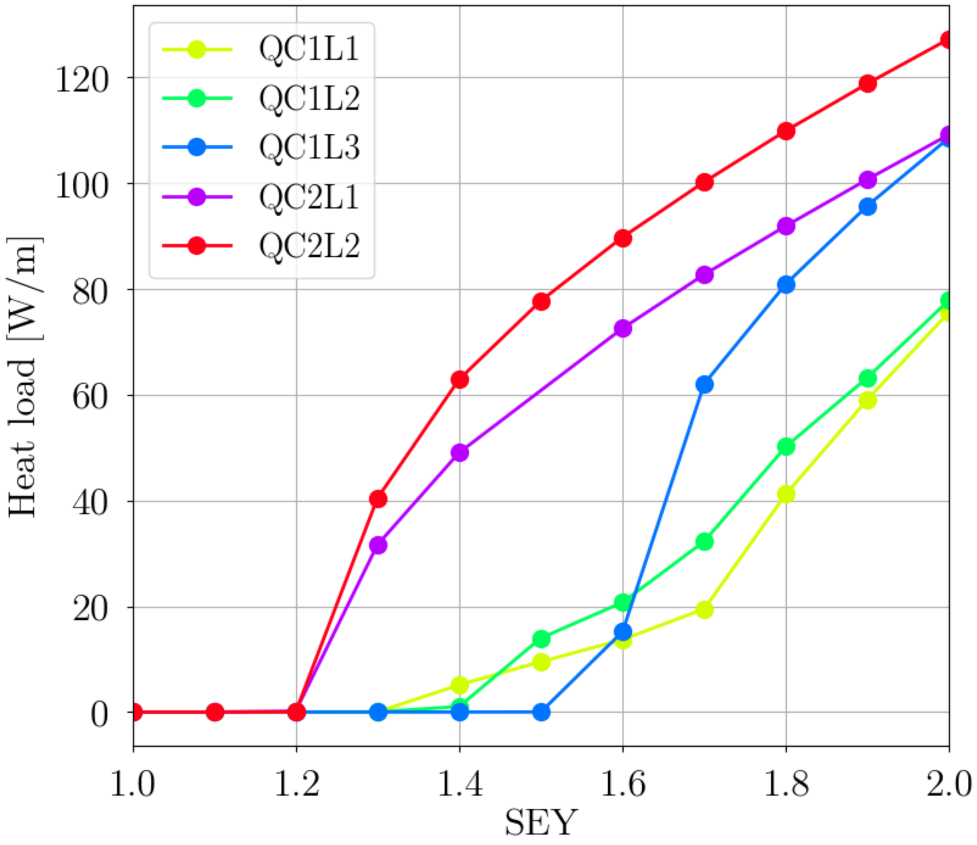


- Above threshold, heat load is still very high

15 ns beam

	Arc dipole	Arc quad	Arc drift	QC1L1	QC1L2	QC1L3	QC2L1	QC2L1
Multipacting threshold*	1.0	<1.0	1.0	1.3	1.4	1.5	1.2	1.2





- Higher thresholds in the IR with a heat load up to 15x lower compared to the 2.5ns beam
- In the arcs, lower thresholds but heat load within acceptable limit (< 100 W/m)

Electron density threshold

$$\rho_{\text{th}} = \frac{2\gamma Q_s}{\sqrt{3} Q r_0 \beta_y C} \quad \text{with} \quad \omega_e = \sqrt{\frac{2\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}} \quad \text{and} \quad Q = \min(\omega_e \sigma_z / c, 7)$$ *

Beam energy [GeV]	45.6	80	120	175	182.5
Circumference [km]	97.75				
Bending radius [km]	10.747				
RF frequency [MHz]	400				
Bunch population [10^{11}]	1.7	2.3	1.8	3.2	3.35
Horizontal emittance [nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance [pm]	1	1.7	1.3	2.7	2.9
Horizontal tune Q_x	269.14	389.124	389.13	389.108	389.108
Vertical tune Q_y	267.22	391.20	391.20	391.18	391.18
Synchrotron tune Q_s	0.025	0.0506	0.0358	0.0598	0.0622
Bunch length [mm]	3.5	3.0	3.15	2.75	2.76
Electron frequency $\omega_e/2\pi$ [GHz]	392.47	395.21	392	385.94	379.03
Electron oscillation $\omega_e\sigma_z/c$	28.79	24.85	25.88	22.24	21.92
Density threshold ρ_{th} [$10^{10}/m^3$]	**2.29**	**11.92**	**12.65**	**30.83**	**33.45**

- Instability thresholds to be evaluated with macroparticle simulations

***K. Ohmi, F. Zimmermann, "Head-Tail Instability Caused by Electron Clouds in Positron Storage Rings", *Phys. Rev. Lett.*, vol 85, p.3821.**

Conclusions

- NEG coating required for pumping and electron cloud mitigation
  - RW impedance contribution can be reduced by decreasing the thickness of the coating layer
- NEG thin films with $\Delta < 250$ nm analysed in terms of activation performance and SEY
- Reduced activation performance is due to elevated concentrations of O in the film, which is higher for repeated activations and thinner films
  - After 4 short activation cycles, the thinnest layer (30 nm) was unable to activate properly with a max SEY ≈ 1.55
  - Longer activation cycles led to better activation and a lower SEY

- Electron cloud build up estimated in the main elements of FCC-ee
- Multipacting threshold evaluated for different bunch spacings
  - 15 ns beam is the preferable option
    - Higher thresholds in the IR (SEY < 1.2 to run the IR without electron cloud)
    - Heat load within acceptable limit in the arcs (< 100 W/m)
- Analytic single bunch instability threshold estimated for all the energies
  - Instability thresholds to be evaluated with macroparticle simulations

Future steps

- The minimum effective thickness to be used in the machine also depends on the desired number of venting and activation cycles required (at least 10 activation and venting cycles to be tested)
- Further experimentation recommended for a film thickness around 150nm balancing the limitations of activation and impedance
- Photon stimulated desorption measurements for thin films
- Further mitigation techniques to be investigated (clearing electrodes, laser treatment, etc.)

Thanks for your attention

Back up slides

RW impedance with coating

- Resistive wall impedance of a two-layer tube with metallic layers[1,2]

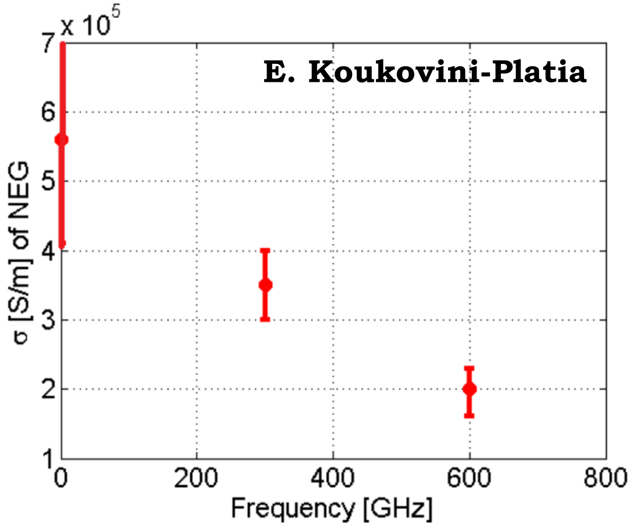
$$\frac{Z_\parallel(\omega)}{C} = \frac{Z_0\omega}{4\pi cb}\left\{[\mathrm{sgn}(\omega)-i]\delta_1 \frac{\alpha\ \tanh\left[\frac{1-i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right]+1}{\alpha+\tanh\left[\frac{1-i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right]}\right\} \approx \frac{Z_0\omega}{4\pi cb}\left\{[\mathrm{sgn}(\omega)-i]\delta_2 - 2i\Delta\left(1-\frac{\sigma_1}{\sigma_2}\right)\right\}$$

$\delta_1 \gg \Delta$ $\qquad$ $\frac{\sigma_1}{\sigma_2} \ll 1$

$$\frac{Z_\perp(\omega)}{C} = \frac{Z_0\omega}{2\pi b^3}\left\{[1-i\,\mathrm{sgn}(\omega)]\delta_1 \frac{\alpha\ \tanh\left[\frac{1-i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right]+1}{\alpha+\tanh\left[\frac{1-i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right]}\right\} \approx \frac{Z_0\omega}{2\pi b^3}\left\{[1-i\mathrm{sgn}(\omega)]\delta_2 - 2i\Delta\,\mathrm{sgn}(\omega)\left(1-\frac{\sigma_1}{\sigma_2}\right)\right\}$$

- Condition 1: the skin depth of the coating material is much bigger than its thickness
  - $f \approx 100\ GHz, 10^3\frac{S}{m} < \sigma_1 < 10^6\frac{S}{m}$ → $\mathbf{50\mu m < \delta_1 < 1.5\mu m}$
- Condition 2: the conductivity of the coating material is much smaller than the conductivity of the substrate
  - $\sigma_2 \approx 6\cdot 10^7\frac{S}{m} \gg \sigma_1$

In the case of FCC-ee, both conditions are always verified



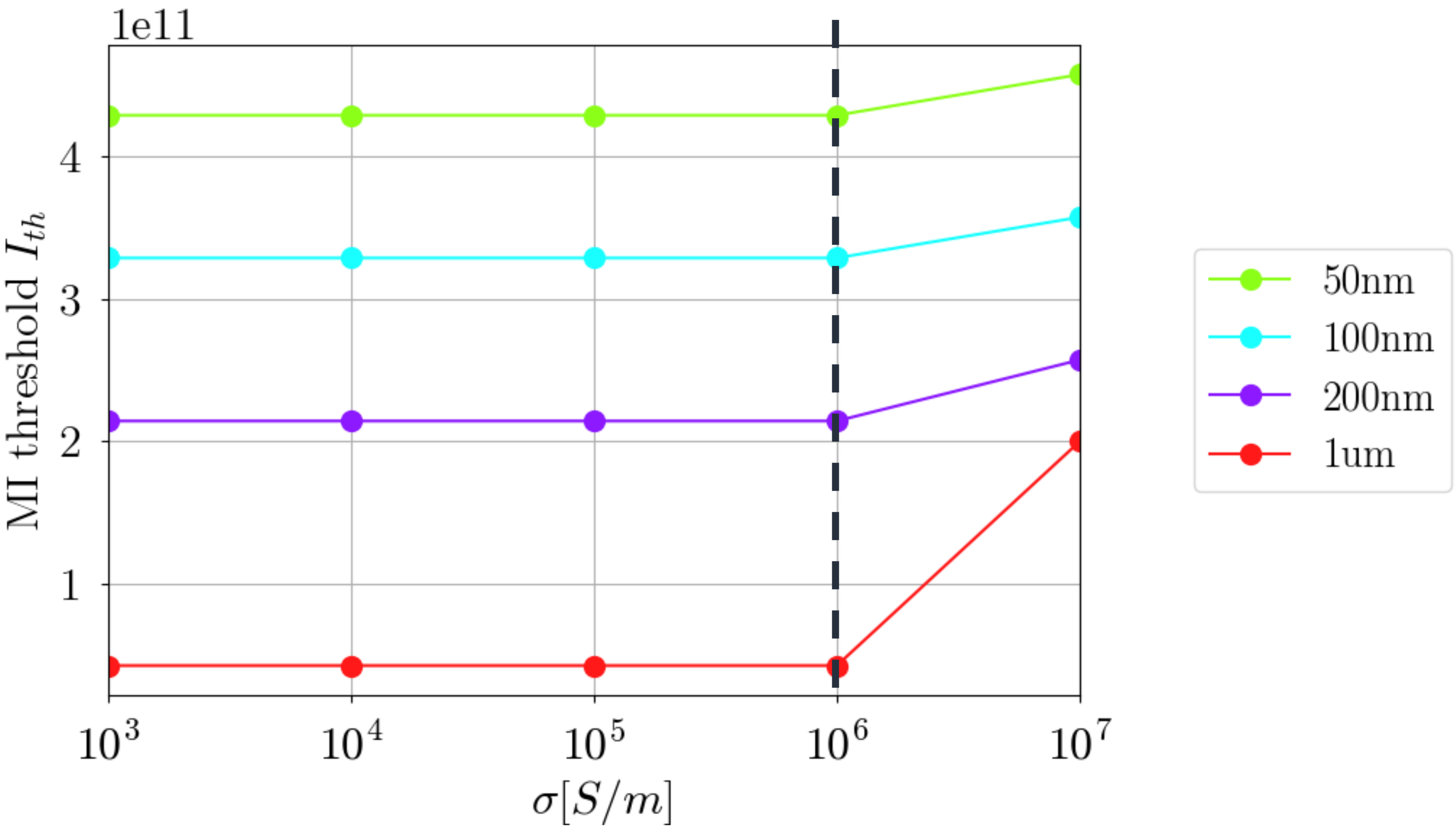
[1] N. Wang and Q. Qin, "Resistive wall impedance of two-layer tube", *Phys. Rev. ST Accel. And Beams,* vol. 10, p. 111003

[2] M. Migliorati, E. Belli and M. Zobov, "Impact of the resistive wall impedance on beam dynamics in the Future Circular e+e- Collider", *Phys. Rev. Accel. And Beams,* vol. 21, p. 041001

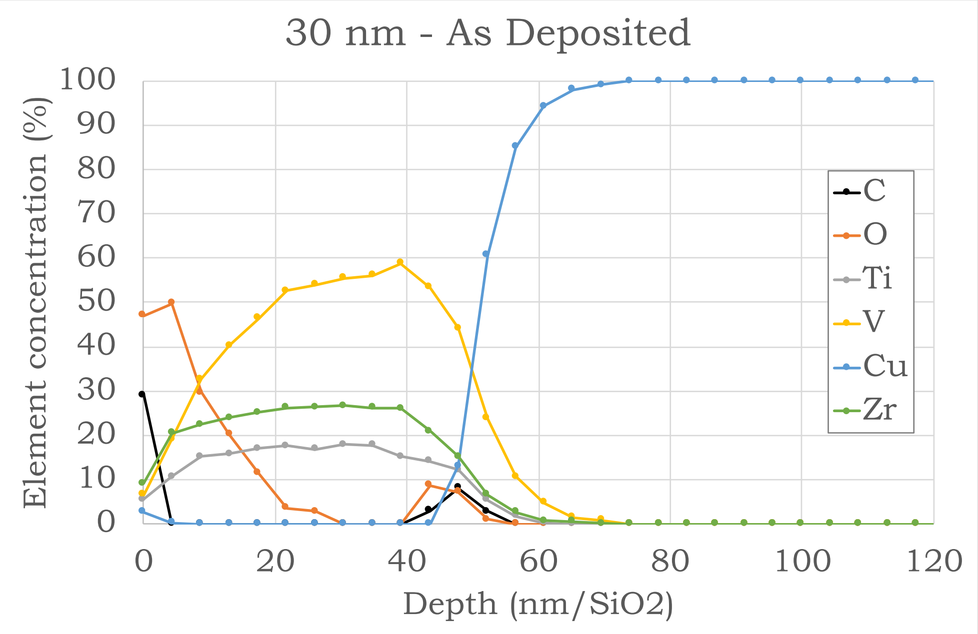
RW impedance with coating at 45.6 GeV

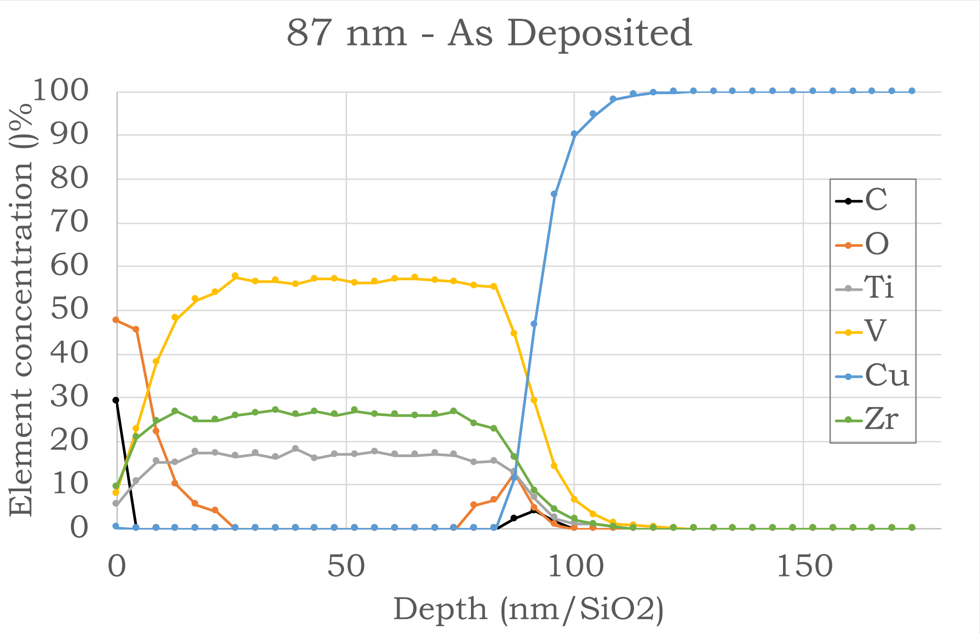
Both conditions verified and the instability threshold mainly depends on thickness

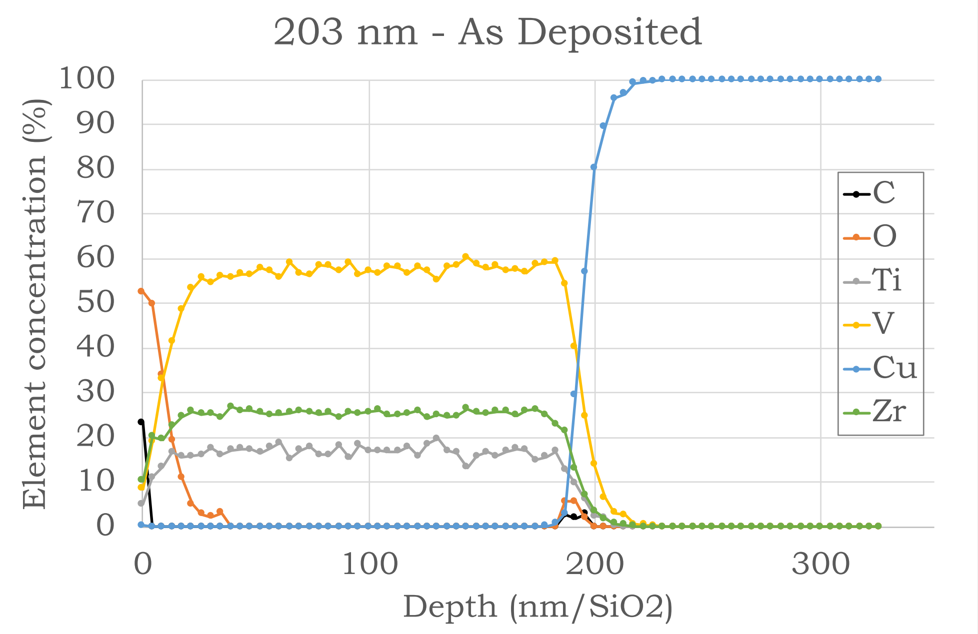
Material conductivity plays a role

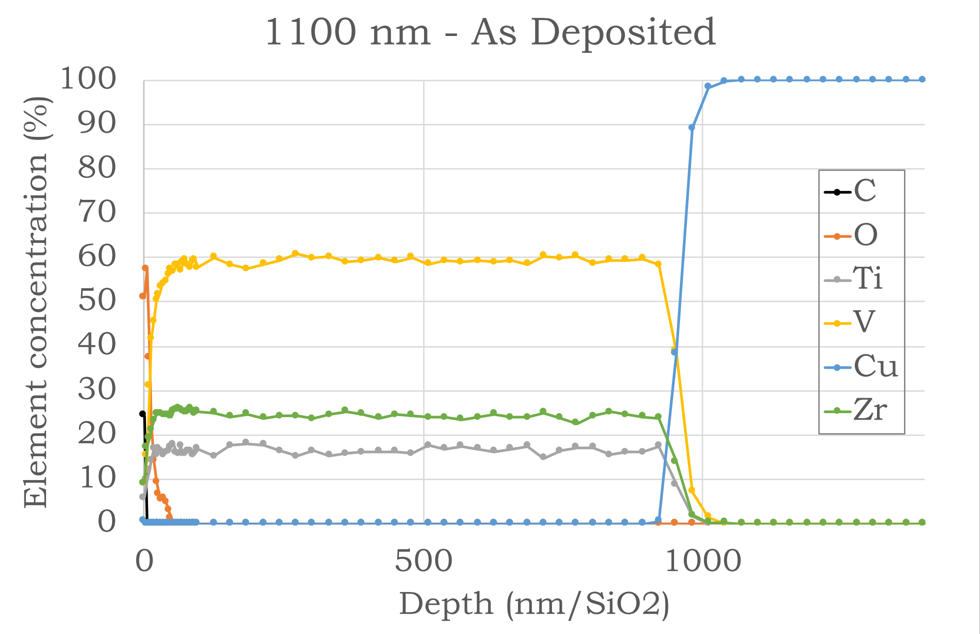


Depth profile – As Received



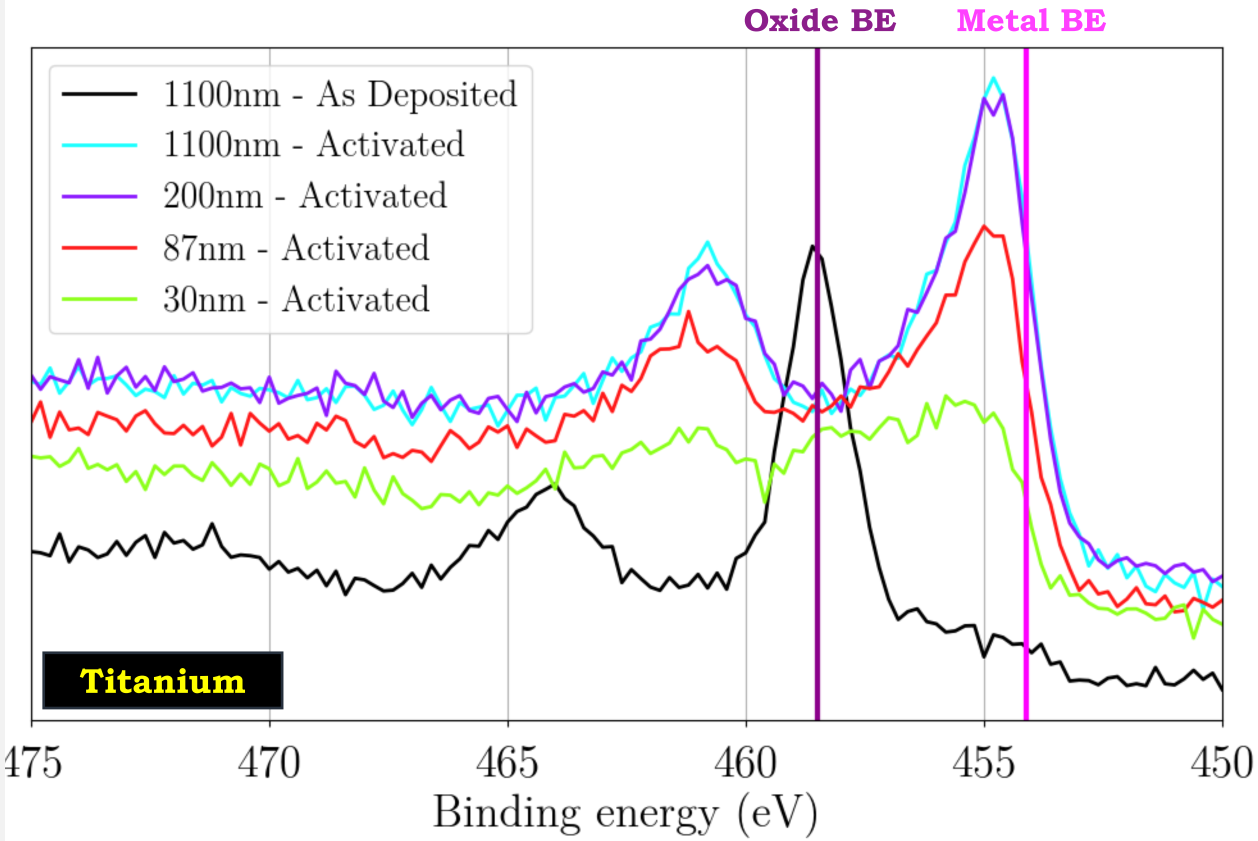


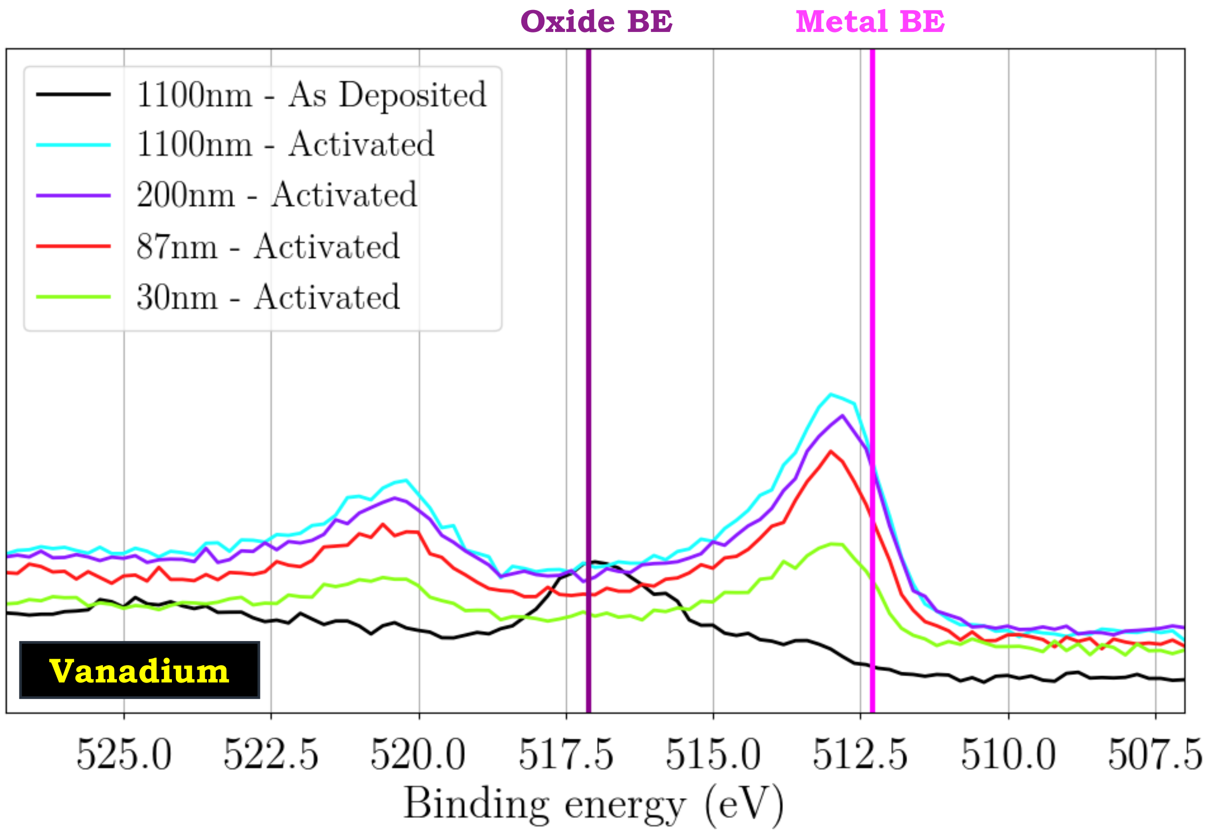




Oxidation state

- Metals' oxidation state after 4th activation cycle





Photoemission due to SR

- Number of SR photons per particle per meter

$$N_\gamma = \frac{5\alpha}{2\sqrt{3}}\frac{\gamma}{\rho} = \mathbf{0.085}$$

- Number of photoelectrons per particle per meter

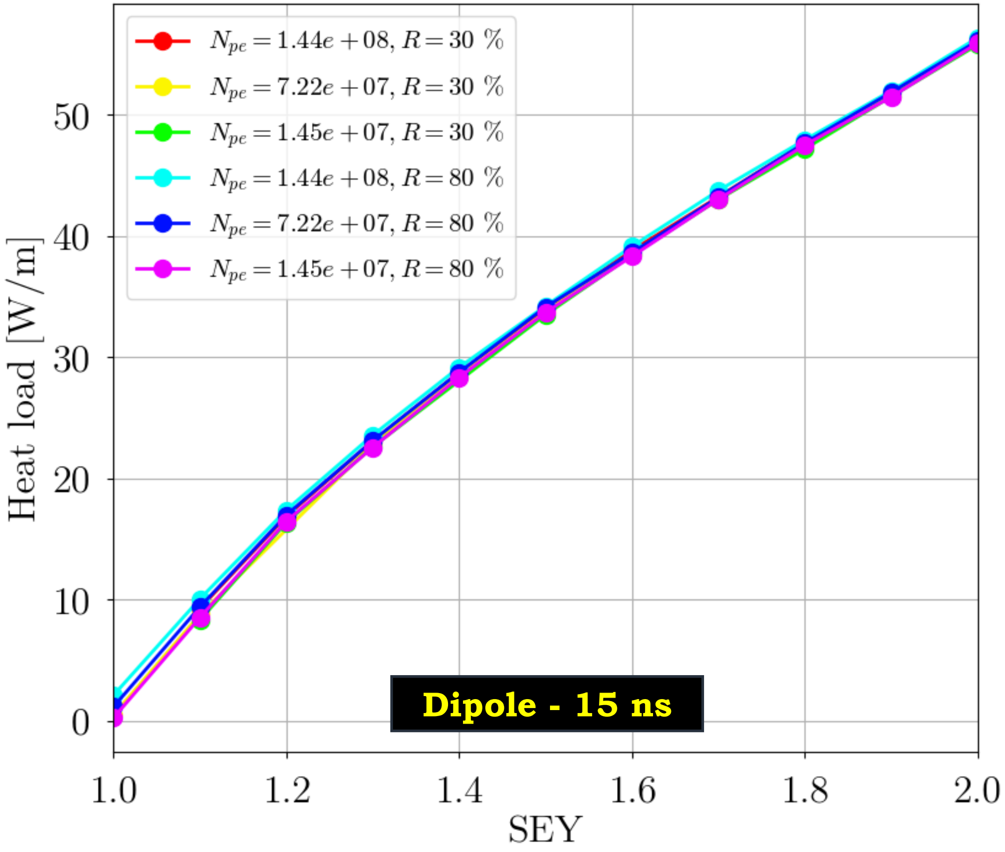
$$N_{ph} = N_\gamma \cdot Y$$

$$N_{ph,d} = N_{ph} \cdot (1 - R)$$

$$N_{ph,rf} = N_{ph} \cdot R$$

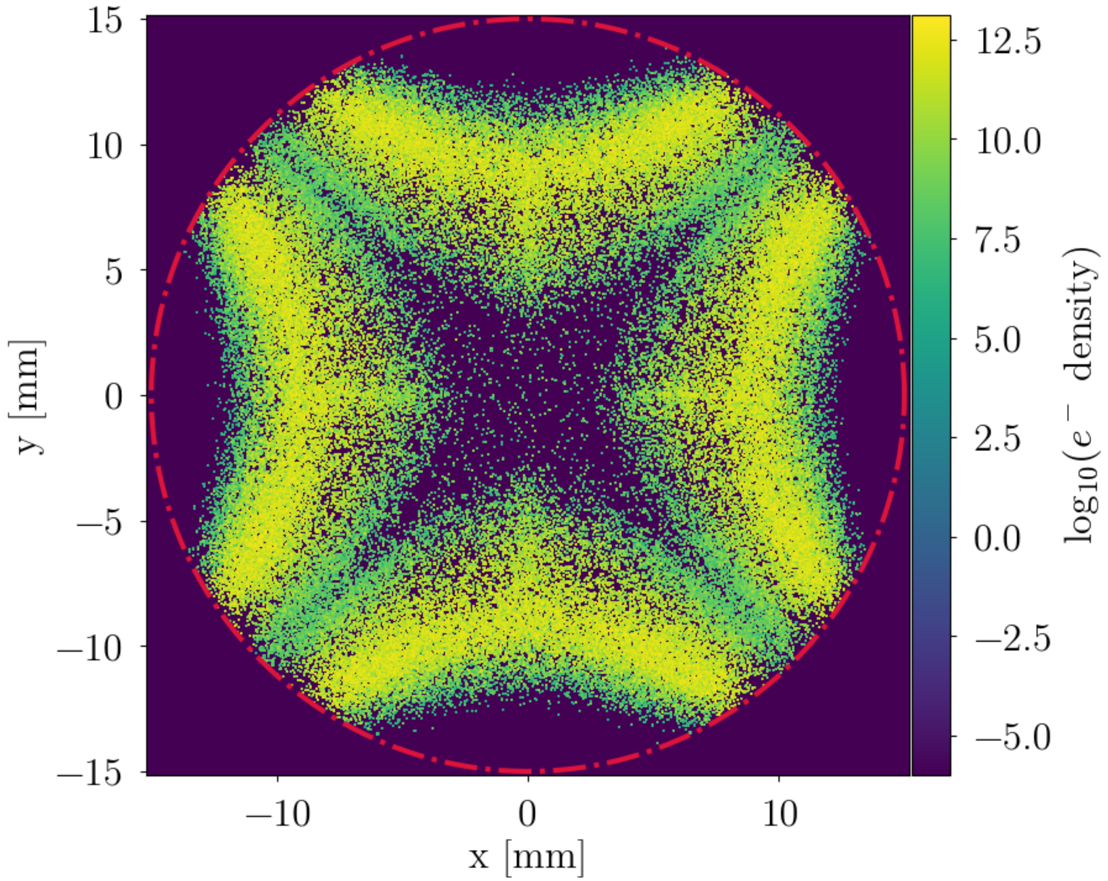
- Photoelectron yield $Y = 0.02$
- Parameters scan
  - SEY
  - Reflectivity
  - Number of photoelectrons (by assuming 50%, 75%, 95% of photons absorbed)

Photoelectrons do not affect the EC build up



Macroparticle size management in PyECLOUD*

- Electrons are grouped in MacroParticles (MPs) with a reference size N_{ref}
- During the build-up, electrons grow exponentially
  - N_{ref} dynamically adapted during a simulation
  - Cleaning procedure to delete all the MPs with charge < $10^{-4} N_{ref}$



Example: QC1L1, SEY = 1.3

- High electron density in some regions of the vacuum chamber
  - Code resolution does not ensure the correct evaluation of the central density
  - More advanced MP size management under development
- Instability studies with PyECLOUD-PyHEADTAIL simulations needed

***G. Iadarola, "Electron cloud studies for CERN particle accelerators and simulation code development", Rep. CERN-THESIS-2014-047.**

SEY dependence on incidence angle

- SEY depends on the angle of incidence θ (defined w.r.t. the normal to the surface) of the impinging electron*

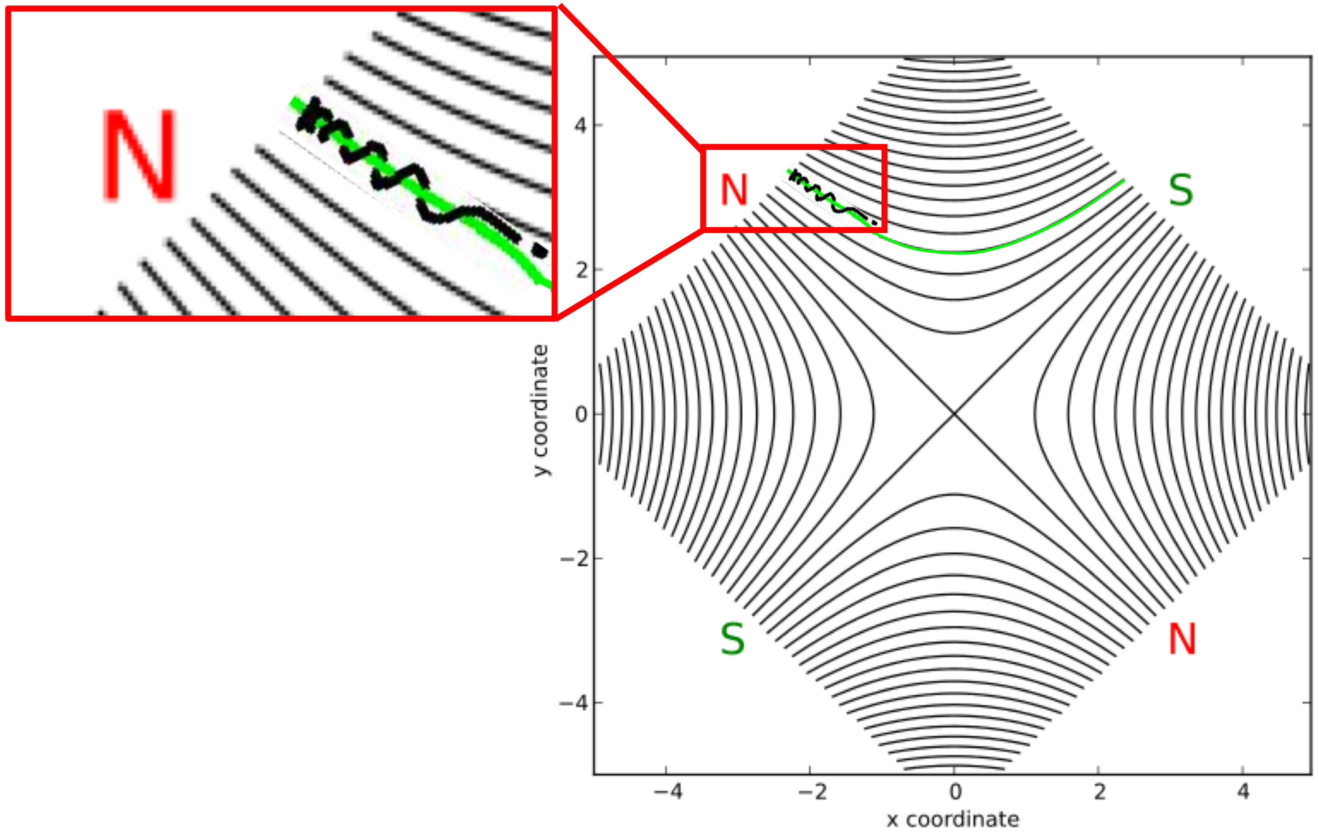
$$E_{max}(\theta) = E_{max}(\theta = 0)[1 + 0.7(1 - \cos\vartheta)]$$

$$\delta_{max}(\theta) = \delta_{max}(\theta = 0)e^{\frac{1-\cos\vartheta}{2}}$$

- **Magnetic mirror**
  - Constant magnetic moment $\mu = \frac{mv_\perp^2}{2B}$
  - Conservation of energy

$$E_{kin} = \frac{1}{2}mv_\perp^2 + \frac{1}{2}mv_\parallel^2$$

  - If $v_\perp$ is rising → $v_\parallel$ is decreasing



*G. Iadarola, "Electron cloud studies for CERN particle accelerators and simulation code development", Rep. CERN-THESIS-2014-047.