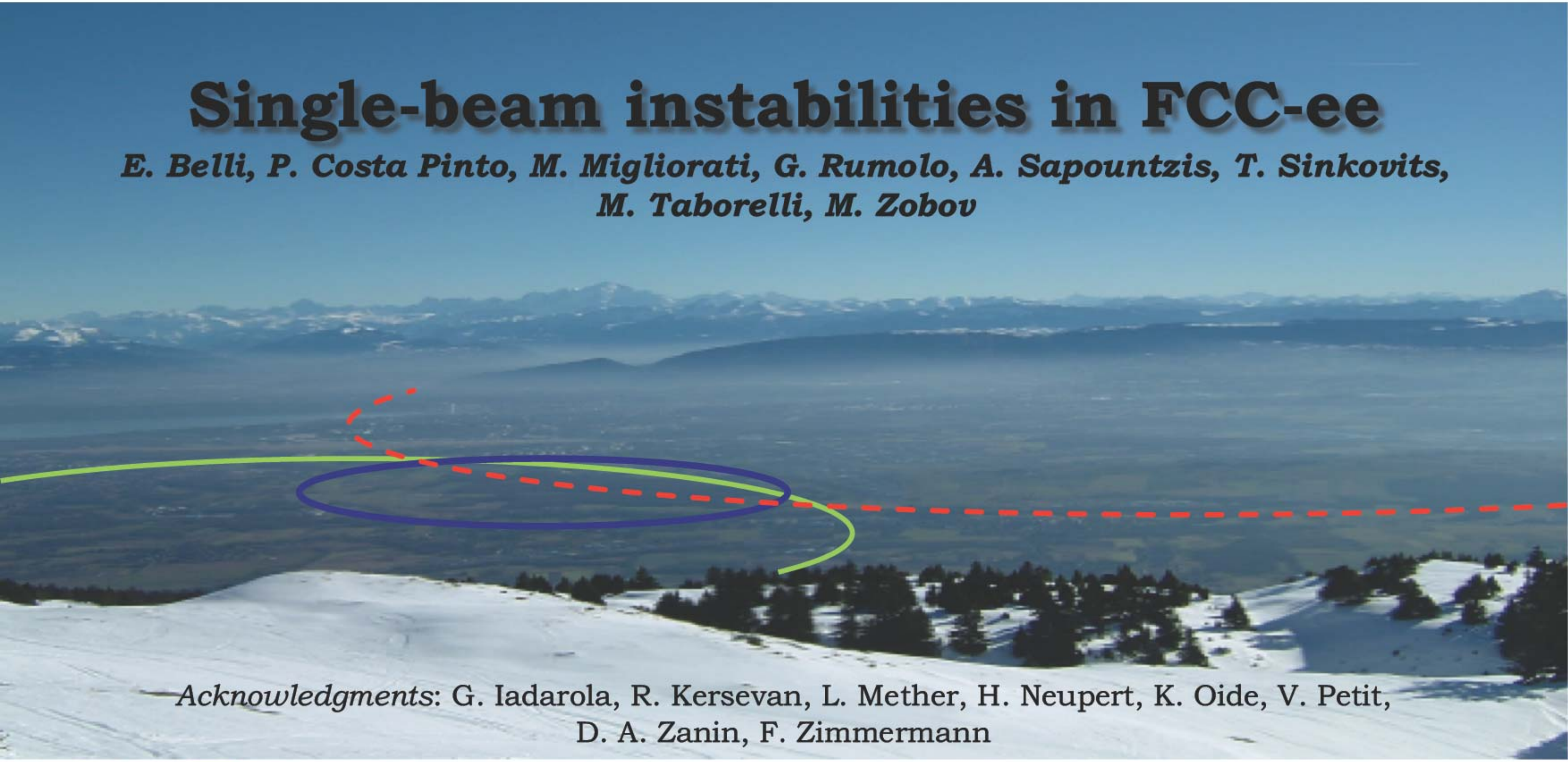


Single-beam instabilities in FCC-ee

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

Acknowledgments: G. Iadarola, R. Kersevan, L. Mether, H. Neupert, K. Oide, V. Petit, D. A. Zanin, F. Zimmermann

INFN Istituto Nazionale di Fisica Nucleare
CERN

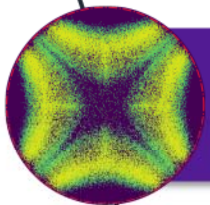
eeFACT2018
Sep 25, 2018 – Hong Kong

FCC hh ee he

This project has received funding from the European Union's Horizon 2020 Research and Innovation program under Grant Agreement No. 730871

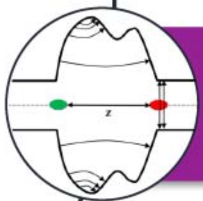
Outline

The FCC-ee project



Electron cloud

- Heat load in the arc components
- Heat load in the IR components
- Single bunch head-tail instability

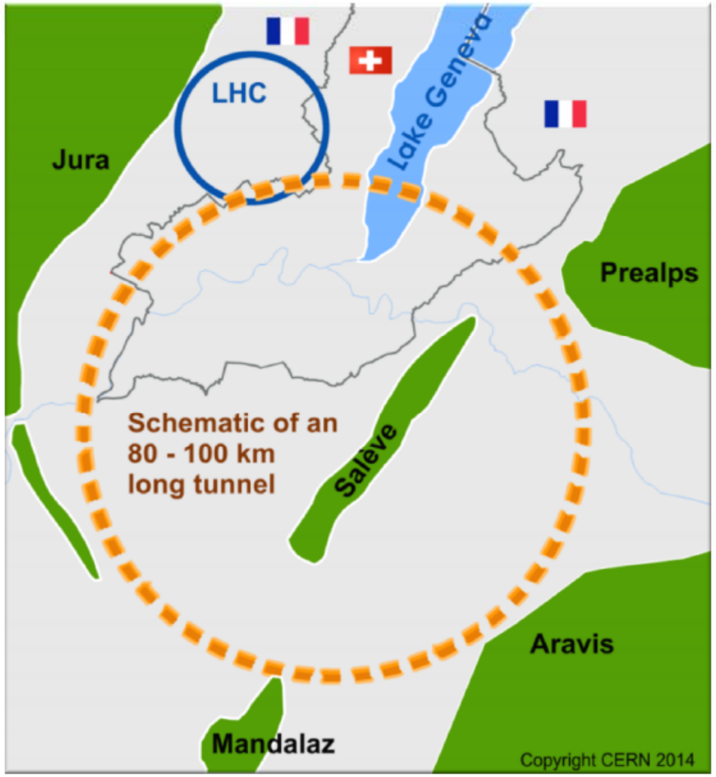


Collective effects

- Resistive wall impedance
- Characterization of NEG thin films
- Longitudinal impedance model

Conclusions

The FCC-ee project

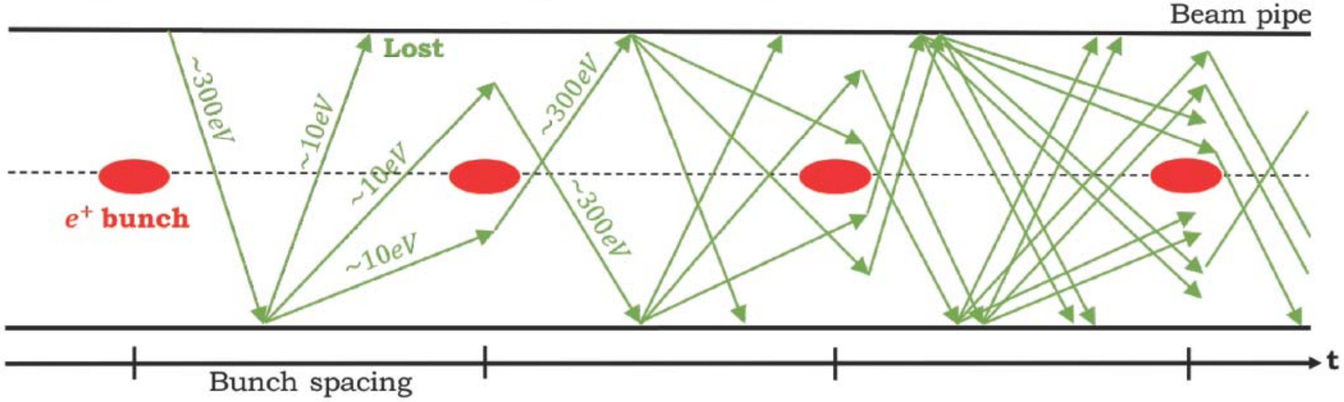


*"High luminosity e^+e^- collider as **potential first step** towards the 100 TeV FCC-hh to study the properties of the Higgs, W and Z bosons and top quark pair production thresholds with unprecedented precision."*

	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

Basics of electron cloud

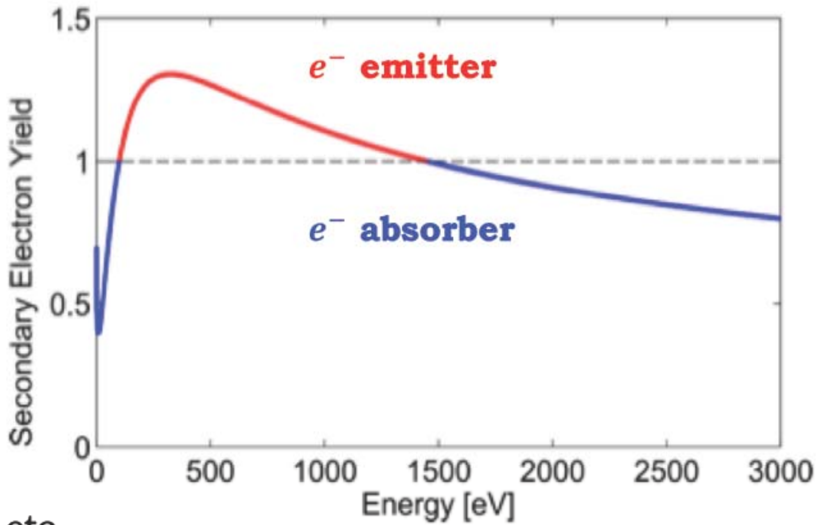
- Electron cloud build up can limit the machine operation and performance



- Primary electrons
  - residual gas ionization, photoemission due to SR
- Secondary electron production when primaries hit the pipe walls
  - described through the Secondary Electron Yield of the surface

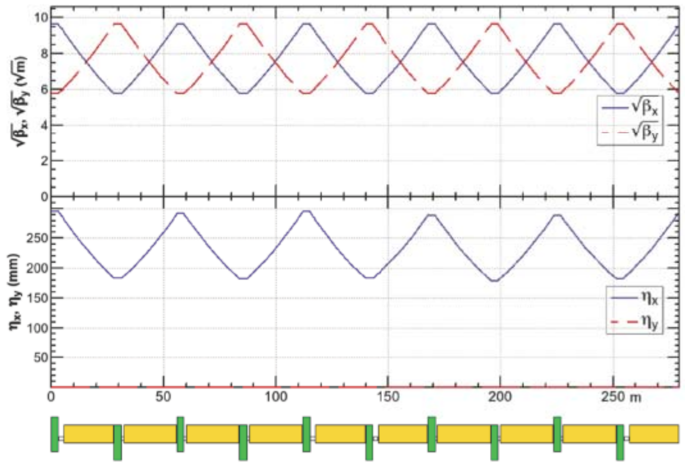
$$\delta(E) = \frac{I_{emit}}{I_{imp}(E)}$$

- Avalanche electron multiplication (***multipacting***)
- Interaction of the EC
  - with the environment
    - heating of the pipe walls, vacuum and diagnostics degradation
  - with the beam
    - transverse instabilities, tune shift and spread, emittance growth, etc.

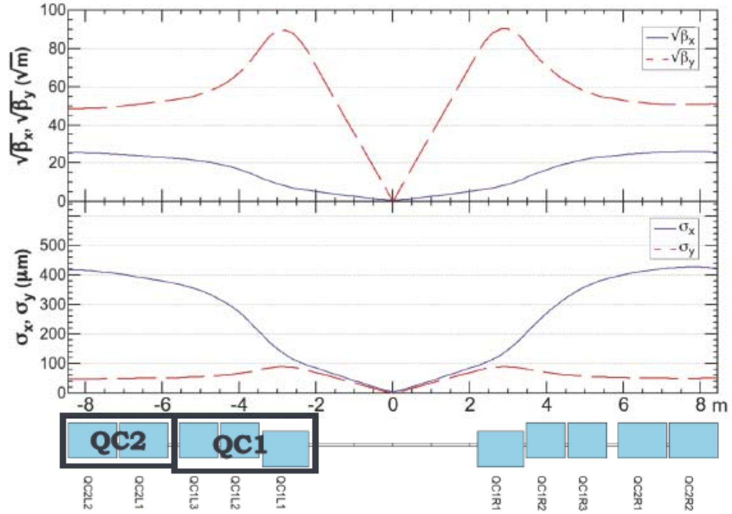


Build up studies at 45.6 GeV

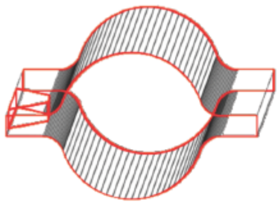
Element	L[m]	Magnetic field
Arc dipole	23.44	0.014 T
Arc quad	3.1	±5.65 T/m
Arc drift	-	-
QC1L1	1.2	-96.3 T/m
QC1L2	1	50.3 T/m
QC1L3	1	9.8 T/m
QC2L1	1.25	6.7 T/m
QC2L2	1.25	3.2 T/m



K. Oide



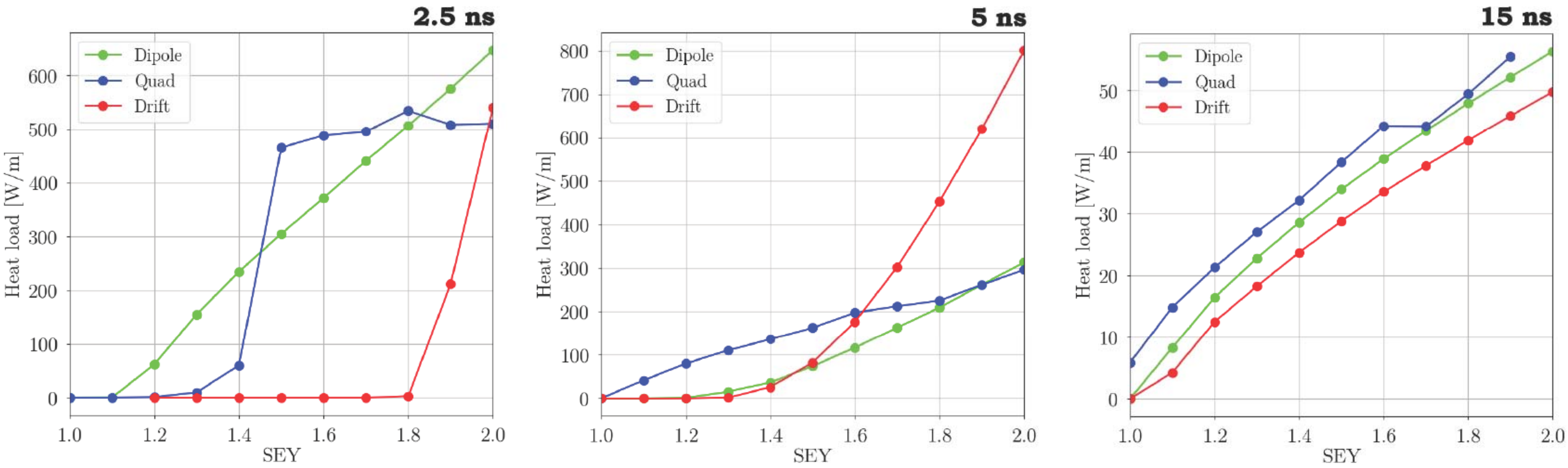
- Realistic shape of the vacuum chamber in the arcs (35 mm radius)
- Round chamber of 15 mm (20 mm) radius in Q1 (Q2)
- Electron cloud build-up in the arcs and IR magnets
  - Initial uniform distribution 10^9 e^-/m
  - SEY scan
  - Bunch spacing scan: 2.5 ns, 5 ns, 15 ns
  - Filling pattern: 80b + 25e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

* I. Karpov, R. Calaga, and E.Chapochnikova, HOM power in FCC-ee cavities, Phys. Rev. Accel. Beams, vol. 21, p. 071001 (2018).

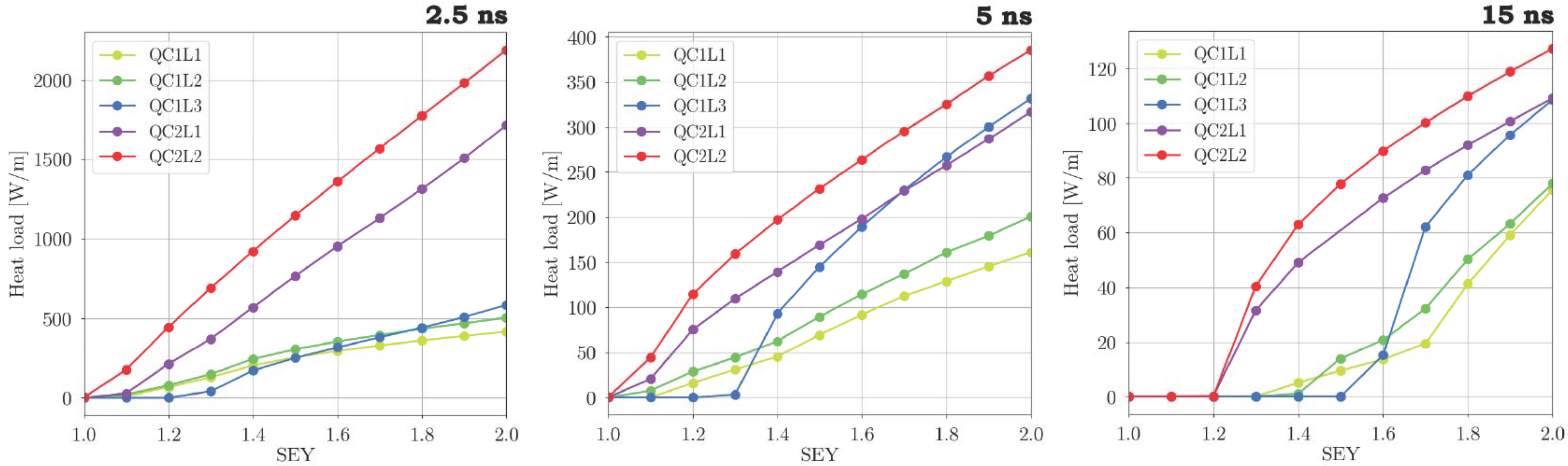
Heat load in the arc components



Multipacting threshold defined as the highest SEY without multipacting

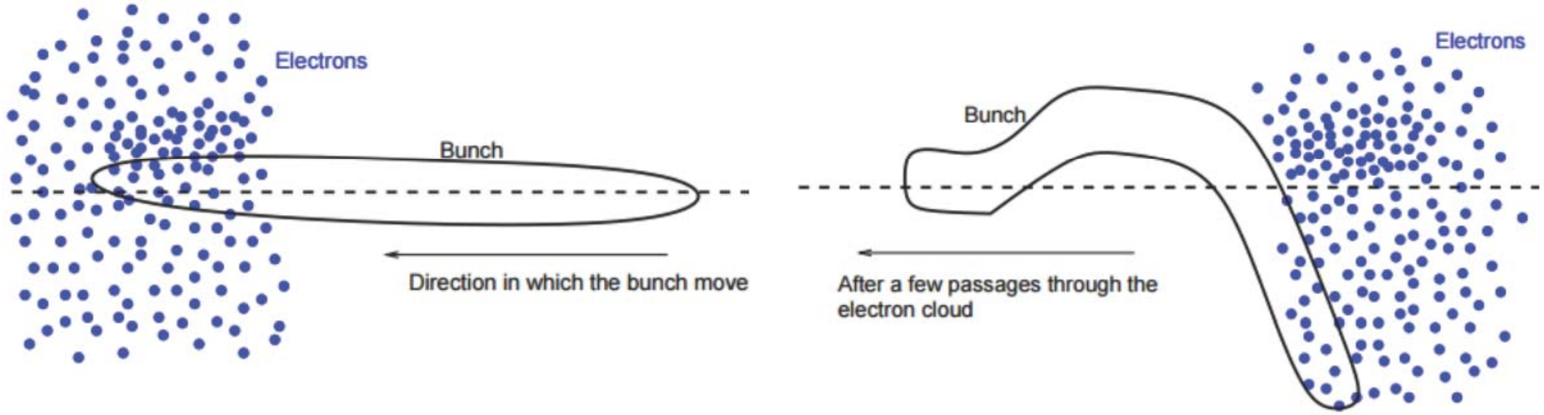
	2.5 ns	5 ns	15 ns
Dipole	1.1	1.1	1.0
Quadrupole	1.2	1.0	< 1.0
Drift	1.8	1.3	1.0

Heat load in the IR components



	2.5 ns	5 ns	15 ns
QC1L1	1.0	1.1	1.3
QC1L2	1.0	1.0	1.4
QC1L3	1.2	1.3	1.5
QC2L1	1.0	1.0	1.2
QC2L2	1.0	1.0	1.2

Single bunch head tail instability



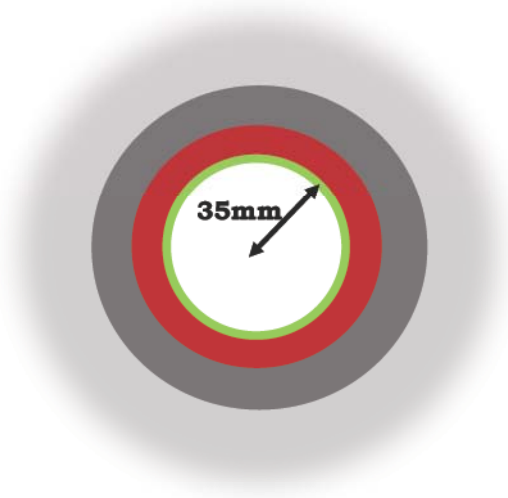
- Electron cloud acts as a short range wakefield with frequency $\omega_e = \sqrt{\frac{2\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$

- Analytic electron density threshold for instability* $\rho_{\mathrm{th}} = \frac{2\gamma Q_s}{\sqrt{3} Q r_0 \beta_y C}$ with $Q = \min(\omega_e \sigma_z / c, 7)$

- At 45.6 GeV: $\rho_{th} = 2.29 \cdot 10^{10}/m^3$
  - **Minimise the SEY in the entire ring by applying a low SEY coating**

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

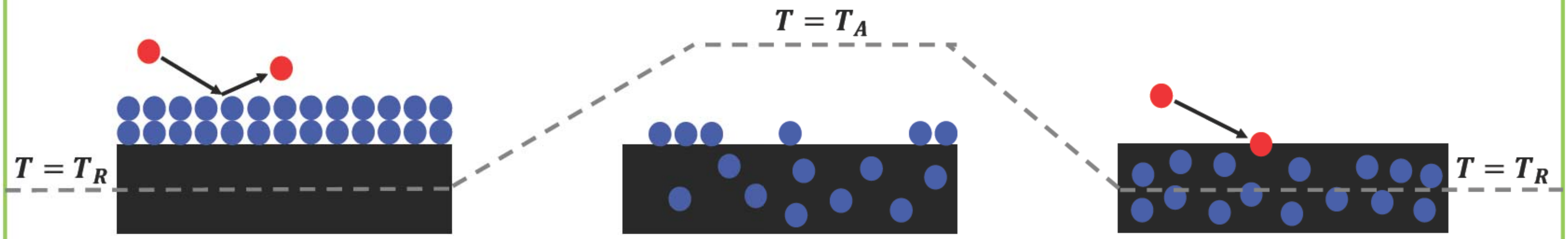
Resistive wall impedance: the chamber model



- **Iron**
  - $\Delta = \infty$
  - $\rho = 6.89 \cdot 10^{-7}\ \Omega m$
- **Dielectric**
  - $\Delta = 6$ mm
  - $\rho = 10^{15}\ \Omega m$
- **Copper**
  - $\Delta = 2$ mm
  - $\rho = 1.66 \cdot 10^{-8}\ \Omega m$
- **Low SEY Coating**
  - Required for 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)



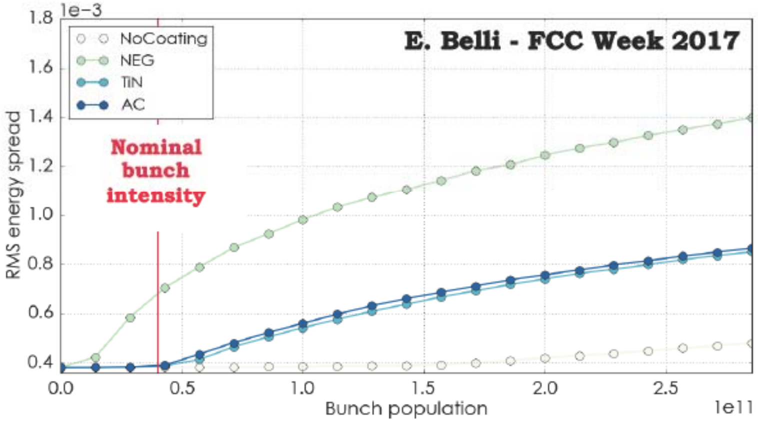
Oxide layer on the surface
➢ **No pumping**

Oxide diffusion into the bulk
➢ **Activation**

➢ **Pumping**

Resistive wall impedance: the impact of thickness

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



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

$$\frac{Z_{\parallel}(\omega)}{C} = \frac{Z_0\omega}{4\pi c b}\left\{[\mathrm{sgn}(\omega) - i]\delta_c \frac{\alpha \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_c}\Delta\right] + 1}{\alpha + \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_c}\Delta\right]}\right\}$$

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

[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 (2018).

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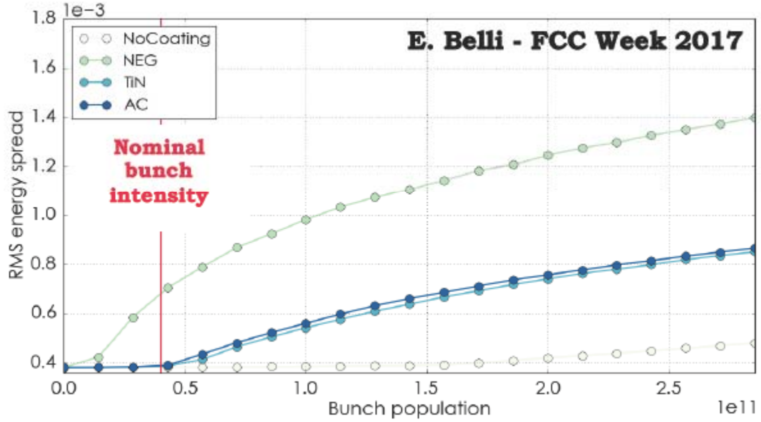

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$$\frac{Z_\parallel(\omega)}{C} = \frac{Z_0\omega}{4\pi cb}\left\{[\mathrm{sgn}(\omega) - i]\delta_c \frac{\alpha\ \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_c}\Delta\right] + 1}{\alpha + \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_c}\Delta\right]}\right\}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

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

$\boldsymbol{\delta_c \gg \Delta}$

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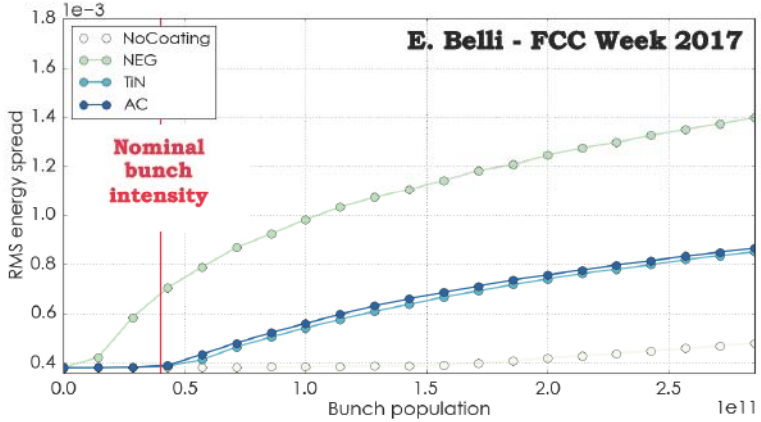

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$\delta_c \gg \Delta$

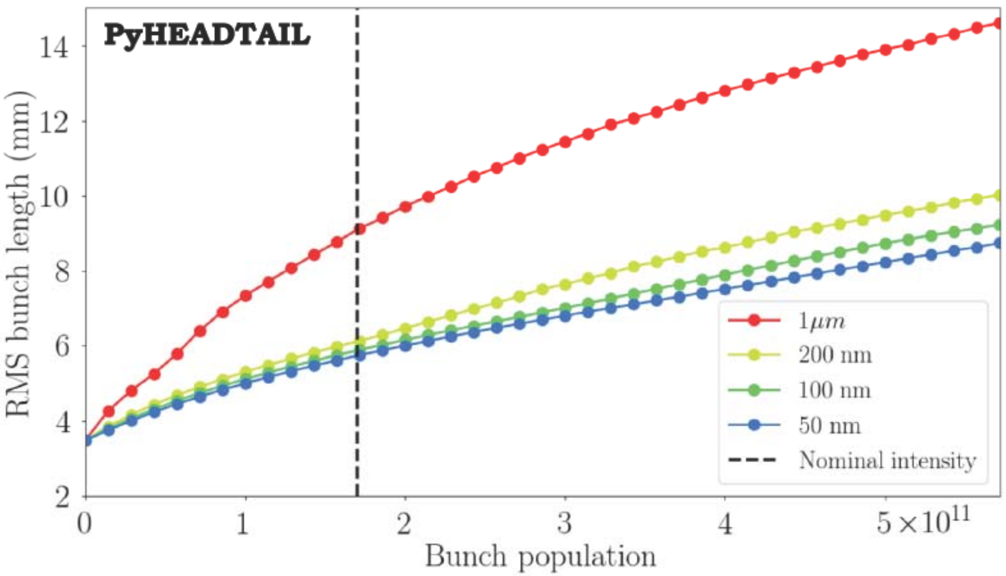
$\frac{\sigma_c}{\sigma_s} \ll 1$

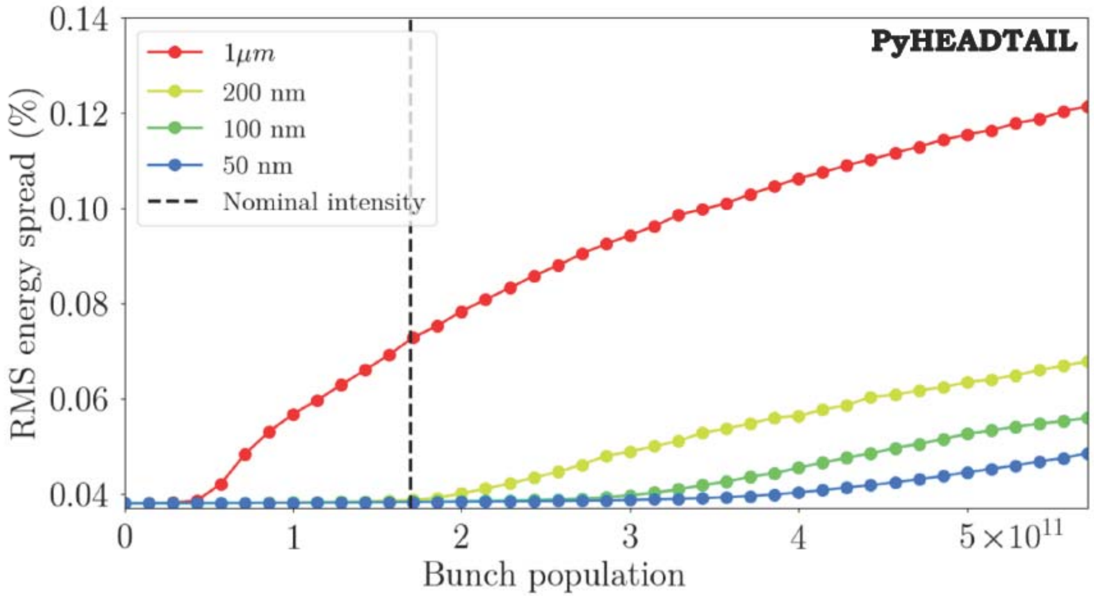
- <u>For FCC-ee at low energy, the RW impedance contribution can be reduced by decreasing the thickness of the coating.</u>

[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 (2018).**

NEG thin films: single bunch longitudinal dynamics

- NEG thin films with 1μm, 200nm, 100nm, 50nm thicknesses
- **Microwave instability (MI)**
  - Instability threshold defined as the value of the bunch population corresponding to an increase of the energy spread of about 10% w.r.t. its nominal value

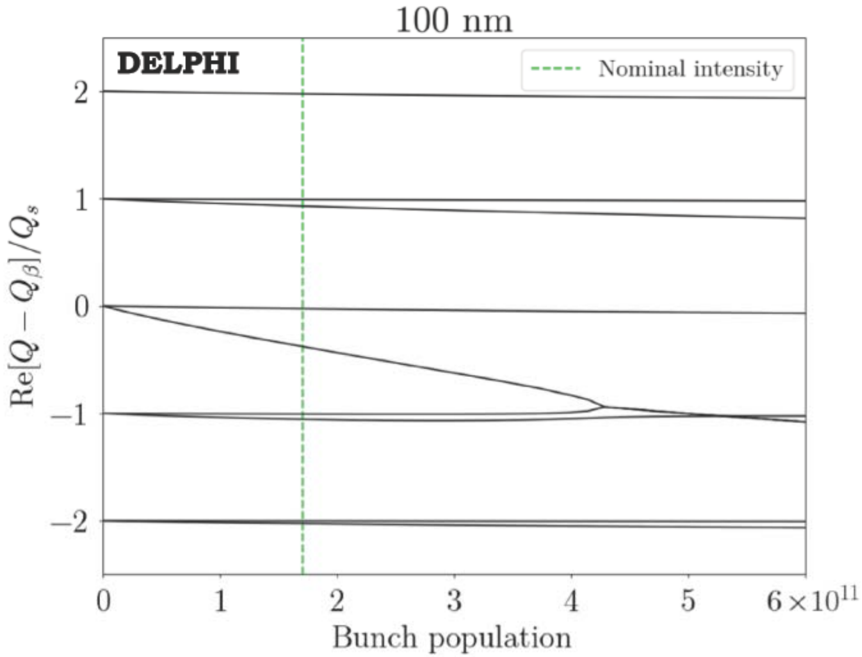


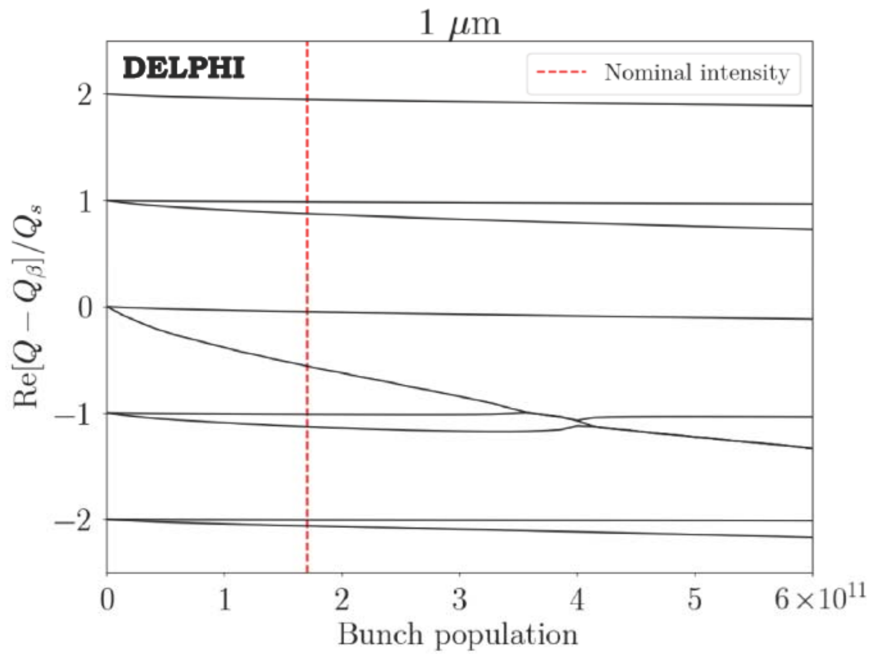


- 1μm thickness makes the bunch unstable
- Thinner films allow to increase the MI threshold
- For 100 nm film, MI threshold ≈ 2x higher than nominal bunch population

NEG thin films: single bunch transverse dynamics

- **Transverse Mode Coupling Instability (TMCI)**
  - Instability threshold defined as the value of the bunch population where the frequencies of two neighboring modes approach each other
- Analytic simulations with DELPHI code including the bunch lengthening due to the longitudinal wake





- For both films, TMCI threshold ≈ 2.5x higher than nominal bunch population
- TMCI threshold affected to a lesser extent by the thickness $N_{th} = \dfrac{4\pi \frac{E}{e} \tau_b Q_s}{e\beta\ Im\{Z_m^{eff}\}}$

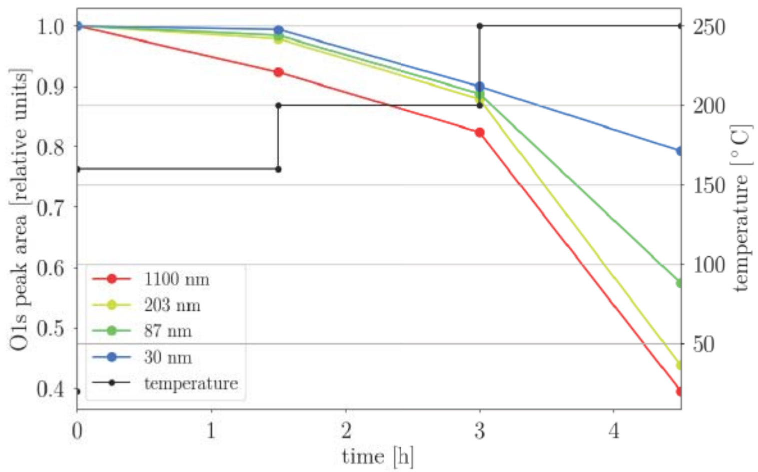
NEG thin films: experimental characterization

- Reducing the thickness of NEG coatings can affect the performance of the material itself and therefore the maximum SEY and related electron cloud mitigation.

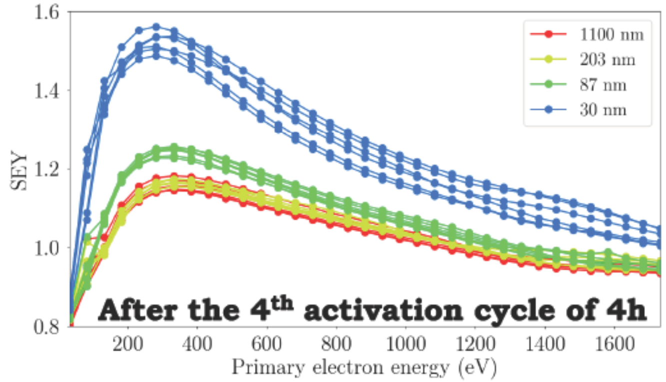
NEG deposition on copper samples via DC magnetron sputtering → **Activation performance (XPS analysis)** → **SEY measurements**

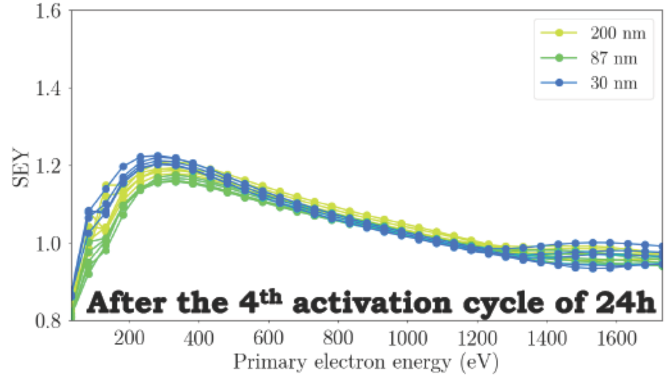
Target Δ [nm]	Measured Δ [nm]
1000	1100
200	203
100	87
50	30

- Reduction of the area of the O peak from the XPS spectrum after the 4th activation cycle



- Higher O reduction → better activation
- O surface concentration increases for thinner layers





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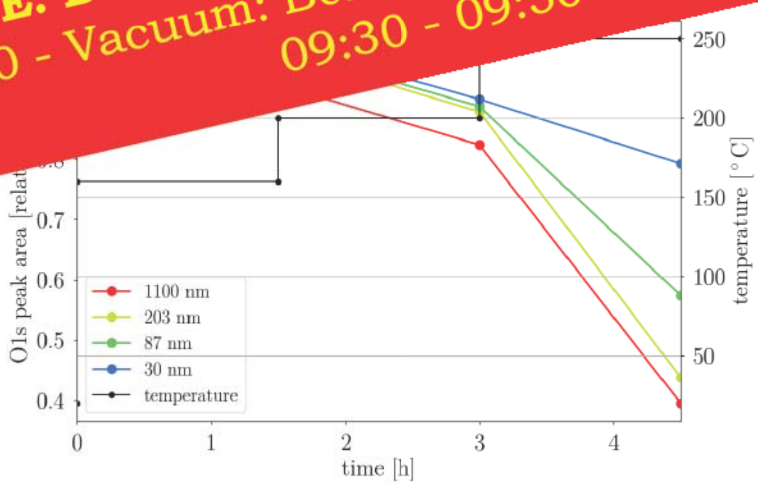
E. Belli: "NEG Coating for FCC-ee"
This conference, WG10 - Vacuum: Beam Vacuum Interaction, Vacuum Technology
09:30 - 09:50

Δ [nm]	Measured Δ [nm]
1000	1100
200	203
100	87
50	30

- Redu



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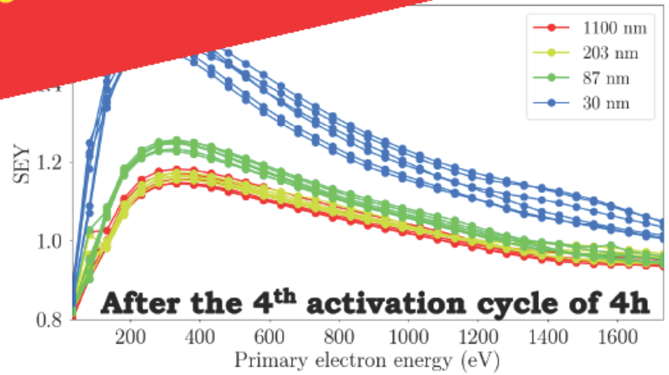
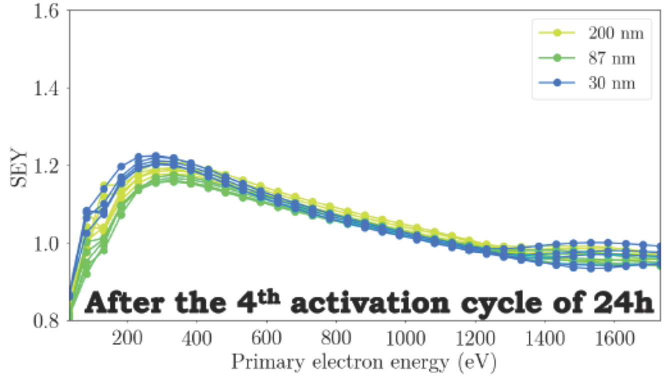
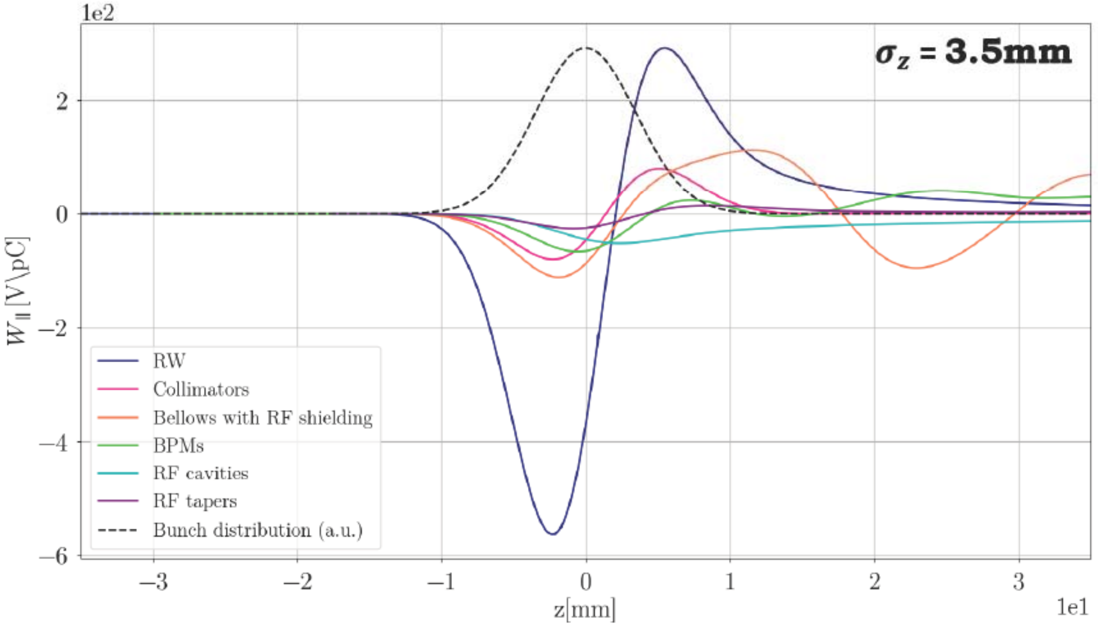




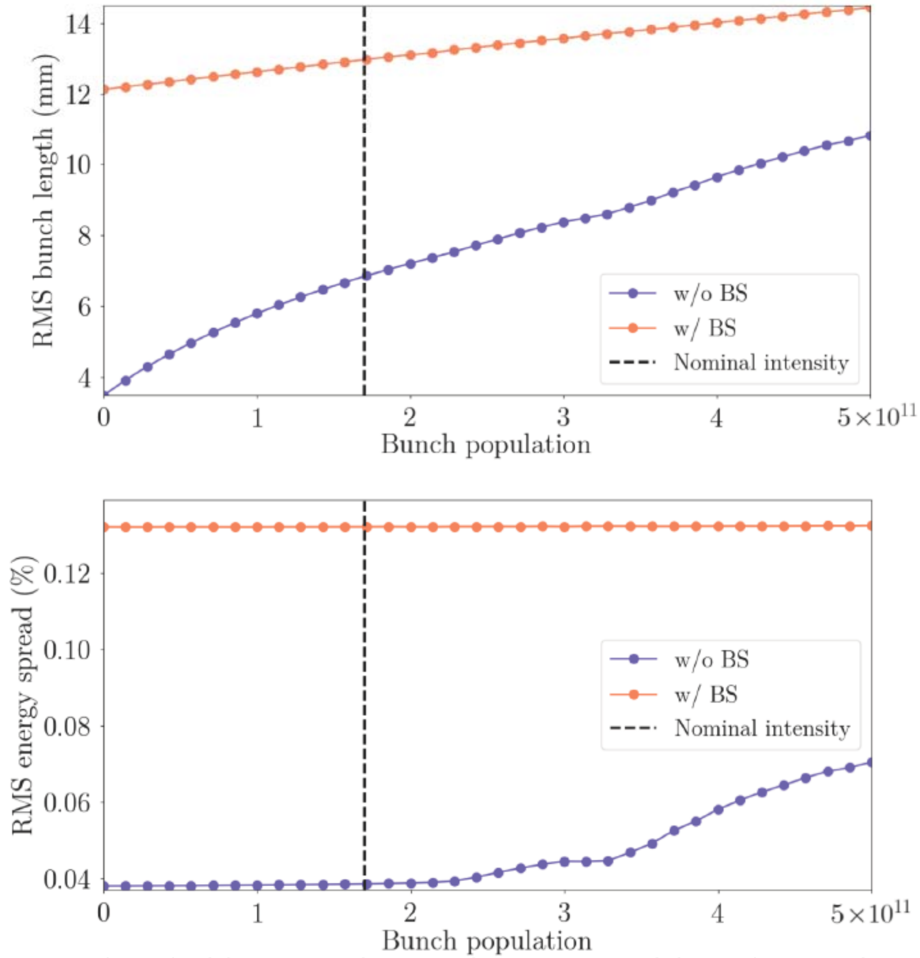
Longitudinal impedance model



Component	Number	k_{loss}[V/pC]	P_{loss}[MW]
Resistive Wall (100 nm)	97.75 km	210	7.95
Collimators	20	18.7	0.7
RF cavities	56	18.5	0.7
RF double tapers	14	26.6	1.0
BPMs	4000	40.1	1.5
Bellows	8000	49.0	1.8
Total		**362.9**	**13.7**

3.6x smaller than 50 MW (SR)

Microwave instability



➢ MI threshold ≈ 1.5x larger than nominal bunch population and much higher w/ BS

Conclusions

Electron cloud

- ❑ Electron cloud build up estimated in the main components of FCC-ee
- ❑ Multipacting threshold and heat load evaluated for different bunch spacings
  - ❖ 15 ns beam is the preferable option
    - o Higher thresholds in the IR
    - o Lower heat load in the arcs
- ❑ Analytic single bunch instability threshold estimated at low energy
  - ❖ Low SEY coating needed in the entire ring
  - ❖ Instability thresholds to be evaluated with macroparticle simulations

Collective effects

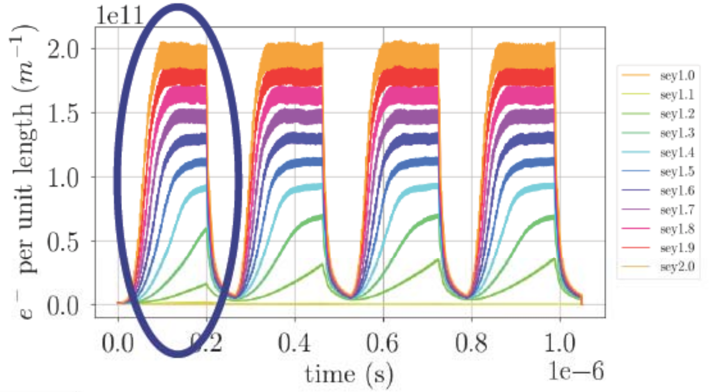
- ❑ Resistive wall is the main source of impedance
  - ❖ Its contribution can be reduced by decreasing the thickness of NEG coating
  - ❖ NEG thin films ($\Delta < 250$ nm) characterized experimentally in terms of activation performance and SEY
- ❑ Other impedance sources considered in the model
  - ❑ Smaller impact compared to the RW one
- ❑ Total dissipated power loss of 13.7 MW (≈ 3.6x smaller than SR power/beam)
- ❑ MI threshold w/o BS 1.5x higher than nominal bunch population and much higher w/ BS
- ❑ Transverse model to be defined


Thanks for your attention

Back up slides

PyECLOUD seeding mechanisms

- Seed electrons
  1. Residual gas ionization ➡ **Physical mechanisms**
  2. Photoemission due to SR ➡ **Physical mechanisms**
  3. Uniform electron density ➡ **Survival of electrons in multi-turn operation**
     This number can only affect the initial transient of the build up process (→ disregarded in heat load computation)



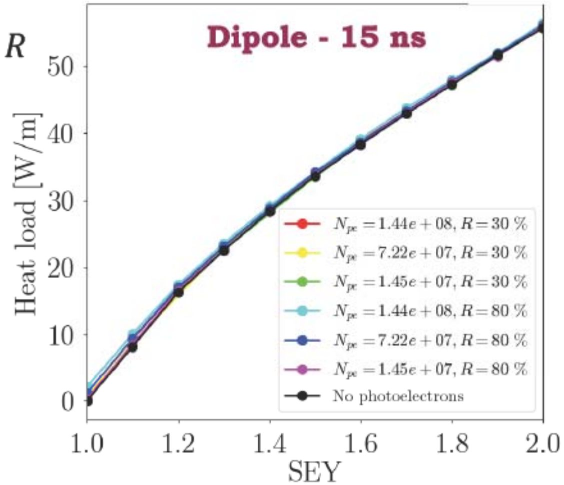
- In most cases additional electrons from physical seeding do not significantly affect the results of build up simulations

Photoemission seeding

- 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

$$N_{ph} = N_\gamma \cdot Y \quad\rightarrow\quad N_{ph,d} = N_{ph} \cdot (1-R), \qquad N_{ph,rf} = N_{ph} \cdot R$$

  - Photoelectron yield $Y = 0.02$
  - Reflectivity $R = [30\%, 80\%]$
- Parameters scan
  - SEY
  - Reflectivity
  - Number of photoelectrons (by assuming 50%, 75%, 95% of photons absorbed)



Heat load is not affected by photoelectrons

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*

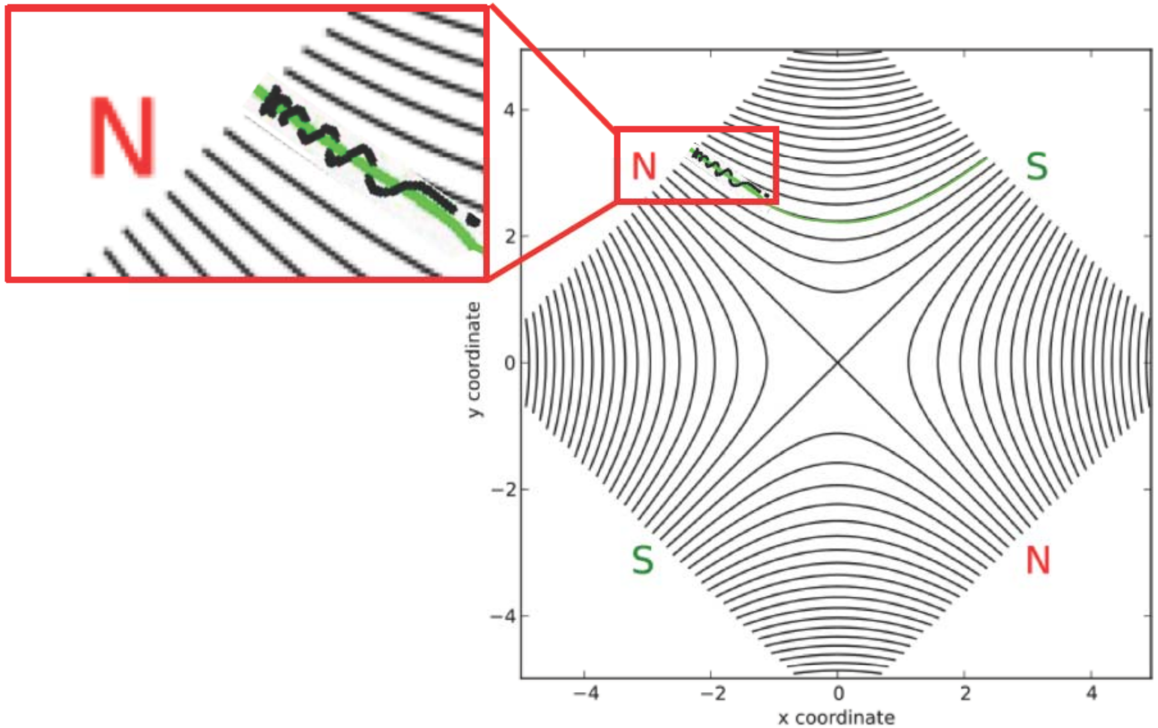
$$E_{max}(\theta) = E_{max}(\theta = 0)[1 + 0.7(1 - \cos\vartheta)]$$

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

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

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

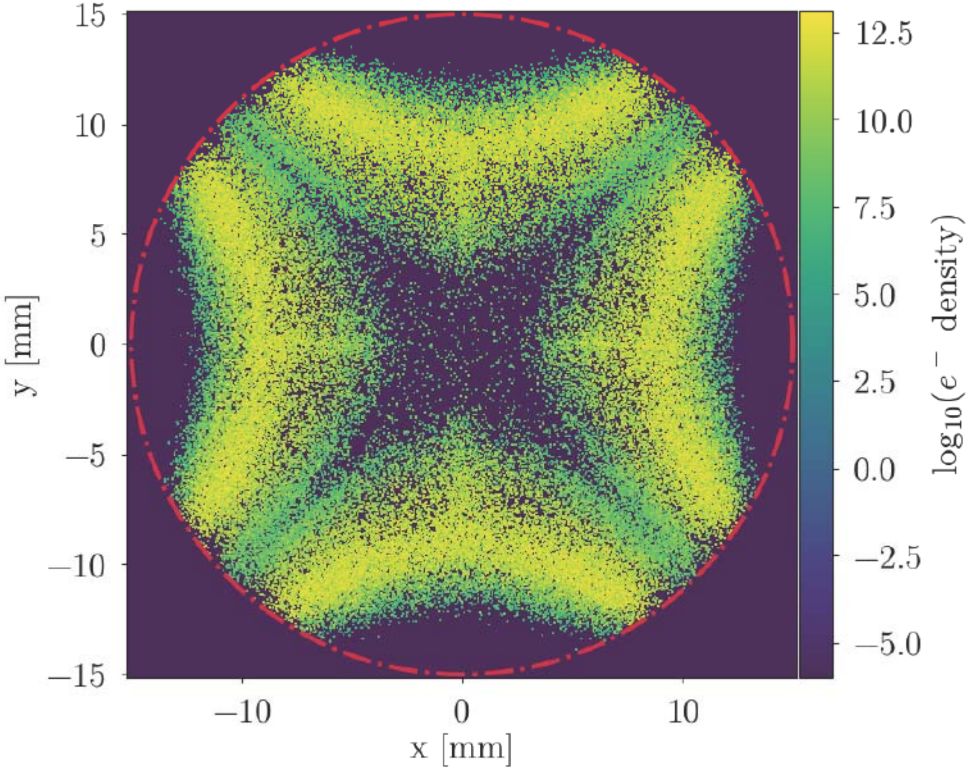
  - If $v_{\perp}$ is rising → $v_{\parallel}$ is decreasing



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

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 < $10^{-4}N_{ref}$



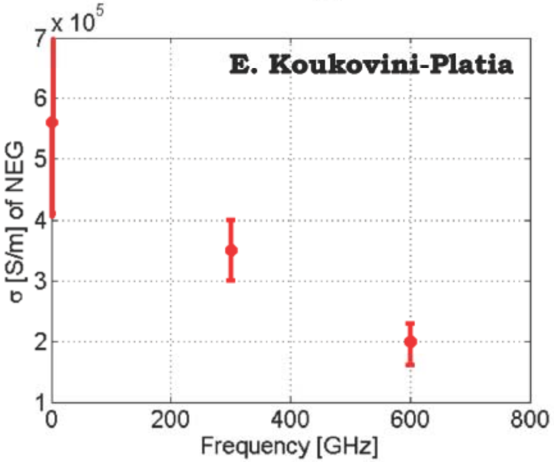
Example: QC1L1, SEY = 1.3

- 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", PhD thesis, 2014.**

RW impedance with coating at 45.6 GeV

- **Condition 1: $\delta_c \gg \Delta$**
  - $f \approx 100\ GHz, 10^3 \frac{S}{m} < \sigma_{NEG} < 10^6 \frac{S}{m} \rightarrow 50\mu m < \delta_{NEG} < 1.5\mu m$ ✓



- **Condition 2: $\sigma_c \ll \sigma_s$**
  - $\sigma_{Cu} \approx 6 \cdot 10^7 \frac{S}{m} \gg \sigma_{NEG}$ ✓