Coupling impedance and single beam collective effects for the Future Circular Collider (lepton option)

Eleonora Belli

Supervisors: Prof. Mauro Migliorati, Dr. Giovanni Rumolo

INFN Istituto Nazionale di Fisica Nucleare

SAPIENZA UNIVERSITÀ DI ROMA

Ph.D. School on Accelerator Physics

Nov 19, 2018 – Rome

CERN

FCC hh ee he

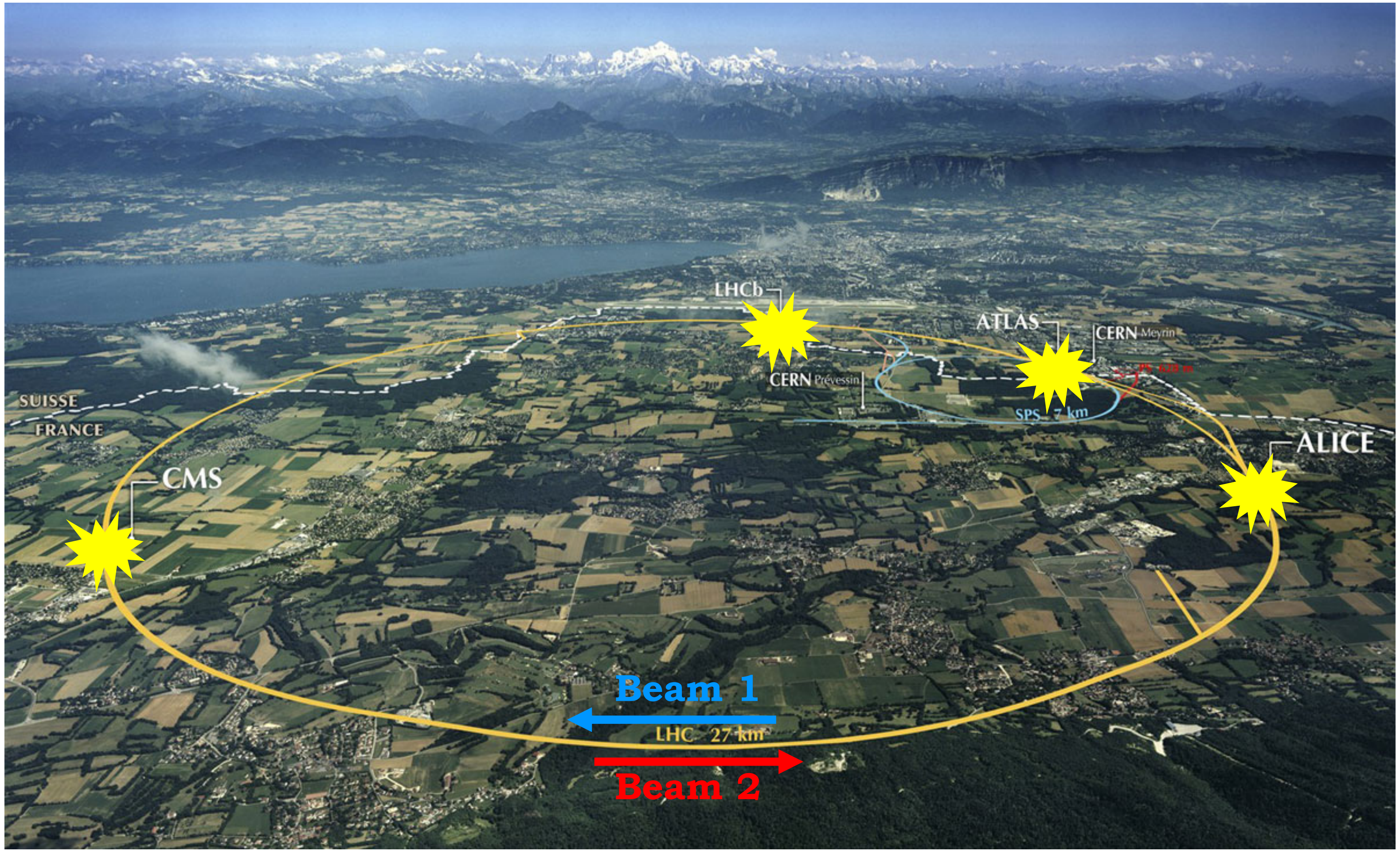
This project has received funding from the European Union's Horizon 2020 Research and Innovation program under Grant Agreement No. 730871

What are we studying?

Coupling impedance and single beam collective effects for the Future Circular Collider (lepton option)

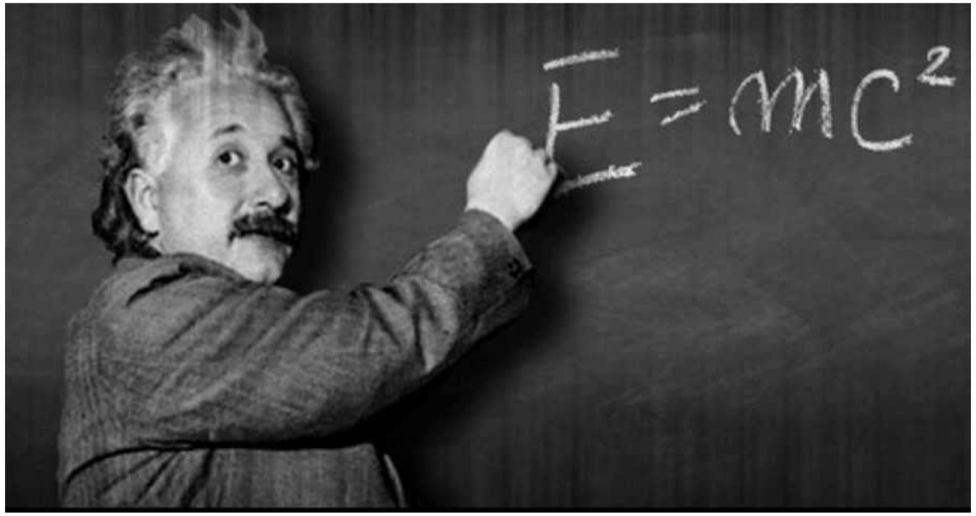
The Large Hadron Collider

- Largest and most powerful particle accelerator ever built
- 27 km in circumference and about 100 m underground
- 2 counter rotating beams colliding at 14 TeV in four points of the ring (ATLAS, CMS, ALICE and LHCb)



The Large Hadron Collider

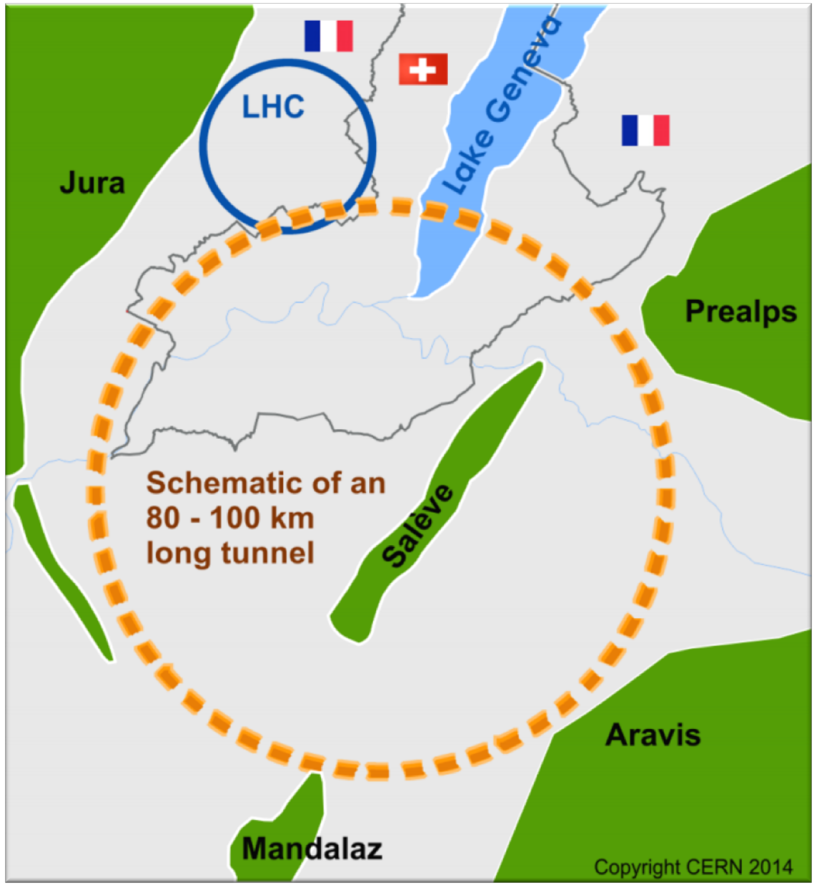
- Largest and most powerful particle accelerator ever built
- 27 km in circumference and about 100 m underground
- 2 counter rotating beams colliding in four points of the ring (ATLAS, CMS, ALICE and LHCb experiments)
- During collisions, **transformation energy ↔ matter**



- **Higher energy produces heavier particles**

- In 2014, CERN launched the Future Circular Collider (FCC) study for the design of different circular collider for the post-LHC era:
  - **100 TeV** hadron collider FCC-hh in 100 km tunnel
  - lepton collider FCC-ee as a potential first step

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."*

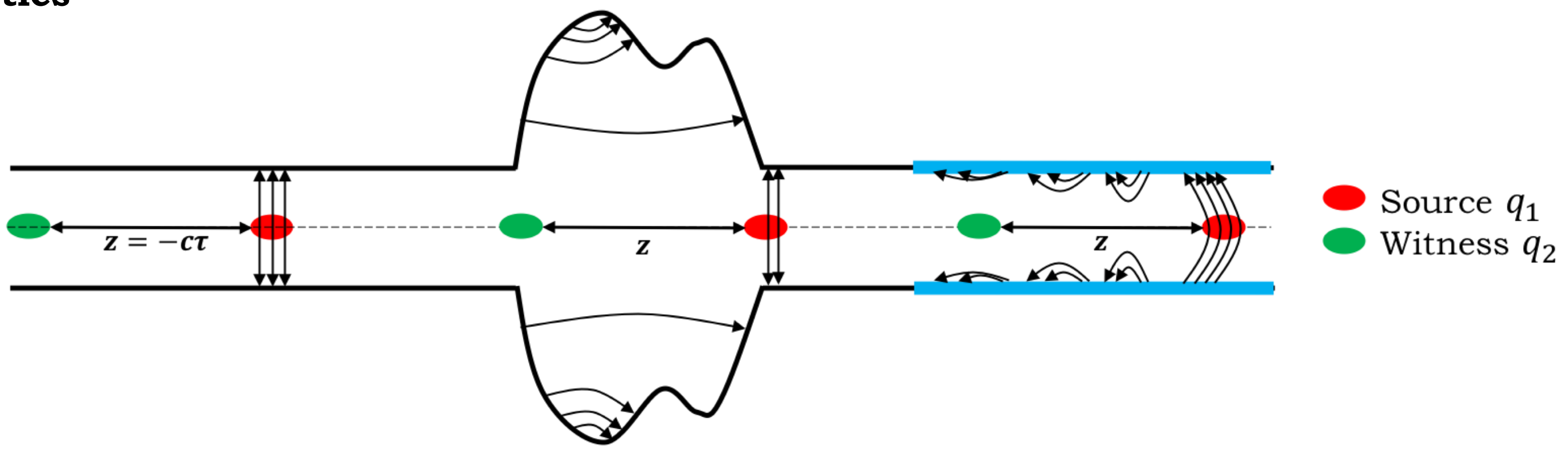
	Z	W	H	tt	
Beam energy [GeV]	**45.6**	**80**	**120**	**175**	**182.5**
Circumference C [km]		97.75			
RF frequency f_{RF} [MHz]		400			
Arc cell	60°/60°	60°/60°	90°/90°	90°/90°	90°/90°
RF voltage V_{RF} [GV]	0.1	0.75	2.0	8.8	10.3
Momentum compaction α_c [10^{-5}]	1.48	1.48	0.73	0.73	0.73
Horizontal tune 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

Coupling impedance and single beam collective effects for the Future Circular Collider (lepton option)

- **Electron cloud** and **collective effects** due to the electromagnetic fields generated by the interaction of the beam with the vacuum chamber represent very critical aspects by producing instabilities that can limit the machine operation and performance.

Collective effects

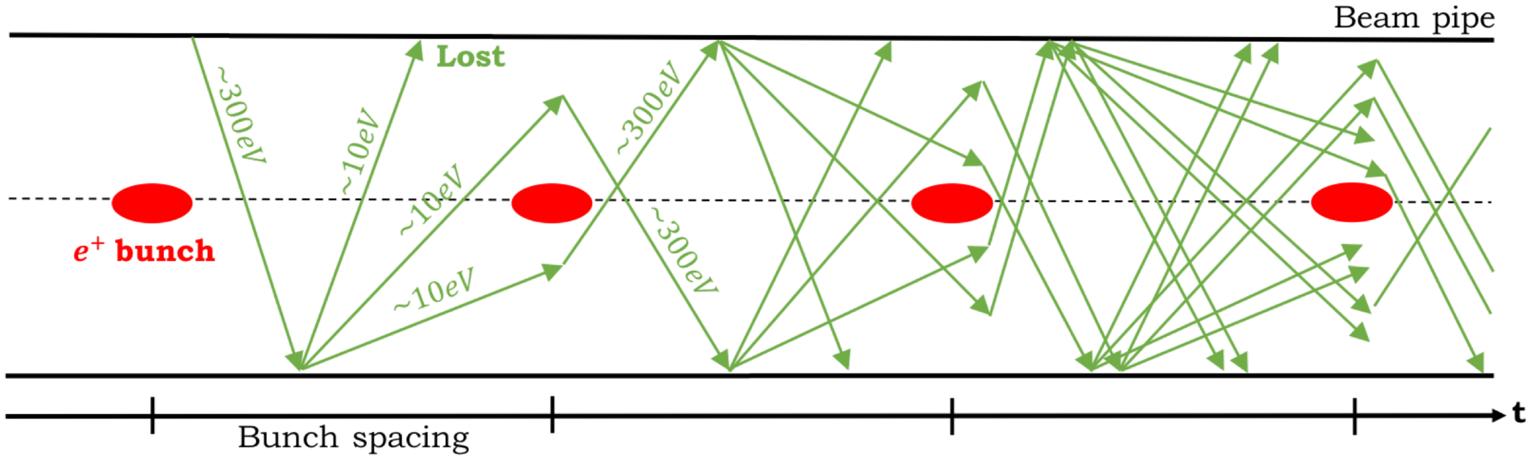
- The interaction of the beam with the environment can produce **wakefields** (**impedances** in the frequency domain) that induce **instabilities**



- **Impedance model needed** to study these instabilities, to predict their effects on beam dynamics and to identify possible mitigation techniques.
  - Impedance characterization and minimization for each component of the vacuum chamber
    - Resistive wall
    - Beam Position Monitors
    - Collimators
    - RF cavities with tapers
    - Bellows with RF shielding
  - Effects on the beam stability

Basics of electron cloud

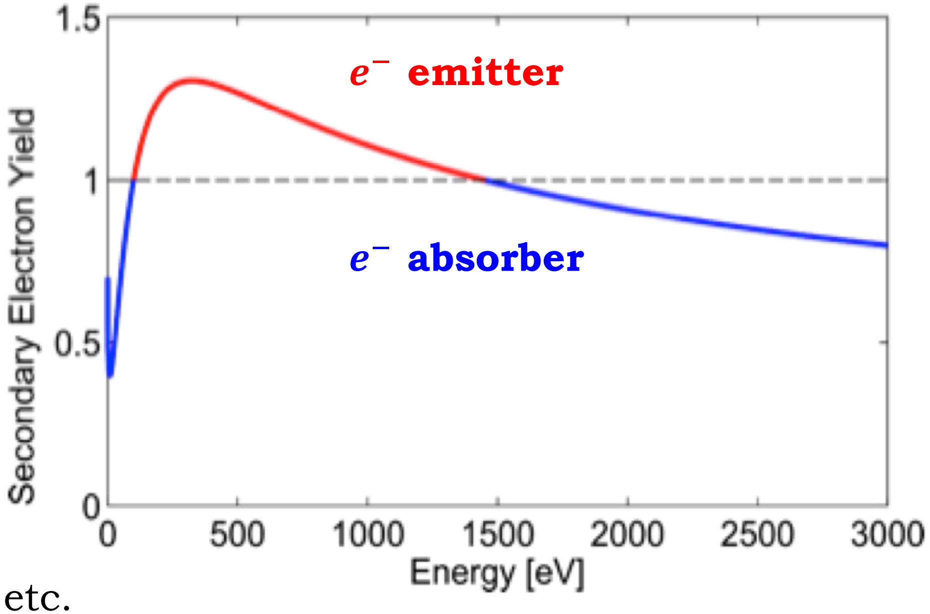
- Electron cloud build up can limit the machine operation and performance



- 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

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

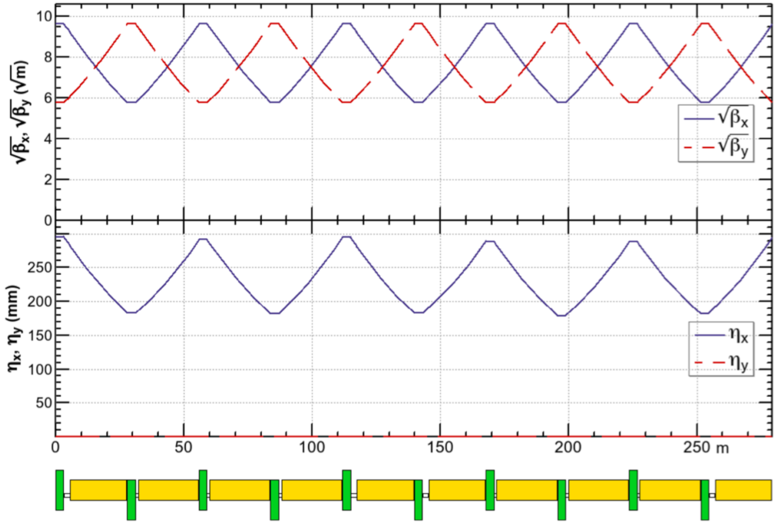
- Avalanche electron multiplication (***multipacting***)
- Interaction of the EC
  - with the environment
    - heating of the pipe walls, vacuum and diagnostics degradation
  - with the beam
    - transverse instabilities, tune shift and spread, emittance growth, etc.

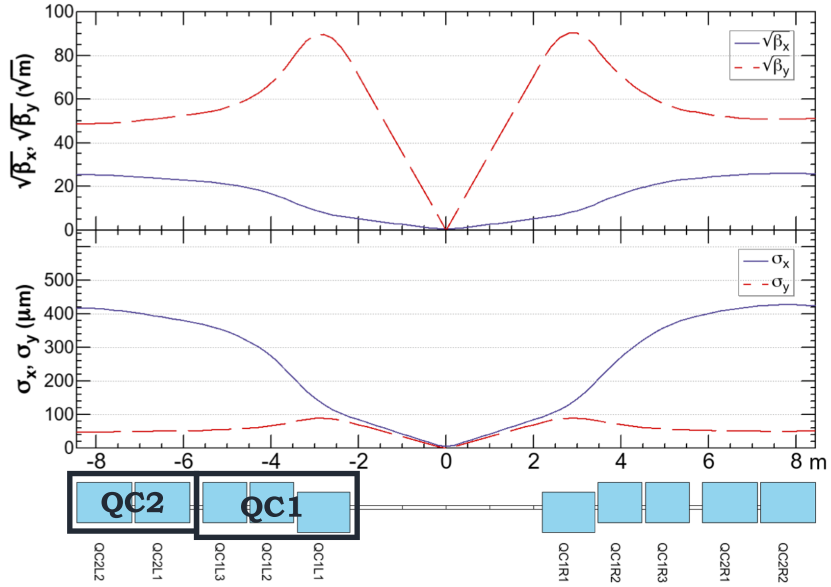


Build up studies at 45.6 GeV

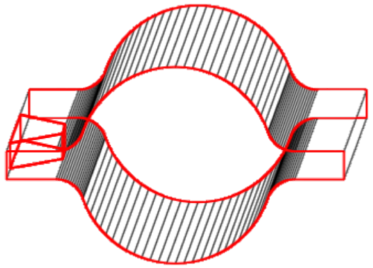
K. Oide

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

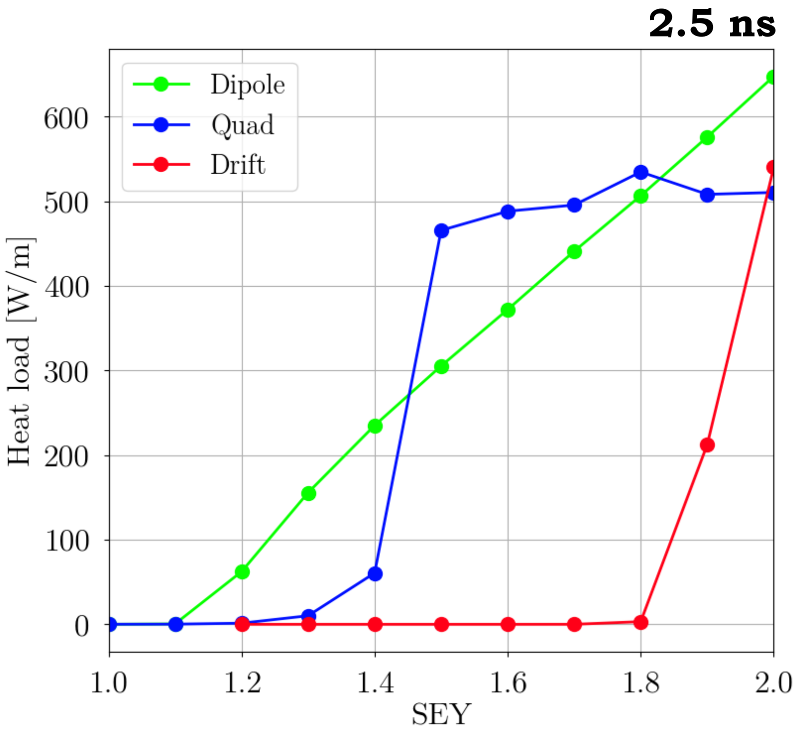


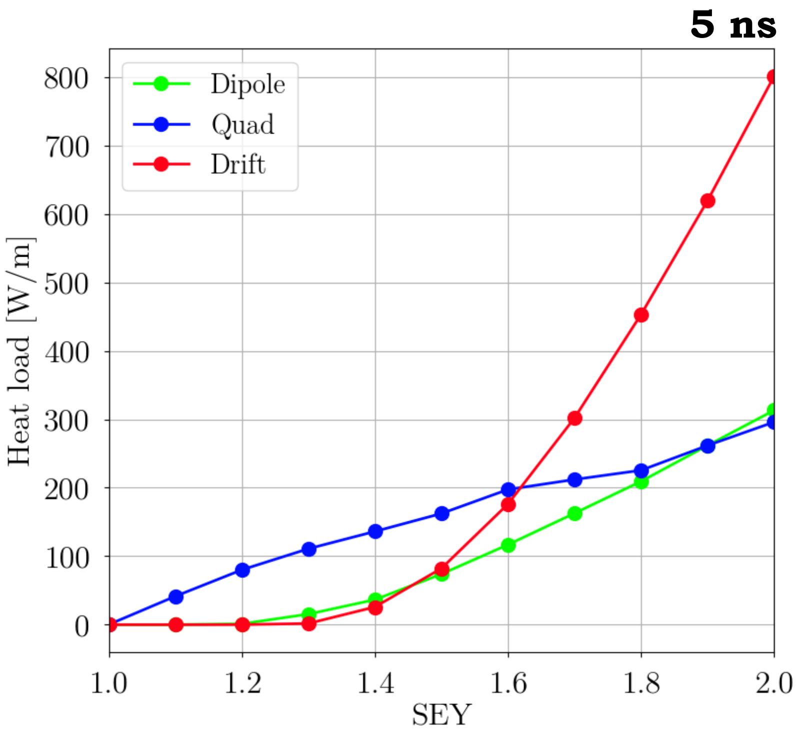


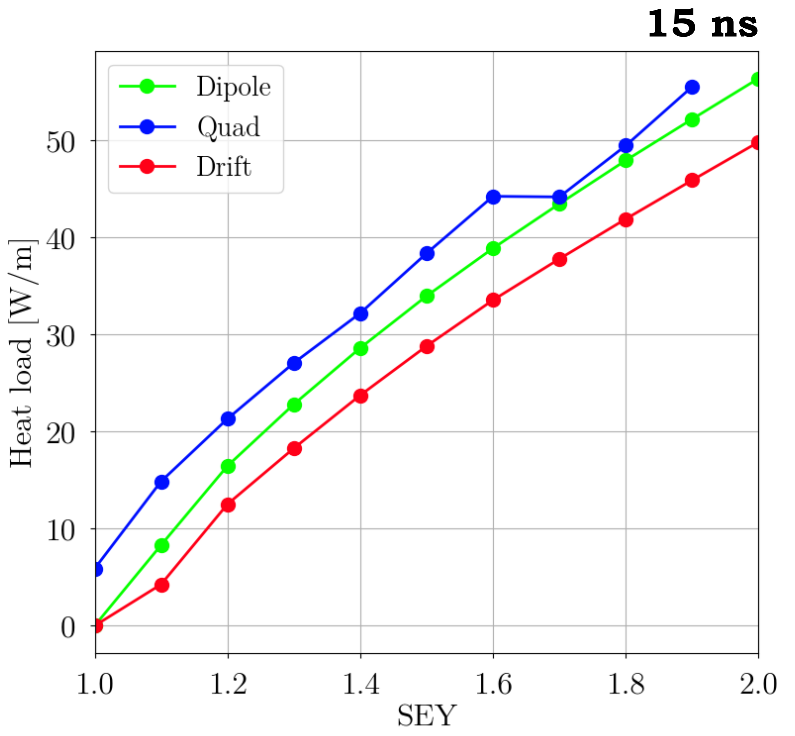
- Realistic shape of the vacuum chamber in the arcs (35 mm radius)
- Round chamber of 15 mm (20 mm) radius in Q1 (Q2)
- Electron cloud build-up in the arcs and IR magnets
  - Initial uniform distribution 10^9 e-/m
  - SEY scan
  - Bunch spacing scan: 2.5 ns, 5 ns, 15 ns
  - Filling pattern: 80b + 25e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



Heat load in the arc components



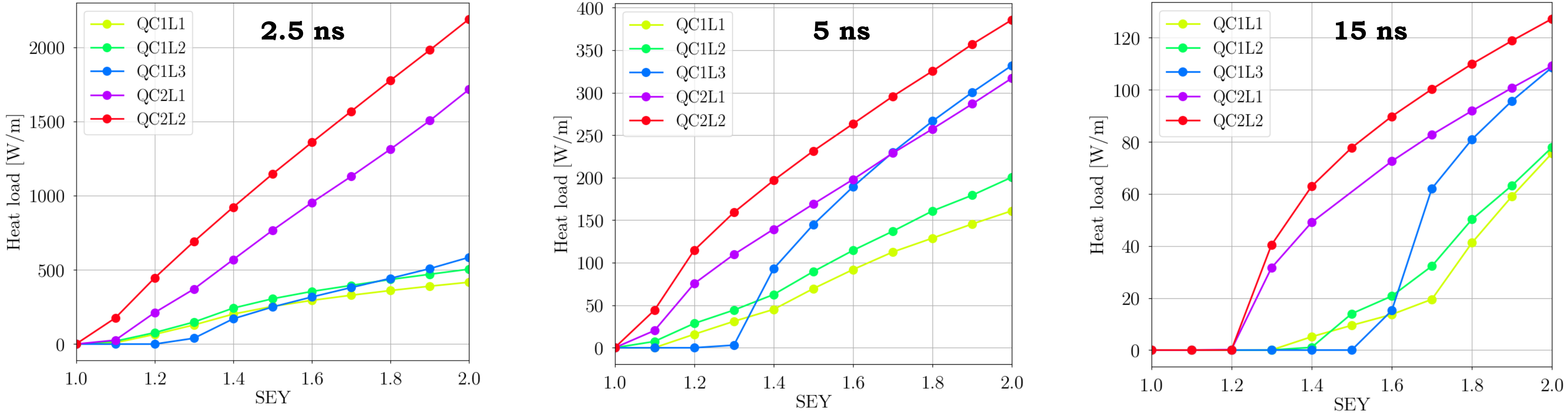




- Multipacting threshold defined as the highest SEY without multipacting

	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

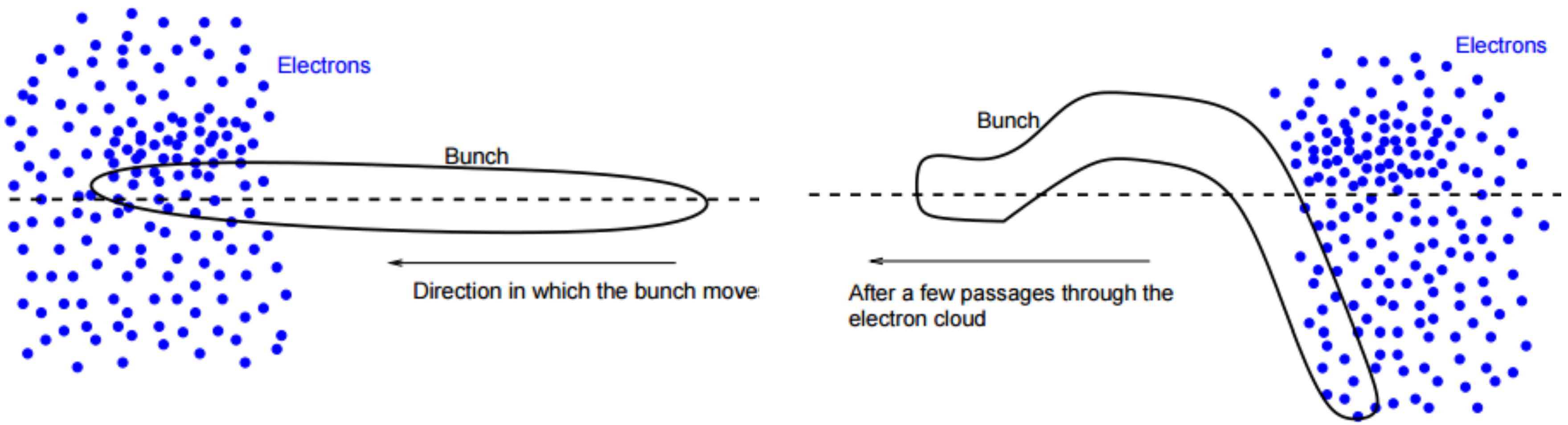


➢ Multipacting threshold defined as the highest SEY without multipacting

	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

➢ Higher thresholds and lower heat load for 15 ns beam

Single bunch head tail instability

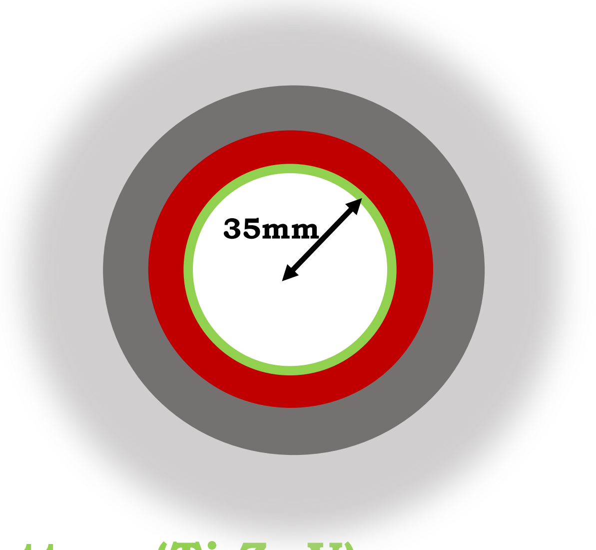


- Electron cloud acts as a short range wakefield with frequency $\omega_e = \sqrt{\frac{2\lambda_p r_e c^2}{\sigma_y(\sigma_x + \sigma_y)}}$
- Analytic electron density threshold for instability* $\rho_{\text{th}} = \frac{2\gamma Q_s}{\sqrt{3} Q r_0 \beta_y C}$ with $Q = \min(\omega_e \sigma_z / c, 7)$
- At 45.6 GeV: $\boldsymbol{\rho_{th} = 2.29 \cdot 10^{10}/m^3}$
  - ❖ **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

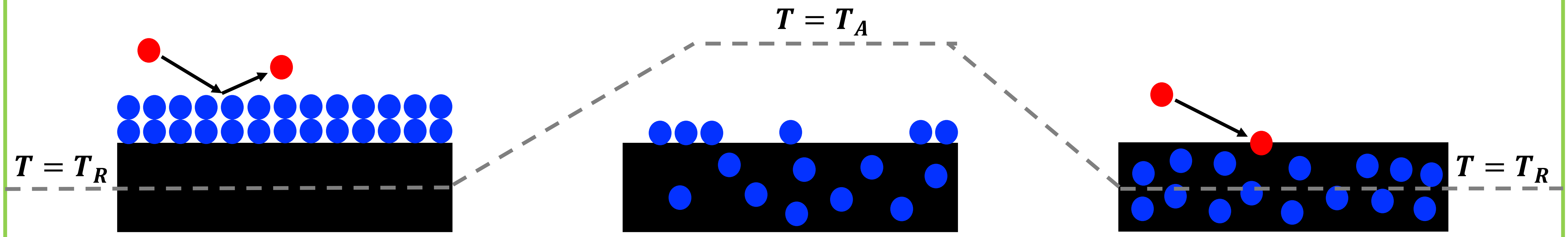
- The presence of the coating affects the RW impedance



- **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
  - $\rho = 1.66 \cdot 10^{-8}\ \Omega\text{m}$
- **Low SEY Coating**
  - Required for electron cloud mitigation

Non Evaporable Getters (Ti-Zr-V)

- 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

- Resistive wall impedance of a two-layer tube with metallic layers[1,2,3]

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

$\boldsymbol{\delta_c \gg \Delta}$ $\qquad$ $\boldsymbol{\frac{\sigma_c}{\sigma_s} \ll 1}$

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

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

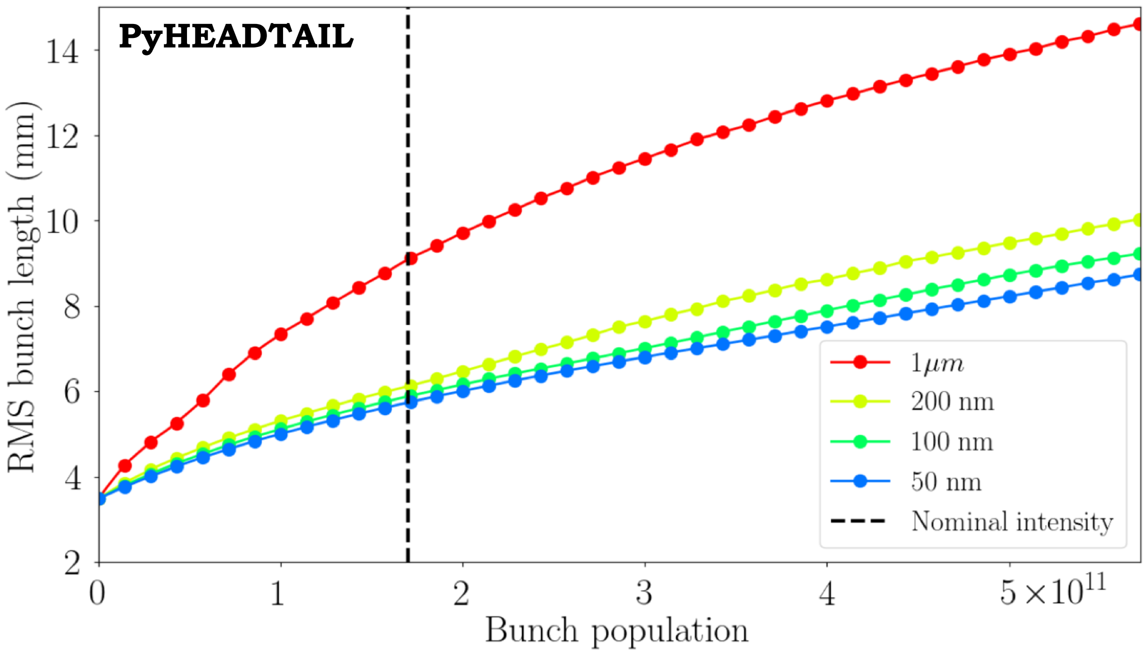
[1]N. Wang and Q. Qin, "Resistive wall impedance of two-layer tube", *Phys. Rev. ST Accel. And Beams*, vol. 10, p. 111003

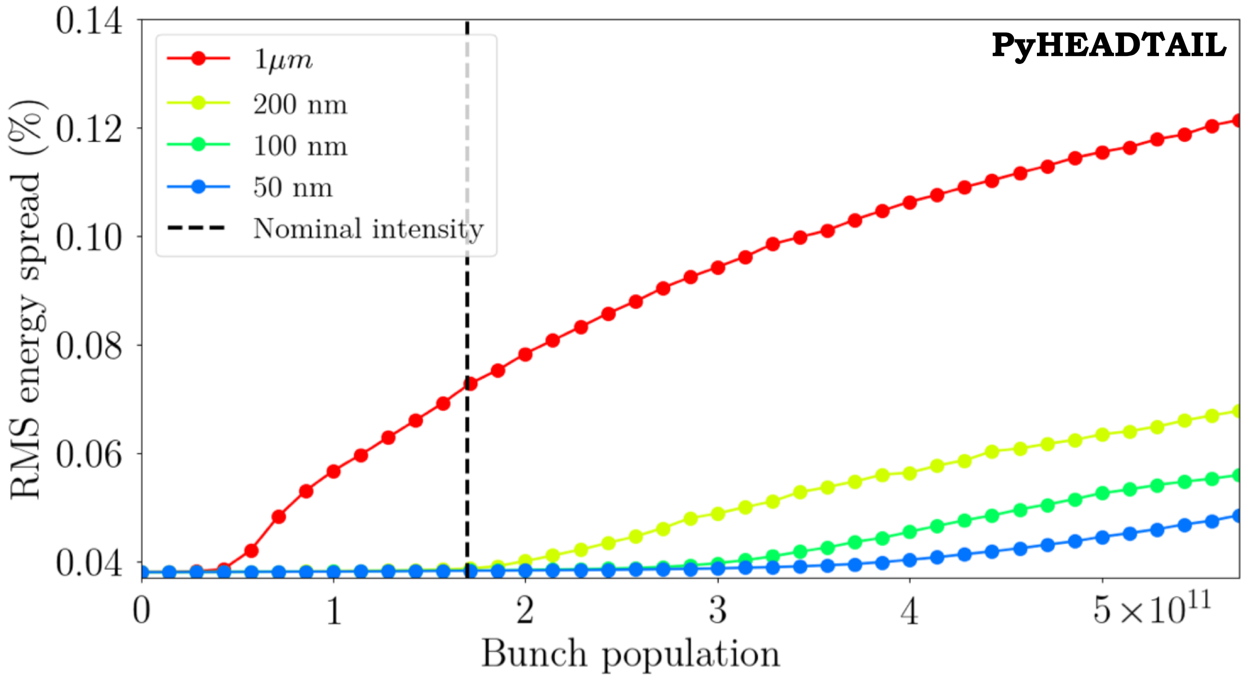
[2]M. Migliorati, E. Belli and M. Zobov, "Impact of the resistive wall impedance on beam dynamics in the Future Circular e+e- Collider", *Phys. Rev. Accel. And Beams*, vol. 21, p. 041001 (2018).

[3]E. Belli, et al., "Electron cloud buildup and impedance effects on beam dynamics in the Future Circular e+e− Collider and experimental characterization of thin TiZrV vacuum chamber coatings", *Phys. Rev. Accel. And Beams*, accepted for publication (2018).

NEG thin films: single bunch longitudinal dynamics

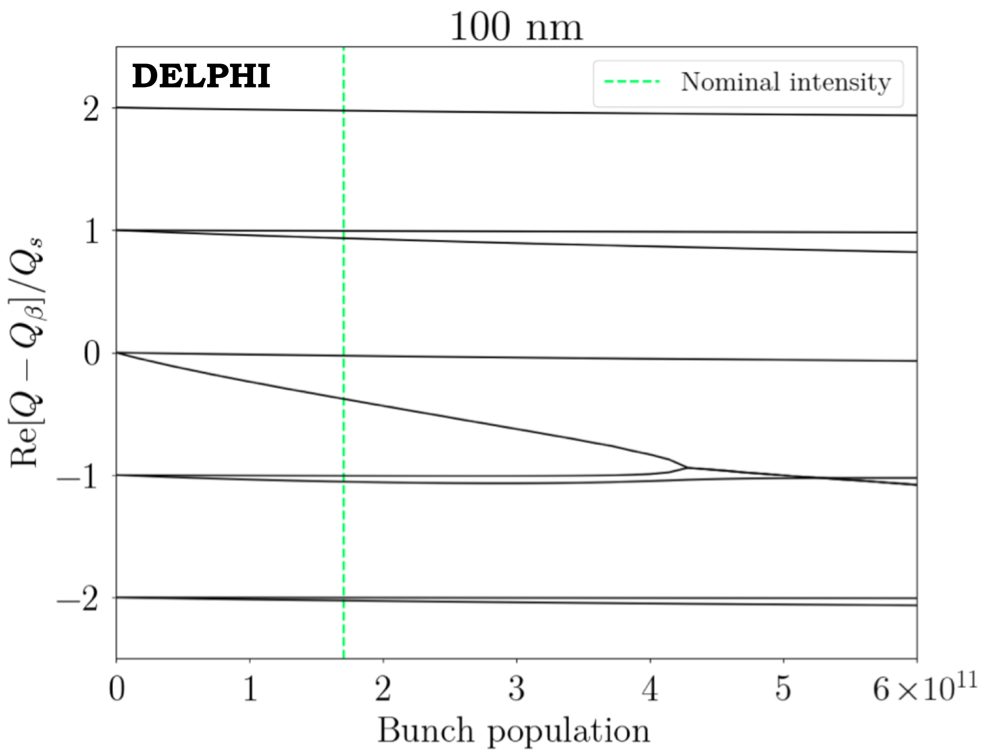
- NEG thin films with 1μm, 200nm, 100nm, 50nm thicknesses
- **Microwave instability (MI)**
  - Instability threshold defined as the value of the bunch population corresponding to an increase of the energy spread of about 10% w.r.t. its nominal value

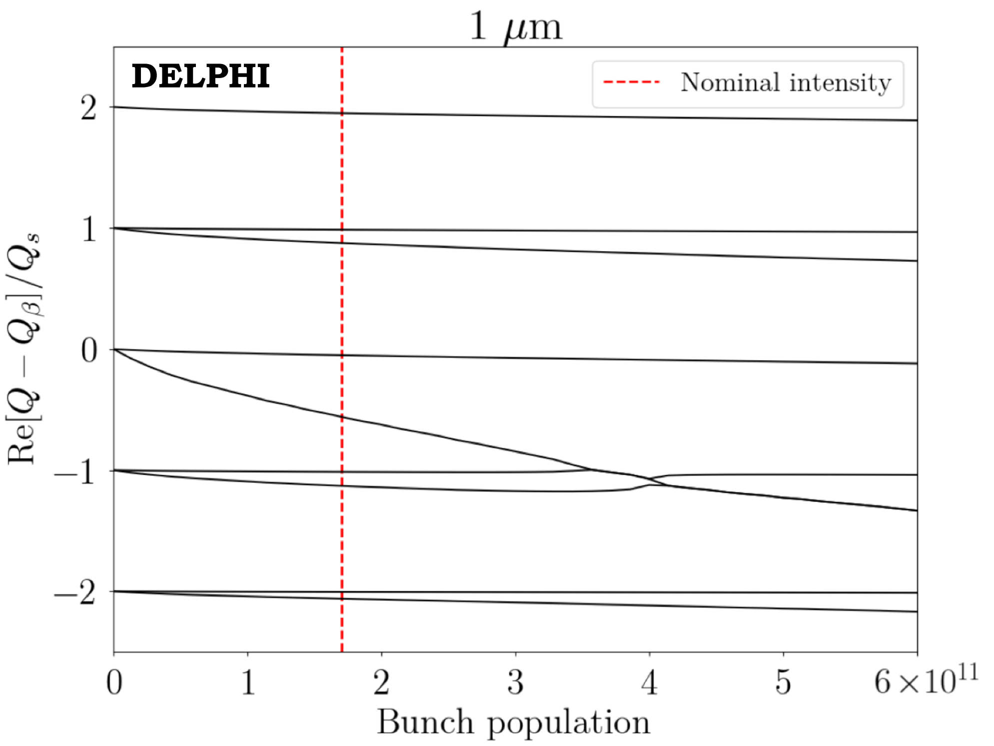




- 1μm thickness makes the bunch unstable
- Thinner films allow to increase the MI threshold
- For 100 nm film, MI threshold ≈ 2x higher than nominal bunch population

- **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



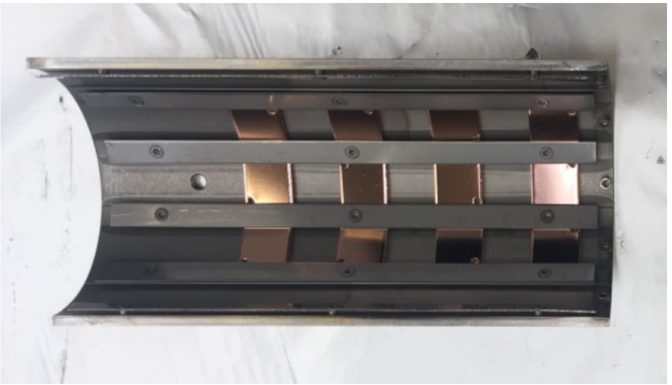


- For both films, TMCI threshold ≈ 2.5x higher than nominal bunch population
- TMCI threshold affected to a lesser extent by the thickness $N_{th} = \dfrac{4\pi \frac{E}{e} \tau_b Q_s}{e\beta \, Im\{Z_m^{eff}\}}$

NEG thin films: experimental characterization

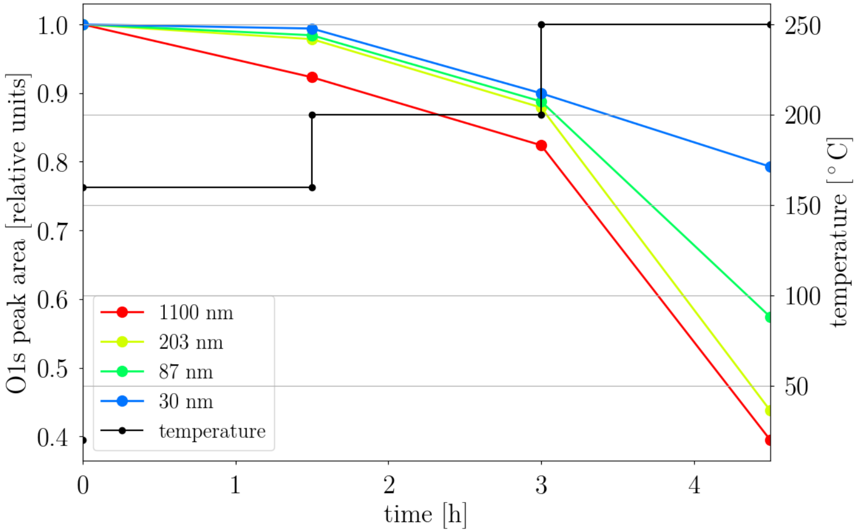
- Reducing the thickness of NEG coatings can affect the performance of the material itself and therefore the maximum SEY and related electron cloud mitigation.

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

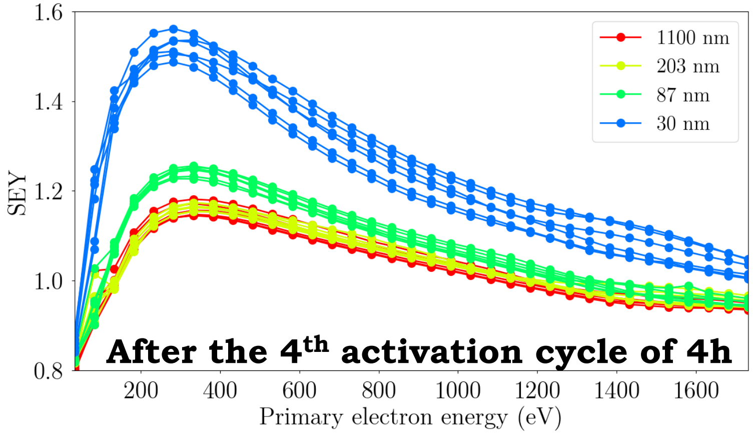


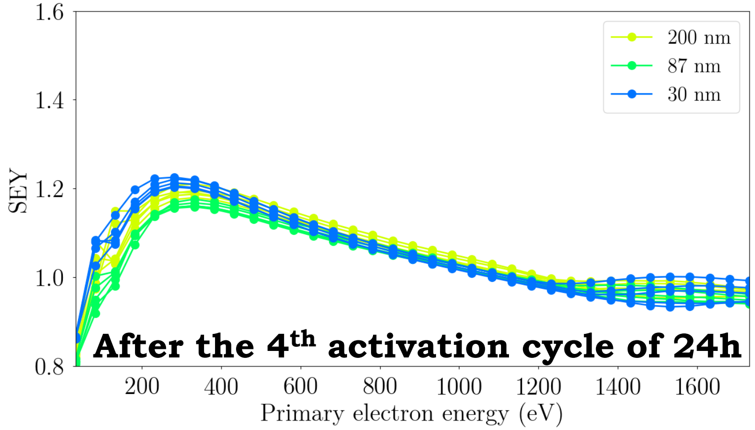
Target Δ [nm]	Measured Δ [nm]
1000	1100
200	203
100	87
50	30

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

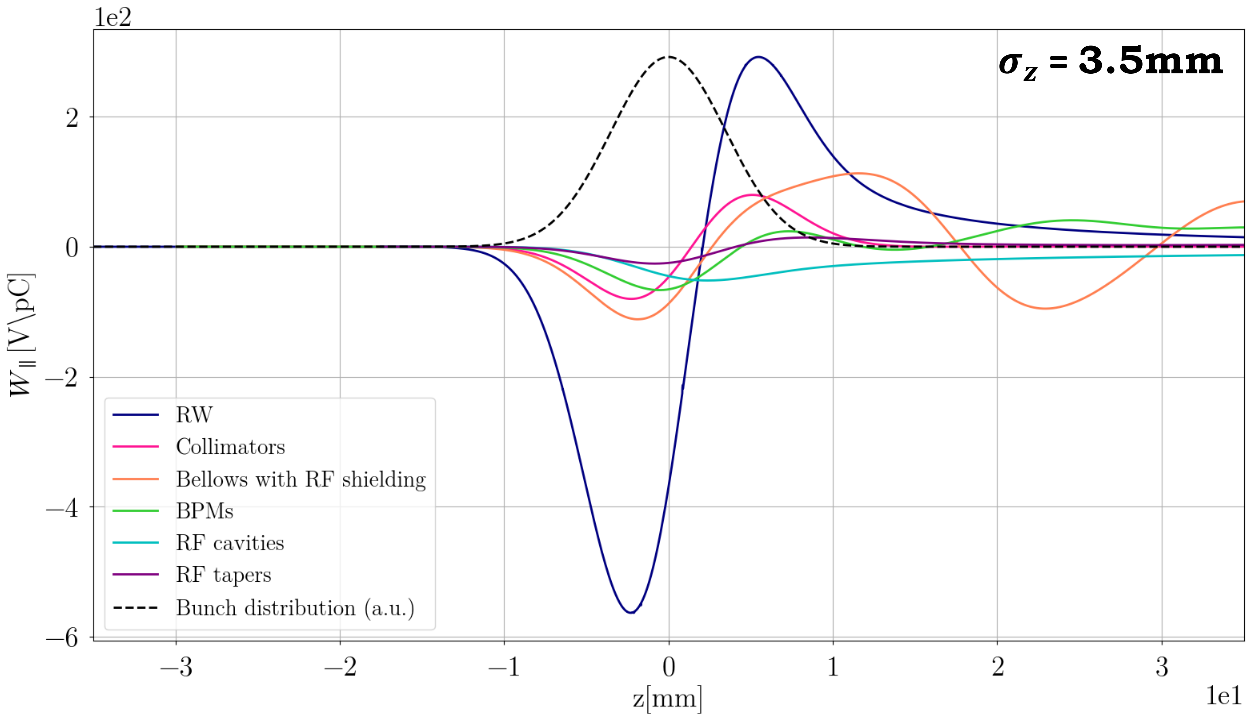


- Higher O reduction → better activation
- **O surface concentration increases for thinner layers**





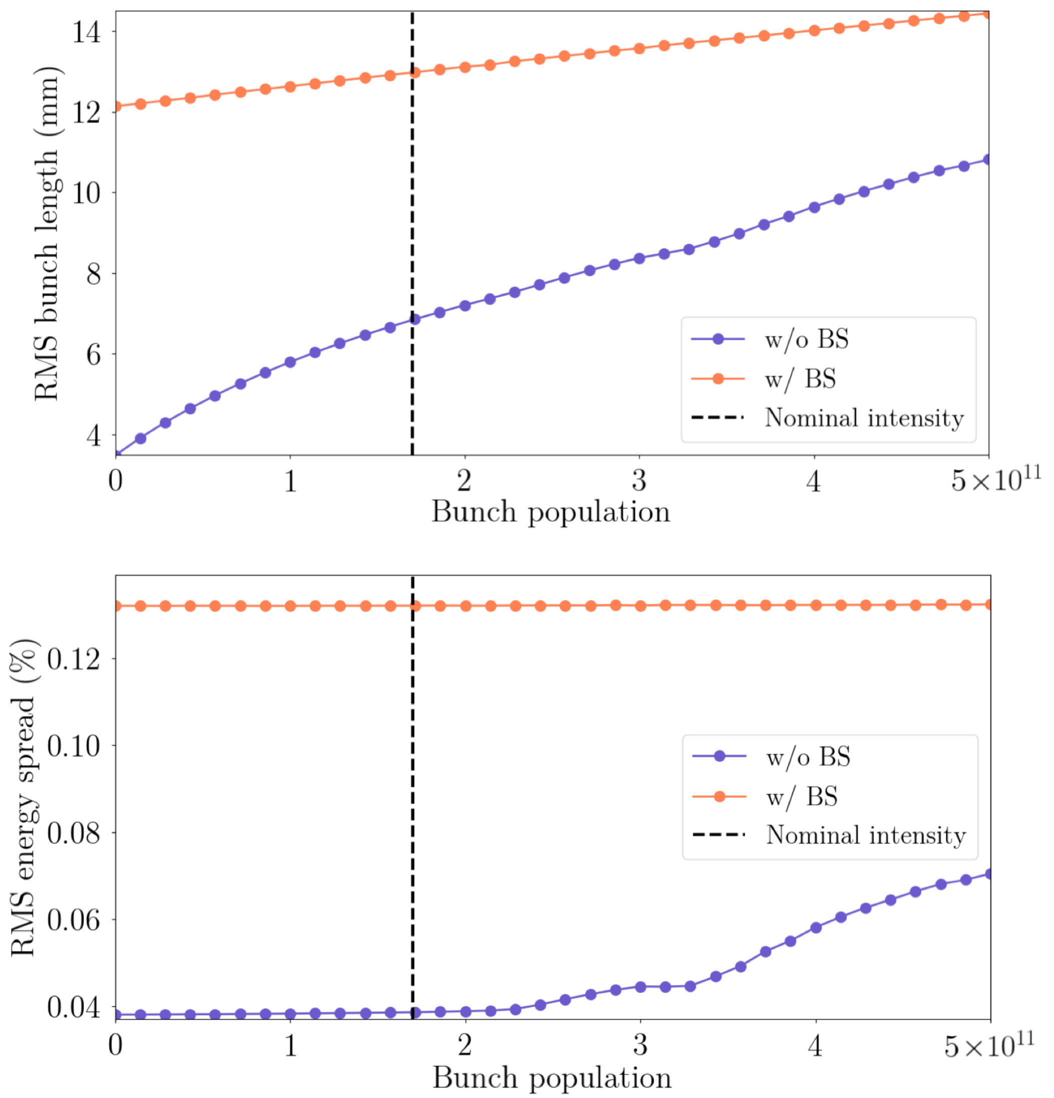
FCC-ee longitudinal impedance model



Component	**Number**	$\mathbf{k_{loss}}$**[V/pC]**	$\mathbf{P_{loss}}$**[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 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)
    - Lower heat load in the arcs
- Analytic single bunch instability threshold estimated at low energy
  - Low SEY coating needed in the entire ring
- NEG coating as baseline choice
  - RW impedance contribution can be reduced by decreasing the thickness of the coating layer
- NEG thin films with $\Delta < 250$ nm analysed experimentally 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
- FCC-ee longitudinal impedance model
  - Smaller contribution of other elements 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


Thanks for your attention