



# Main rings impedance budget

C. Zannini

X. Buffat, D. Gibellieri, A. Ghribi, J. Li, E. Macchia, I. Mases, M. Migliorati, L. Sito, M. Zobov

Acknowledgments: C. Antuono, H. Bartosik, E. Belli, M. Boscolo, G. Broggi, R. Bruce, E. Carideo, E. De la Fuente, W. Hofle, I. Karpov, C. Pasquino, S. Redaelli, E. Rose Howling, G. Rumolo, R. Soos, D. Sittard, H. Sullivan, F. Zimmermann

# Overview

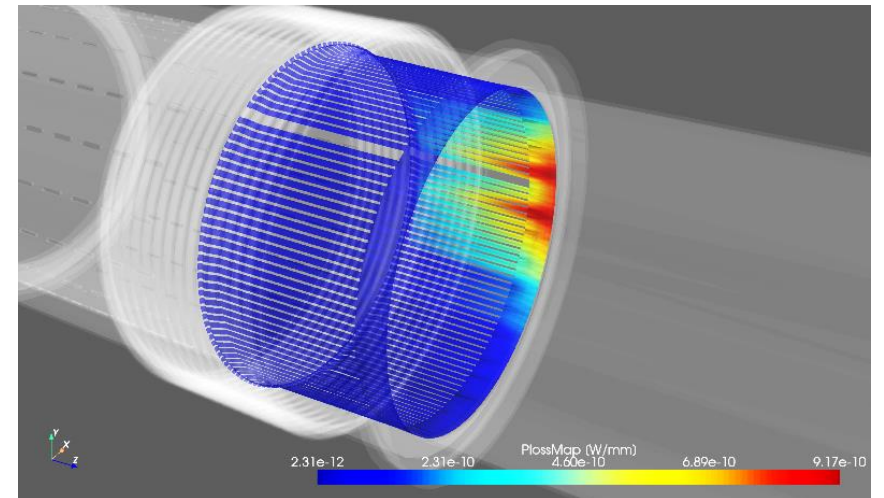
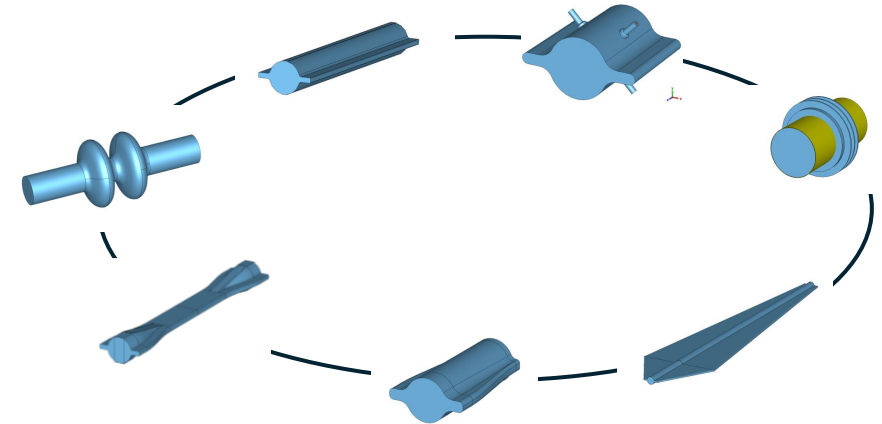
- Introduction
- Impedance beam induced power
- FCC-ee impedance model
- Multi-bunch tune shift considerations
- Summary

# Overview

- Introduction
- Impedance beam induced power
- FCC-ee impedance model
- Multi-bunch tune shift considerations
- Summary

# Introduction

- Impedance optimization of accelerator elements is crucial to avoid
  - Beam instabilities
    - Machine impedance
  - Equipment degradation and damage
    - Beam induced heating
    - Beam induced sparking



# Impedance optimization

Impedance optimization requires the knowledge of the knobs to manipulate the impedance

Having simplified formulas to master the main dependencies

Step by step simulation to have a deep understanding of the impedance mechanism

Impedance evaluation

Simulations, analytical models, measurements

Beam induced power

Established calculation tool **BIHC**  
<https://github.com/ImpedanCEI/BIHC>

Power loss map

Combining 3D simulations and BIHC results

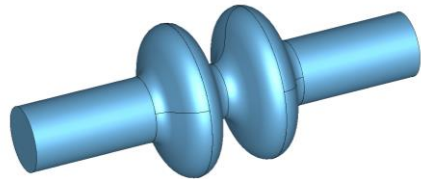
Impedances are included in the global impedance model for beam dynamics assessments and energy loss budget considerations

Design optimization

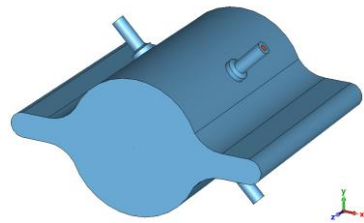
# FCC-ee impedance challenges

- **Challenging simulation regime**
  - Combination of large beam pipe dimensions and short bunch lengths
    - Very high number of mesh cells.

~3000 bilion mesh cells



~3 bilion mesh cells



~15 bilion mesh cells

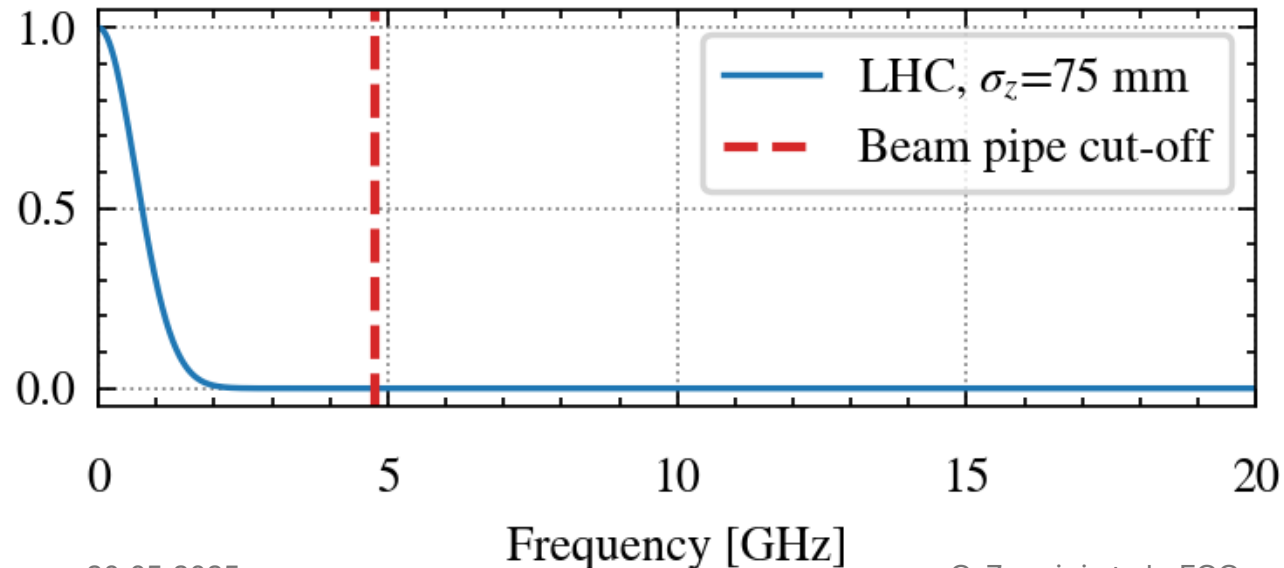
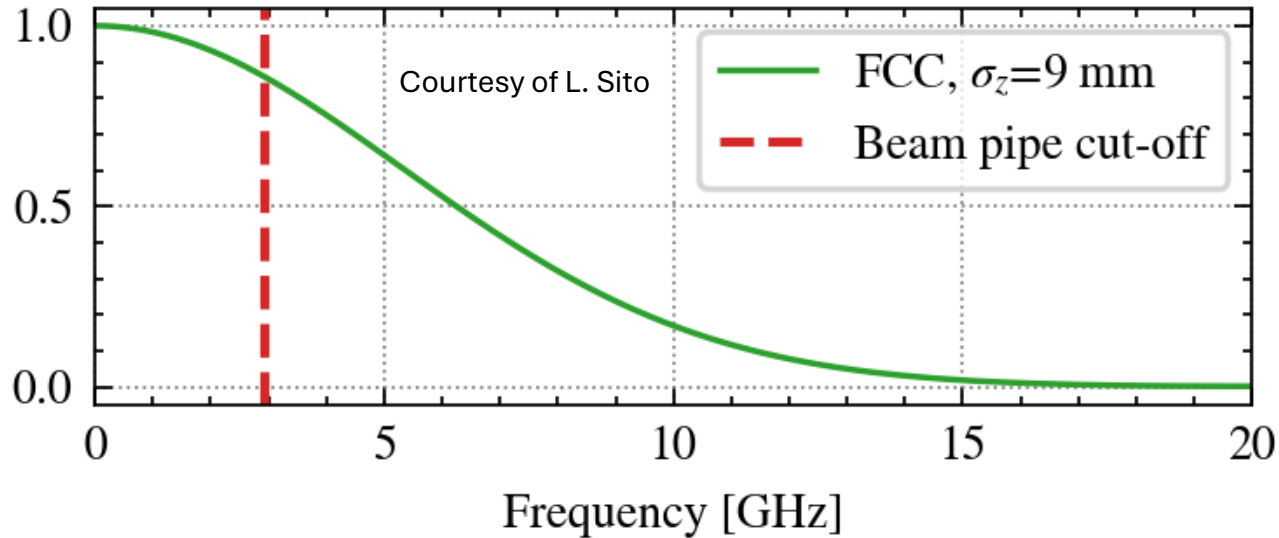


Ad-hoc developments in the open source wakefield solver Wakis are ongoing to address this simulation challenge efficiently <https://github.com/ImpedanCEI/wakis/>



# FCC-ee impedance challenges

Normalized spectrum envelope



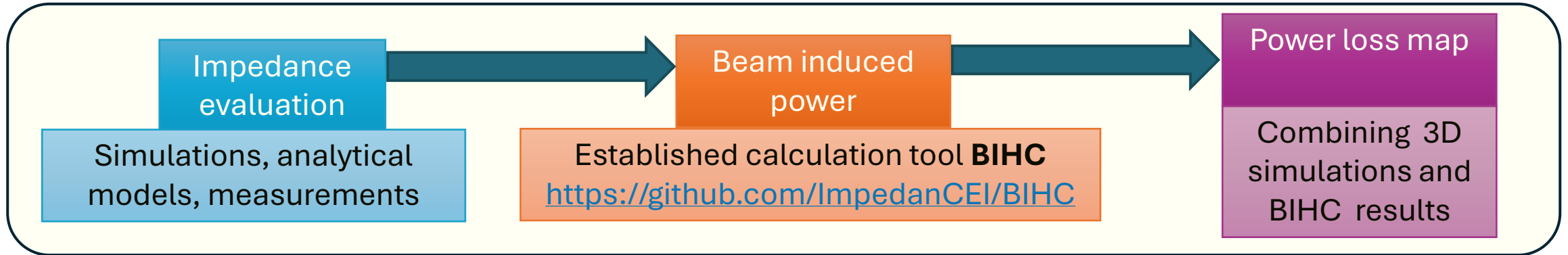
The beam pipe cut-off lies well within the relevant frequency spectrum.

- Several modes above cut-off are strongly excited, leading to significant crosstalk between different accelerator elements.
  - Particularly relevant for long range wakefield and beam induced power assessment
- Multiple modes can propagate along the accelerator. Should we consider implementing ad-hoc devices to absorb the propagating power?

# Overview

- Introduction
- Impedance beam induced power
- FCC-ee impedance model
- Multi-bunch tune shift considerations
- Summary

# Beam induced power



Total number of particles in the beam

Longitudinal impedance

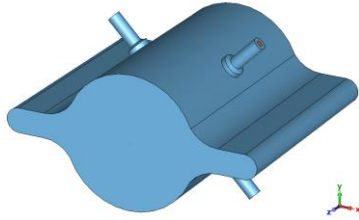
$$\Delta W = (f_0 e N_{\text{beam}})^2 \sum_{p=-\infty}^{p=\infty} \left( |\bar{\Lambda}(p\omega_0)|^2 \text{Re} [Z_{||}(p\omega_0)] \right)$$

Revolution frequency of particles

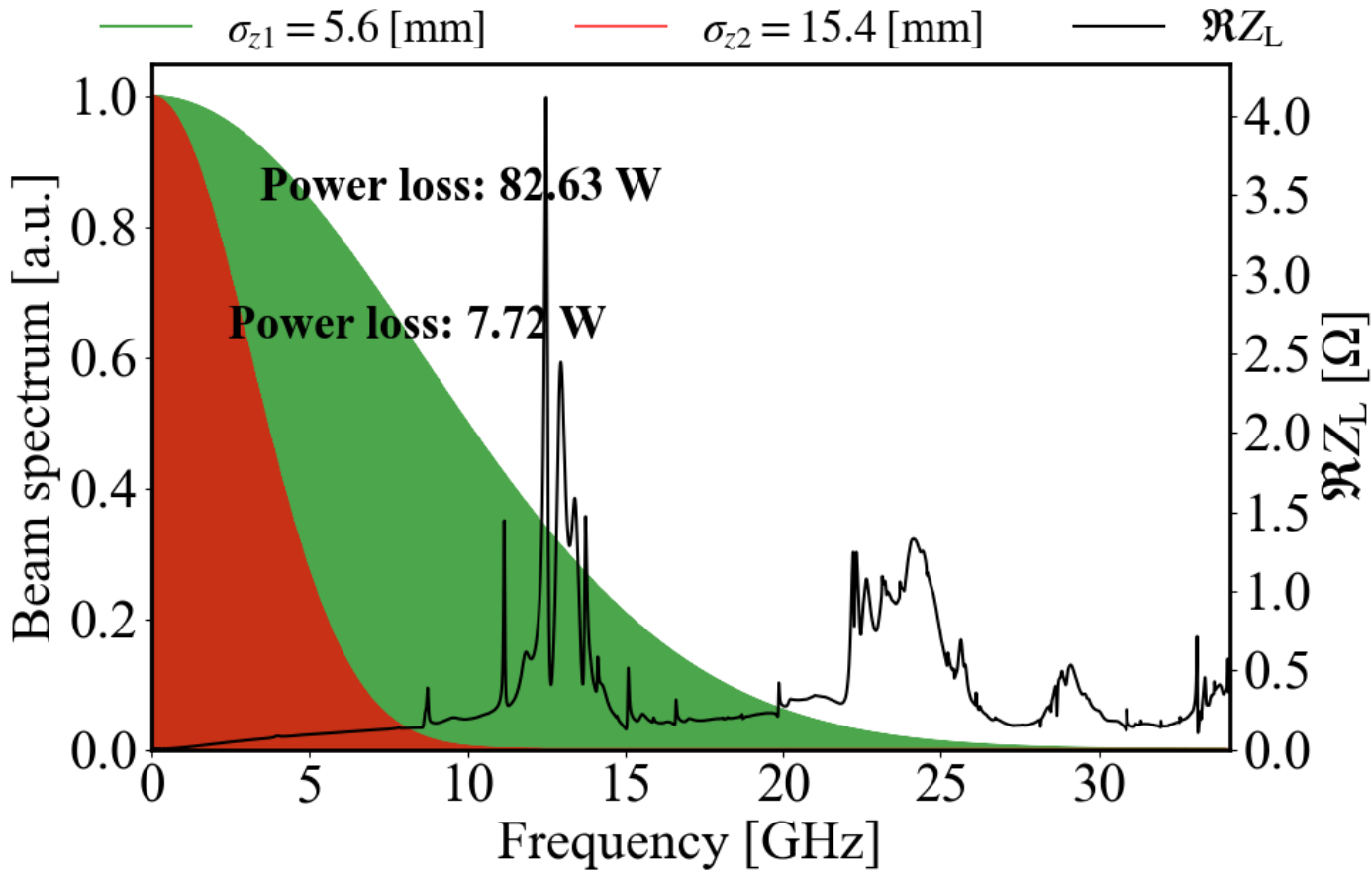
Normalized beam spectrum

Input for equipment owner to assess risks due to beam induced power level

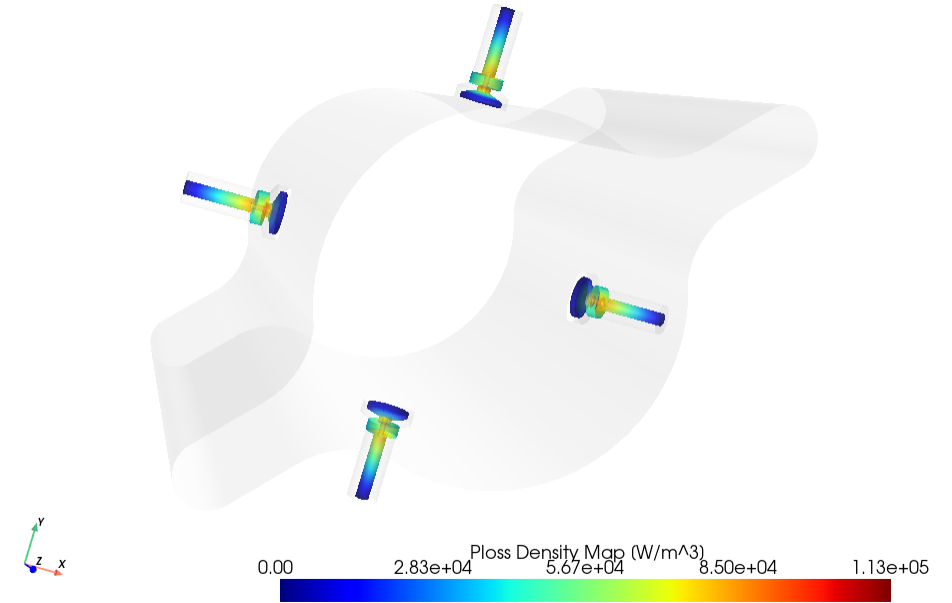
# Beam induced power: the FCC-ee BPM example



Beam induced power loss map obtained combining the effect from all modes is provided to equipment owner for thermo-mechanical assessment

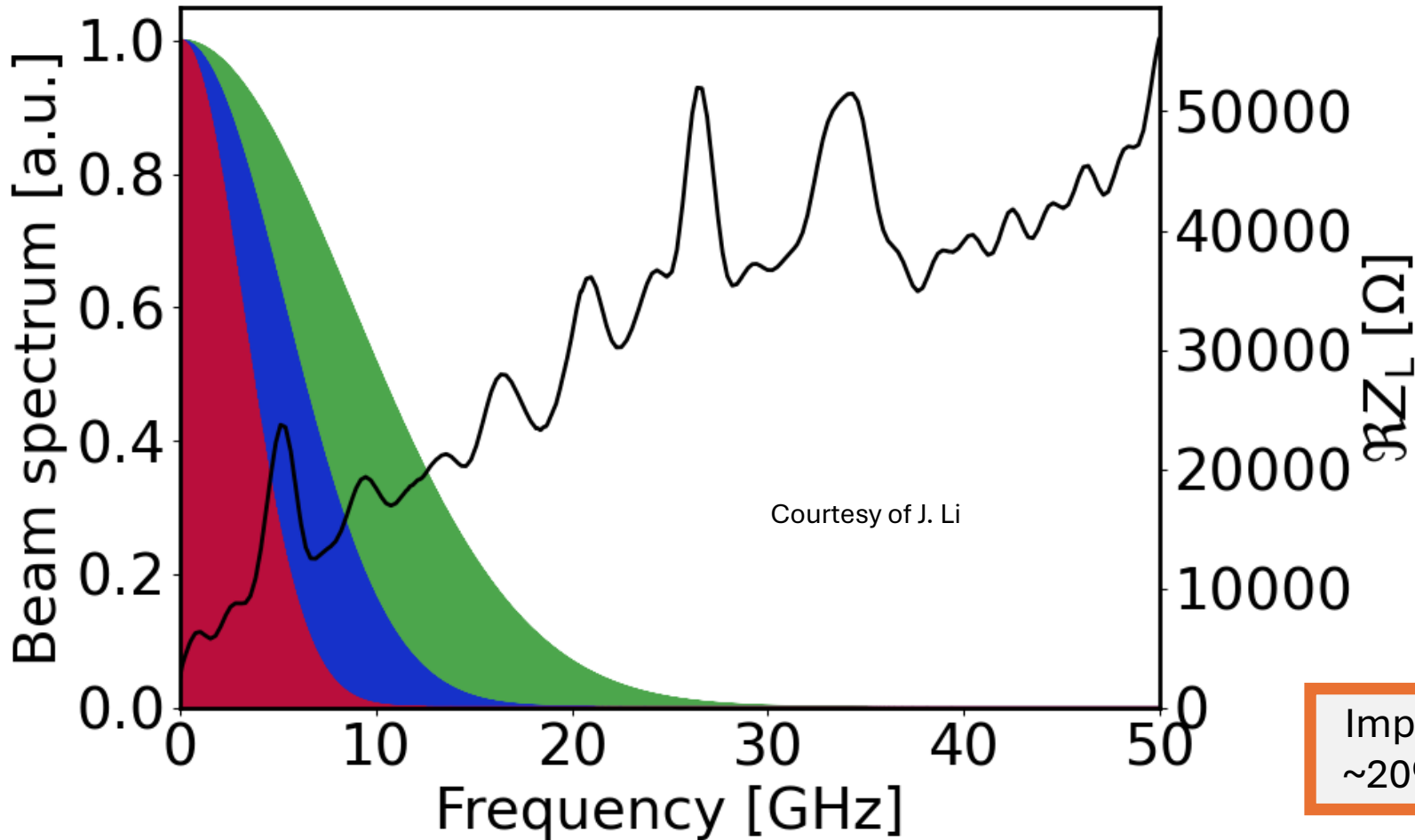


Courtesy of J. Li and E. De la Fuente



# Total beam induced power from impedance

—  $\sigma_{z1} = 5.4$  [mm]      —  $\sigma_{z2} = 9$  [mm]  
—  $\sigma_{z3} = 15.2$  [mm]      —  $\Re Z_L$



Z configuration

**Beam induced power from impedance with the latest impedance model**

1.8 MW at 15.2 mm bunch length  
4.2 MW at 9 mm bunch length  
9 MW at 5.4 mm bunch length

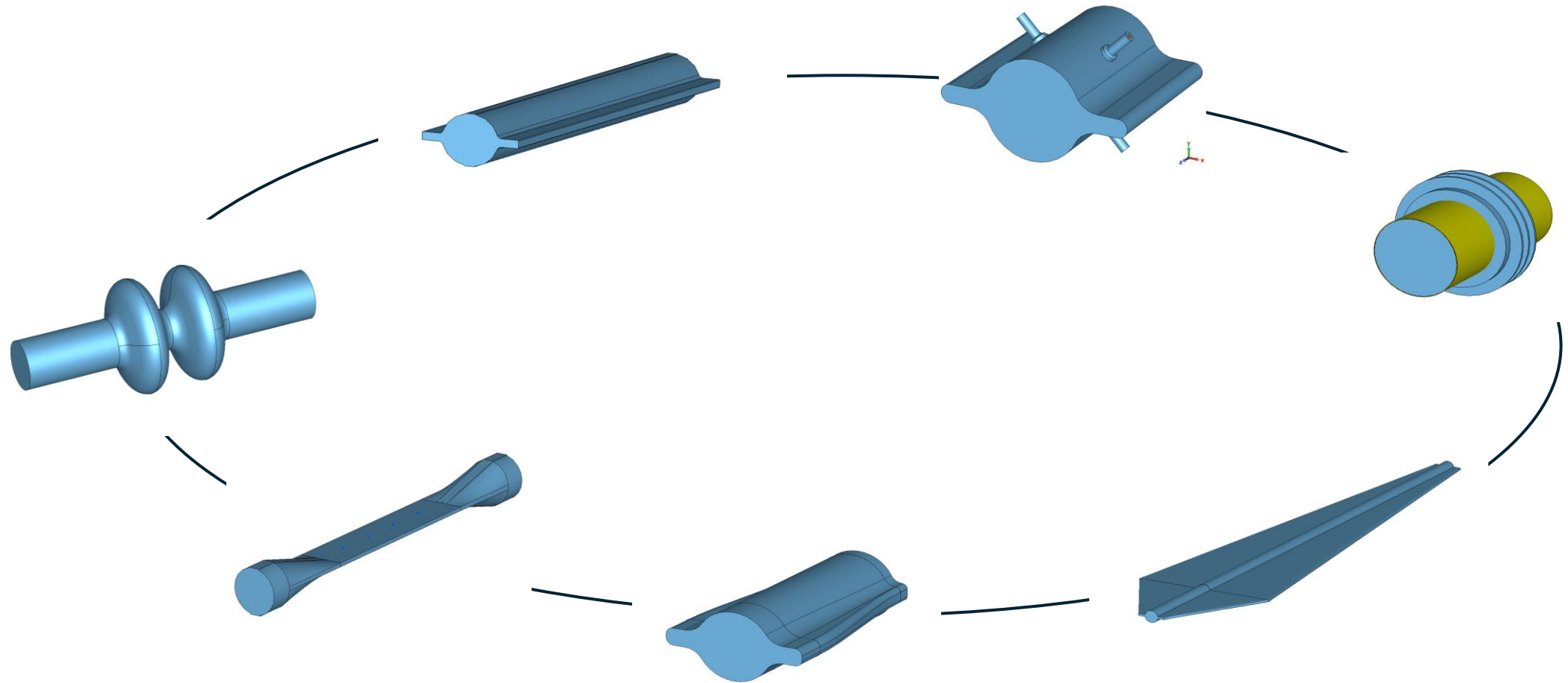
Energy loss per turn from SR 0.039 GeV  
SR power for the full beam ~50 MW

Impedance beam induced power from ~4% to ~20% of SR power depending on bunch length

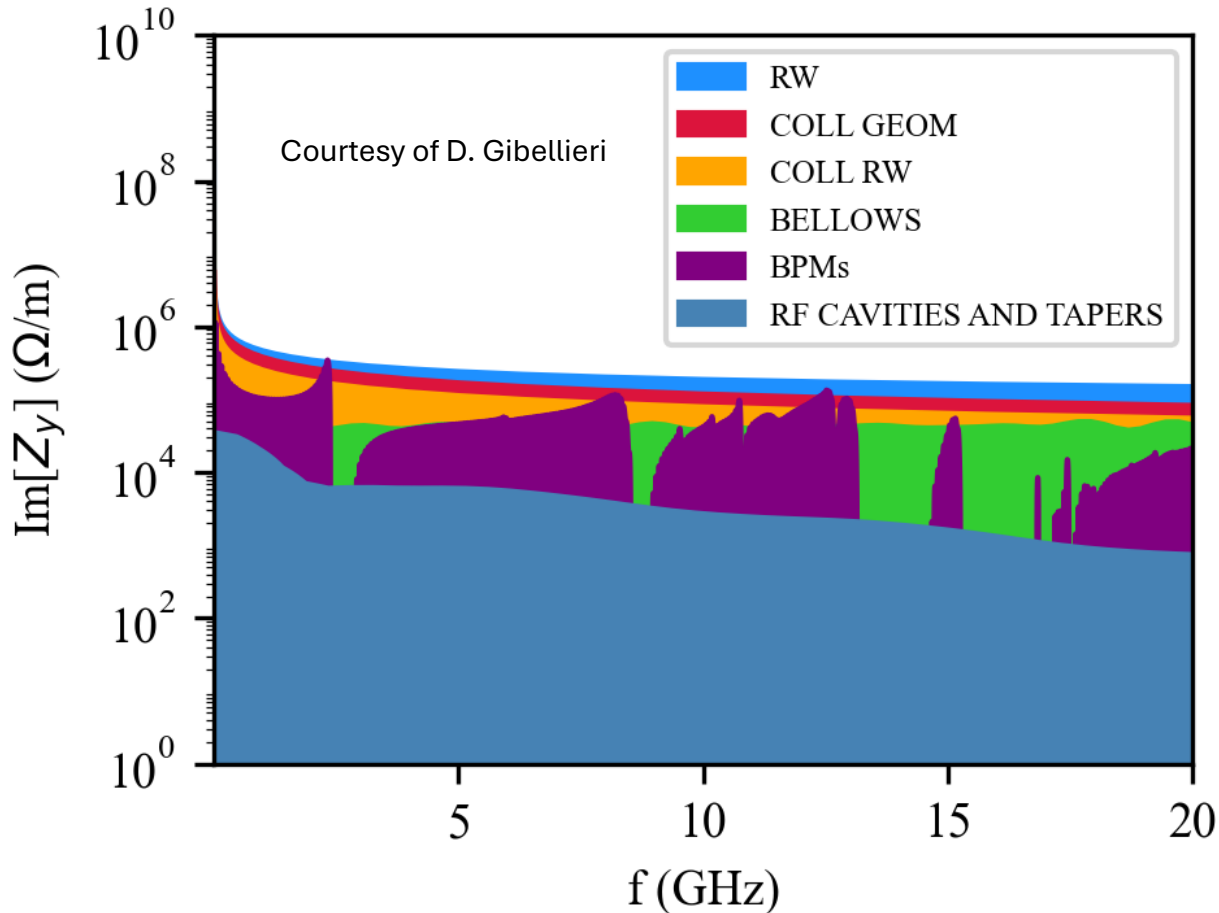
# Overview

- Introduction
- Impedance beam induced power
- FCC-ee impedance model
- Multi-bunch tune shift considerations
- Summary

# FCC-ee impedance budget



# FCC-ee impedance budget



Status of the impedance/wake model		
Accelerator element	Model status	Evaluation method
Beam pipe (RW)	Advanced	Analytical (IW2D)
Collimator RW	Initial	Analytical (IW2D)
Collimator geom.	Initial	3D simulations
Bellows	Initial	3D simulations
BPMs	Initial	3D simulations
RF cavities+tapers	Initial	3D simulations
Polarimeter	Initial	3D simulations
Stripline kickers	Initial	3D simulations
Chamber transitions	Initial	3D simulations

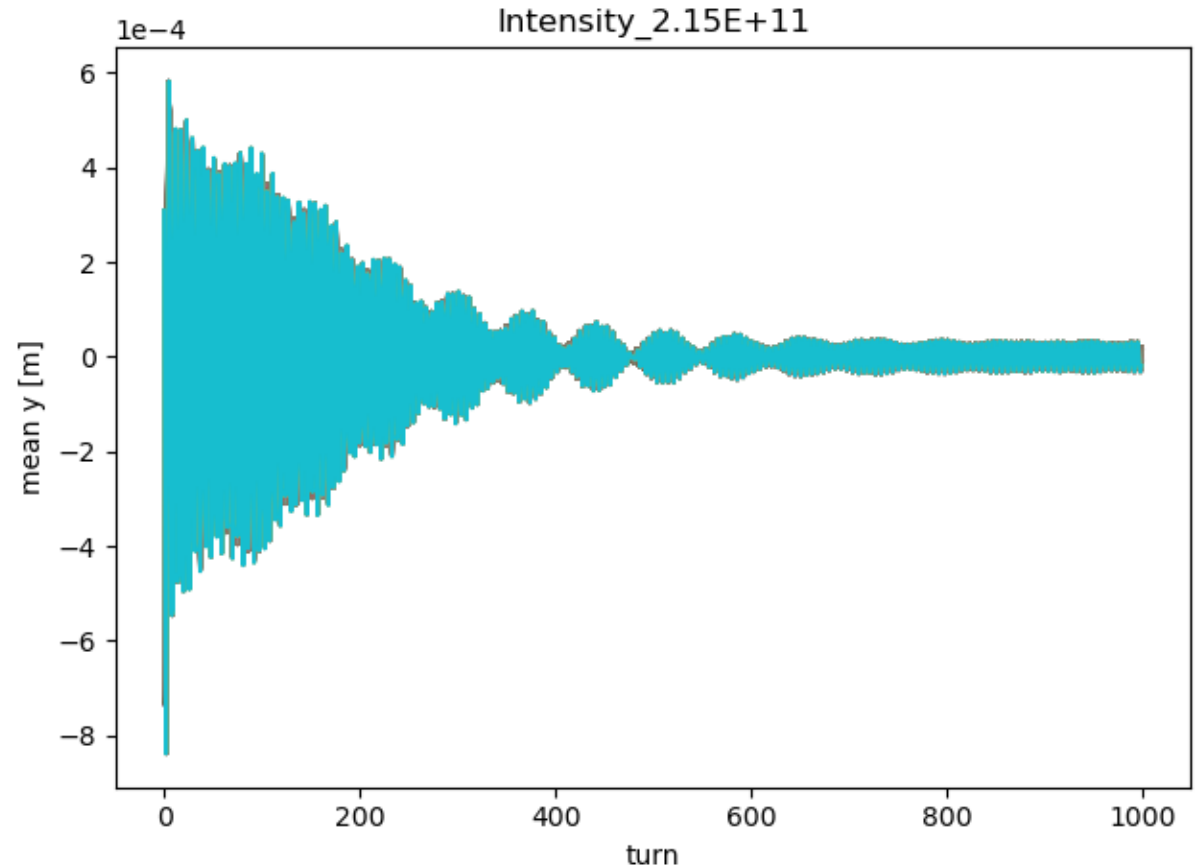
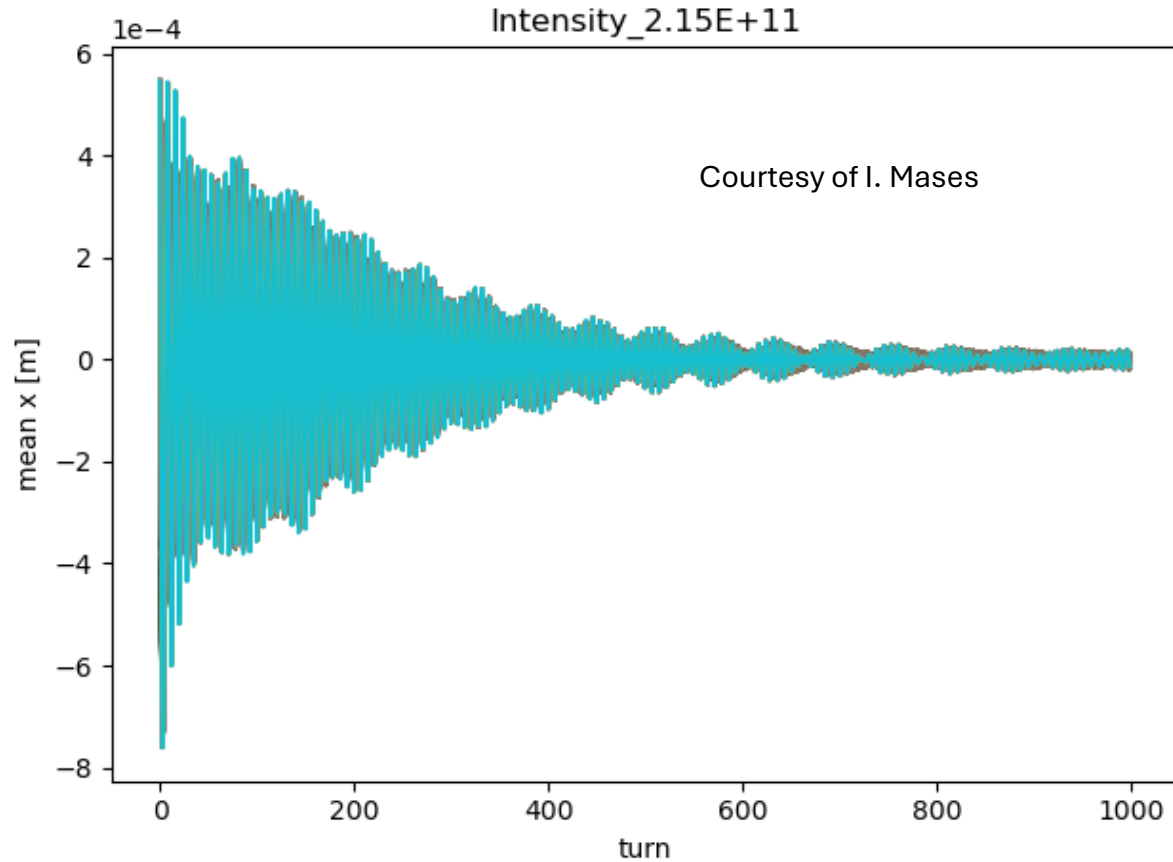
Follow-up design evolution ensuring impedance optimization and update models accordingly  
 Inclusion of additional elements (e.g. injection and extraction devices)

# Overview

- Introduction
- Impedance beam induced power
- FCC-ee impedance model
- Multi-bunch tune shift considerations
- Summary

# Bunch-by-bunch tune shift considerations

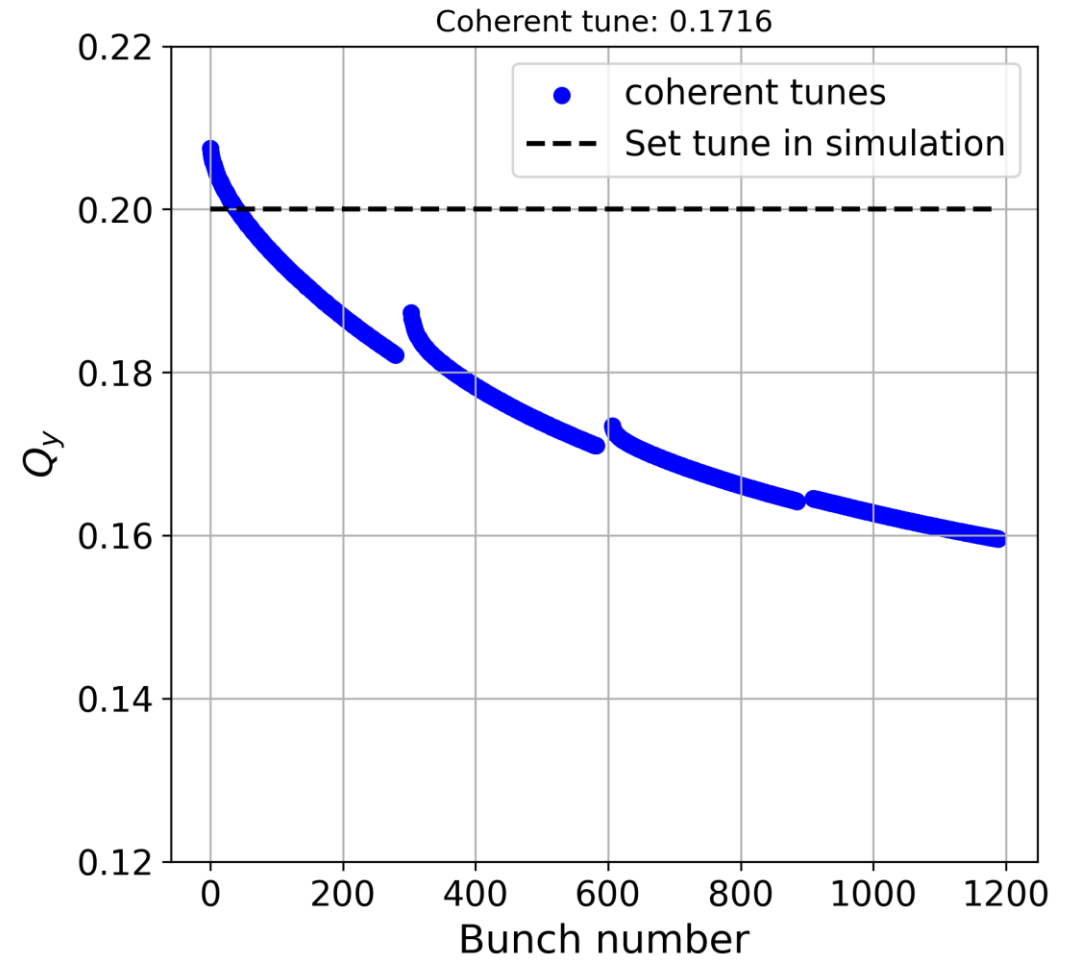
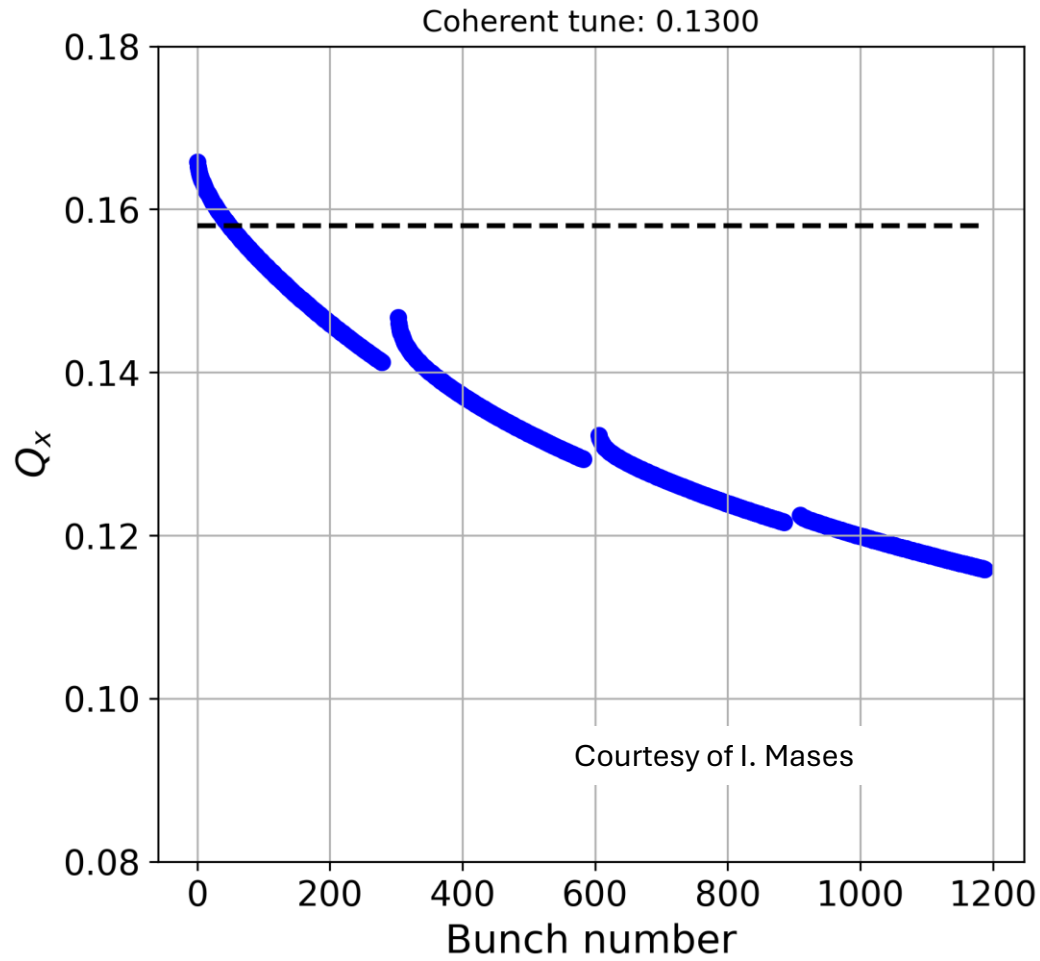
Multi-bunch simulations with resistive wall wake



Bunch-by-bunch tune shifts are obtained from the bunch monitoring of the centroid position

# Bunch-by-bunch tune shift of a partially filled machine

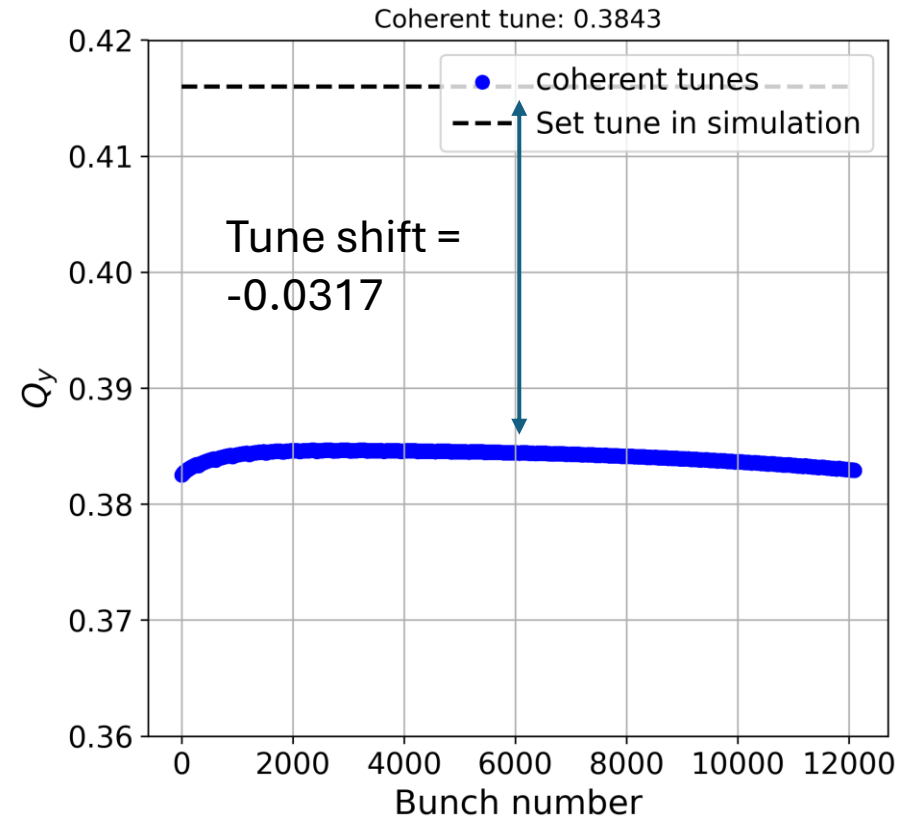
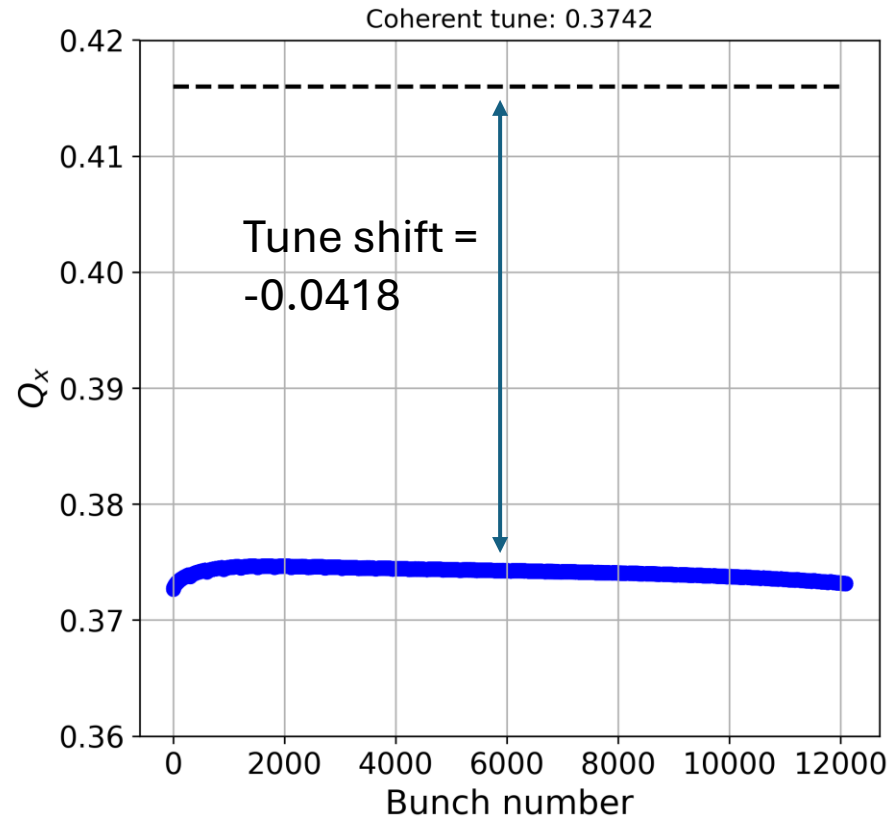
**Coherent tunes.  $2.15 \times 10^{11}$  p/b, 4 x 280 bunches. (25 ns spacing). 16 turns analyzed**



Bunch-by-bunch tune shift of the order of few  $10^{-2}$  over one train of 280 bunches for partially filled machines

# Bunch-by-bunch tune shift of the full machine Z configuration

**Coherent tunes. 2.15e11 p/b, 40 x 280 bunches. (25 ns spacing). 64 turns analyzed**

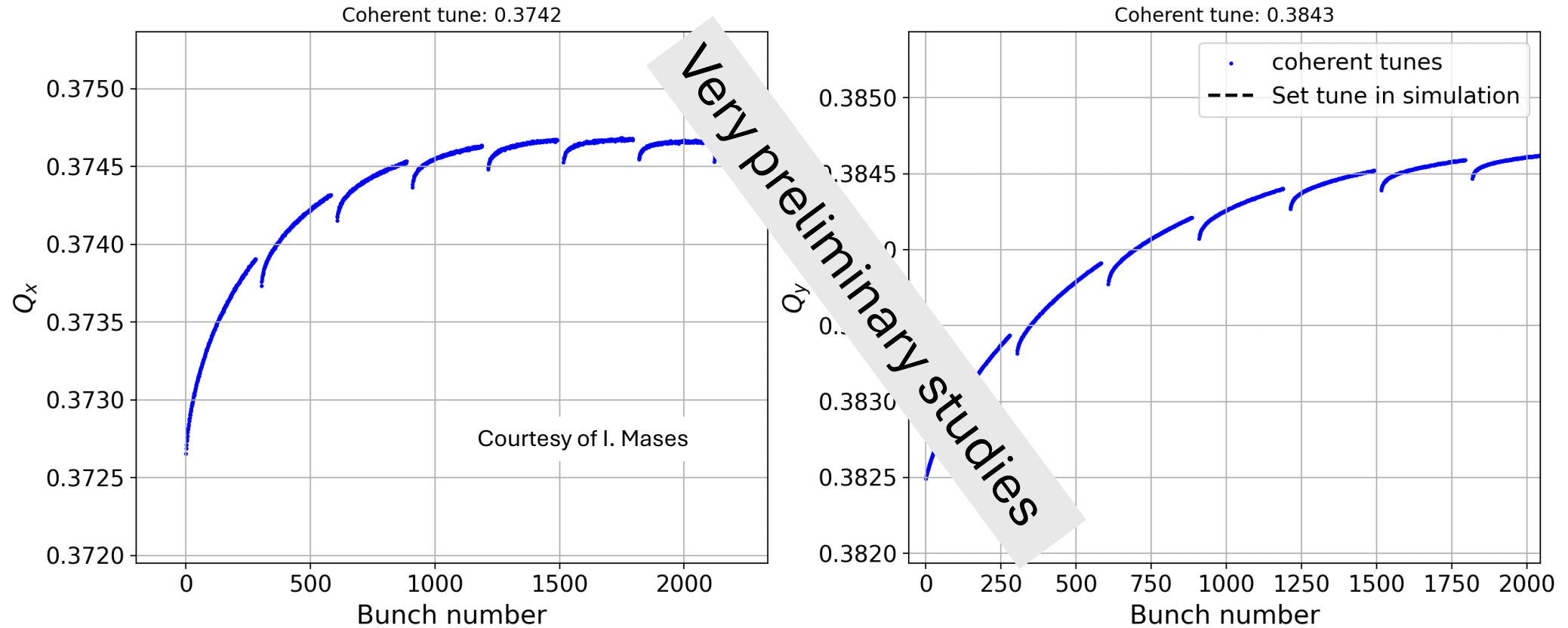


**Critical for X-Z instability (see R. Soos talk)**

Overall bunch-by-bunch tune shift in the order of few  $10^{-3}$  (in the same order of the horizontal beam beam parameter)

# Bunch-by-bunch tune shift of the full machine Z configuration

Coherent tunes.  $2.15 \times 10^{11}$  p/b, 40 x 280 bunches. (25 ns bunch spacing). 64 turns analyzed



Overall bunch-by-bunch tune shift in the order of few  $10^{-3}$  (in the same order of the horizontal beam beam parameter)

Bunch-by-bunch tune shift is a very critical subject for FCC-ee and must be taken into account to define the filling strategy and the overall impedance budget

# Beam stability with multi-bunch beam Z configuration

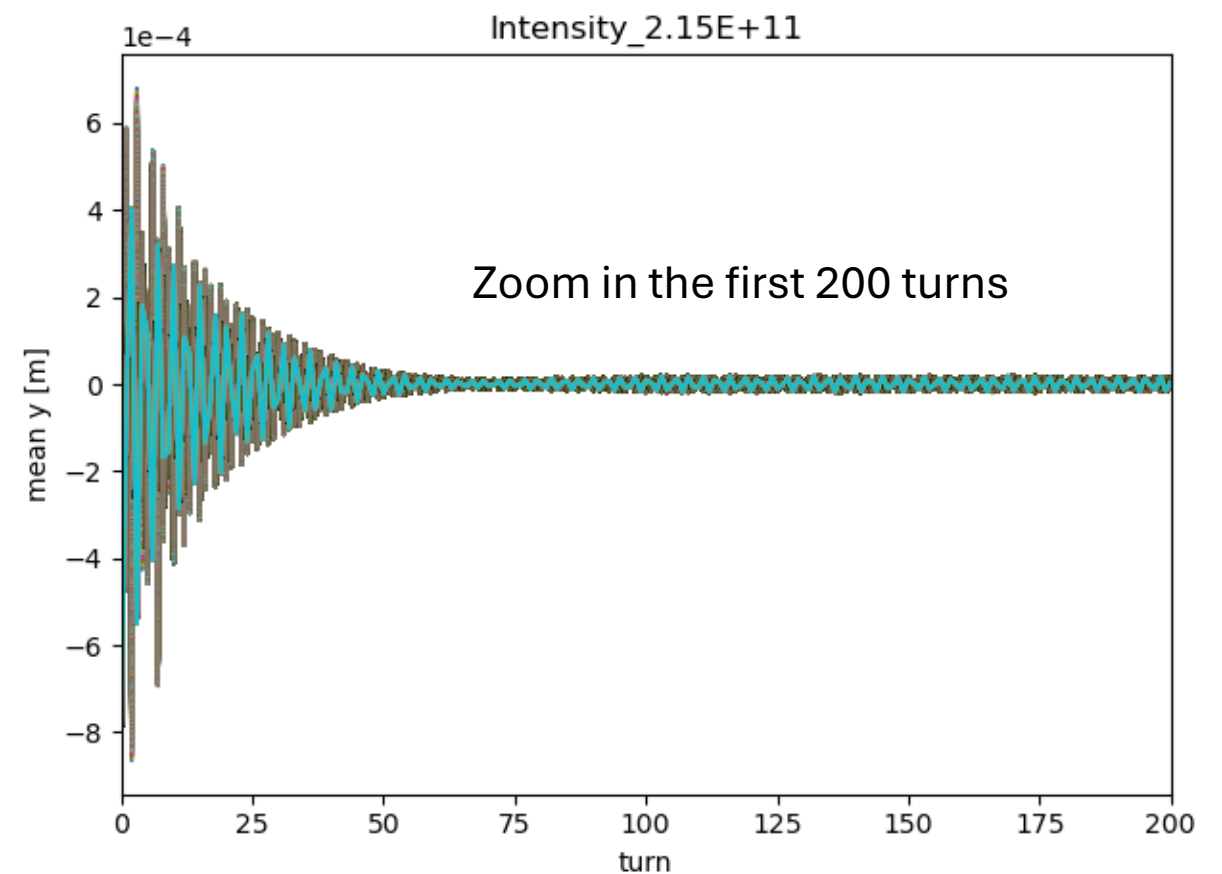
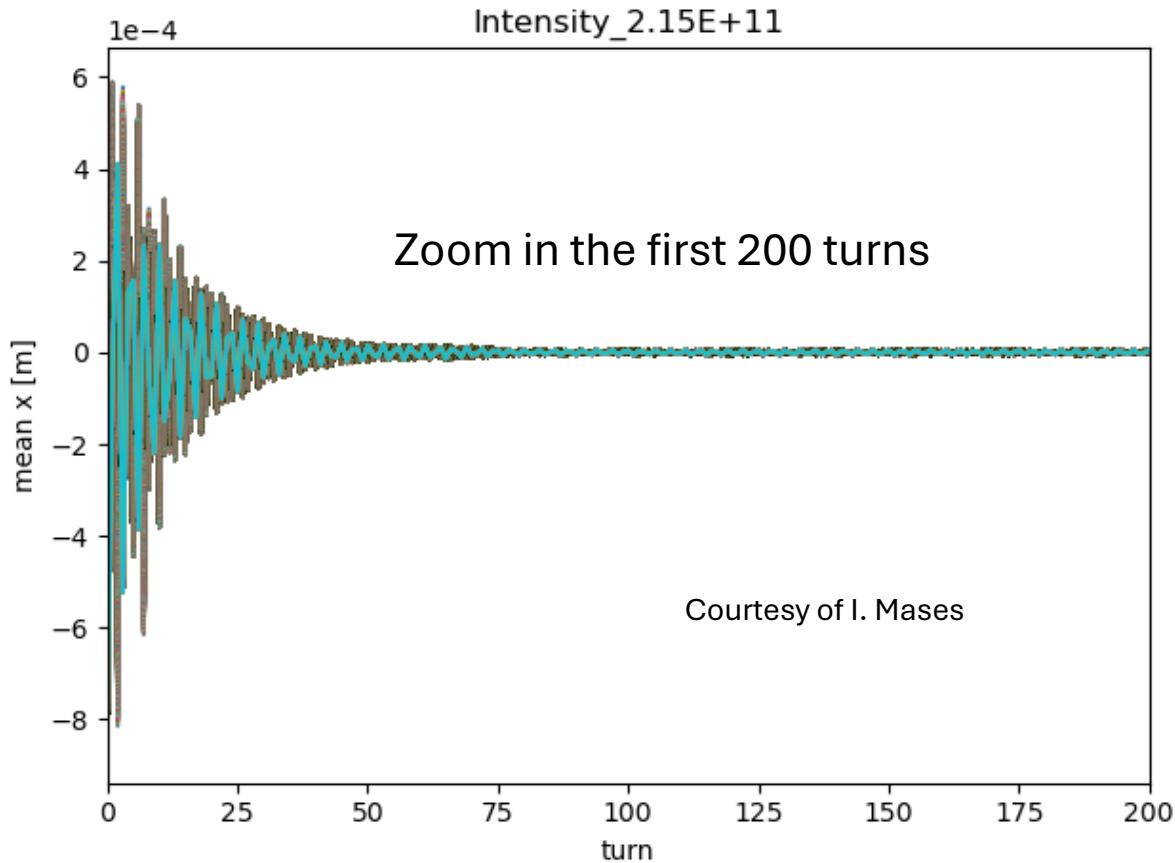
Set tunes:

$Q_x = 218.416$

$Q_y = 222.416$

Stable for damping time  $\leq 5$  turns

Chromaticity = 5



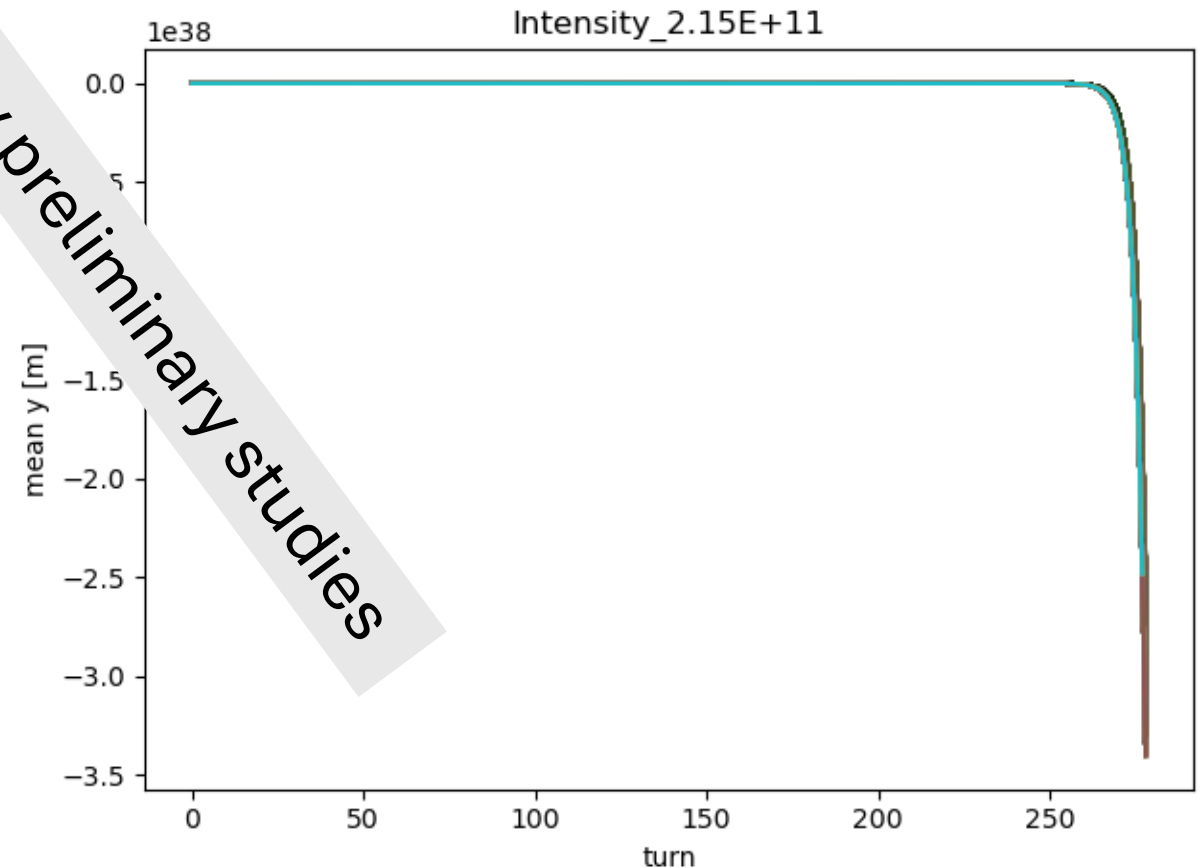
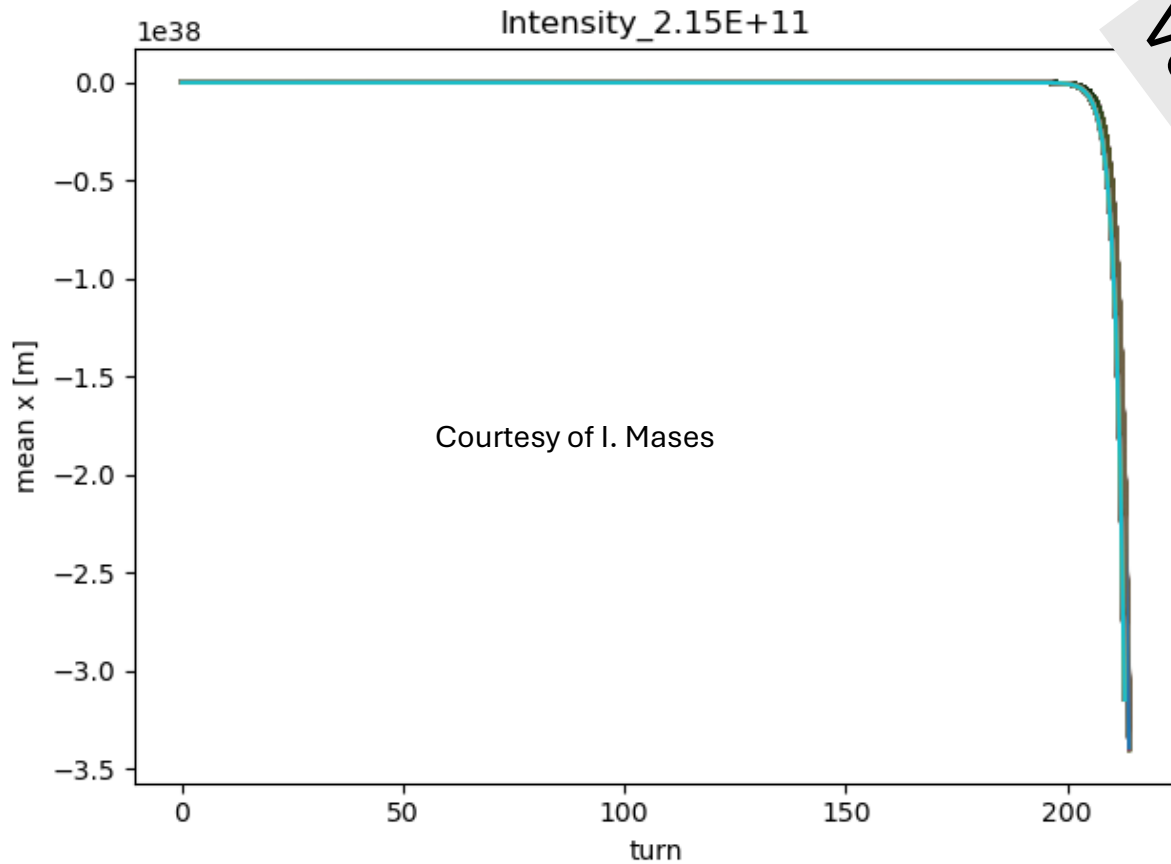
# Beam stability with multi-bunch beam Z configuration

Set tunes:

$Q_x = 218.198$

$Q_y = 222.232$

Stability at nominal tune extremely challenging. Unstable with 4 turns damper



Very preliminary studies

Simulations including beam-beam and more realistic damper model to be performed.  
**Stability with multiple bunches at the nominal working point looks challenging**

# Overview

- Introduction
- Impedance beam induced power
- FCC-ee impedance model
- Multi-bunch tune shift considerations
- **Summary**

# Summary

- FCC-ee challenging regime
  - Combination of large beam pipe dimensions and short bunch lengths
  - The beam pipe cut-off lies well within the relevant frequency spectrum
    - Significant crosstalk between different accelerator elements
- Follow-up design evolution ensuring impedance optimization
  - Update FCC-ee model accordingly
- Impedance beam induced power has a significant impact on the energy loss per turn from  $\sim 4\%$  to  $\sim 20\%$  depending on bunch length
- Impedance induced multi-bunch effects
  - Bunch-by-bunch tune shifts must be taken into account to define the filling strategy and the overall impedance budget
  - Stability at nominal working point looks critical due to very fast coupled bunch instability ( $\sim 2$  turns growth rate).
    - Studies including beam-beam and realistic feedback system are needed

**Thank you for your attention**