Impedance Modelling and Collective Effects in FCC-ee: Impact of Collimators and Optimization Strategies

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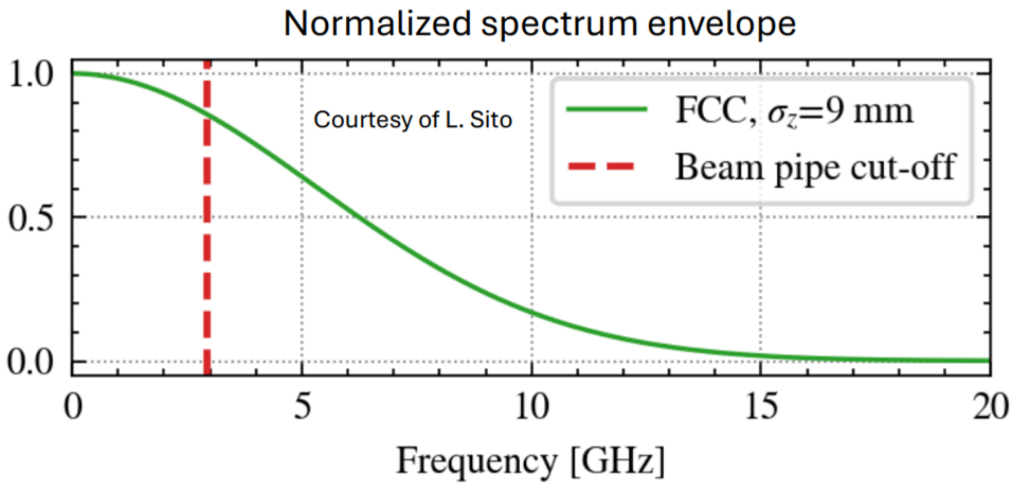
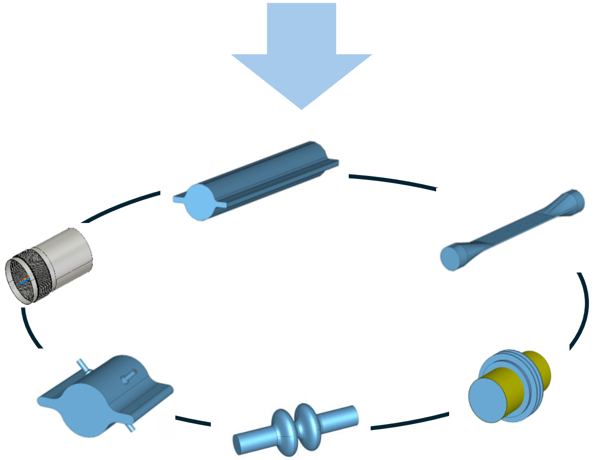
FCC-ee: impedance challenges

- **Model challenges:**
  - Necessity of a highly flexible impedance/wake (I/W) model in the development phase.
  - Improvement of devices' design after evaluation of impedance and impact on the machine.
  - Constant update of the FCC-ee impedance model.
- **Challenging simulation regime:**
  - Combination of large beam pipe dimension (30 mm radius) and short bunch lengths (5÷15 mm) ➔ computationally demanding simulations.
  - Very high number of mesh cells (~billions) in electromagnetic solvers ➔ CST.
  - Very high number of slices (~500) in tracking simulations ➔ Xsuite.
- **Beam pipe cut-off frequency:**
  - The beam pipe cut-off (~3 GHz) lies within the relevant frequency spectrum (up to ~20 GHz).
  - Modes above cut-off can be strongly excited ➔ leading to significant crosstalk between different devices.



FCC-ee main ring impedance model

Identify main impedance contributors



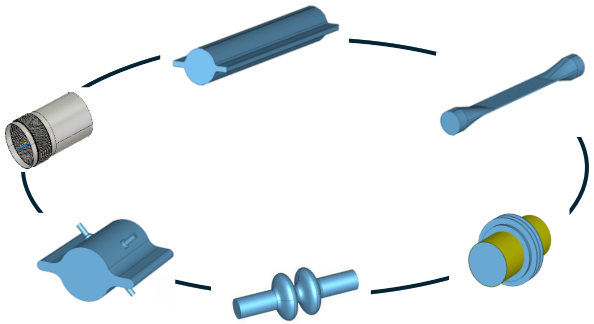
Updated elements in the FCC-ee I/W model:

- **beam pipe**: circular copper cross-section with a radius of 30 mm and two lateral winglets. Coated with a thin 150 nm layer of Non-Evaporable Getter (NEG)
- 41 collimators
- 132 single-cell 400 MHz RF cavities
- 10 000 BPMs
- 10 000 bellows
- tapers

FCC-ee main ring impedance model

Identify main impedance contributors

3D EM Simulations and Analytical Model



SIMULIA CST STUDIO SUITE

IRIS / IW2D · GitLab

Welcome - ECHO4D

zagorodnov/pyECHO4D

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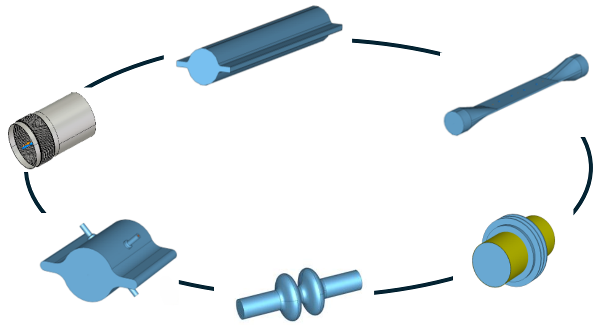
FCC-ee main ring impedance model

Identify main impedance contributors → 3D EM Simulations and Analytical Model → Accelerator I/W Model



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Beta function for the i^{th} element

$$Z_{\perp}(f) = \sum_{i=1}^{N} Z_{\perp}^{i}(f) \frac{\beta_{\perp}^{i}}{\langle \beta_{\perp} \rangle}$$

Transverse impedance for the i^{th} element

Average beta function

FCC-ee main ring impedance model

Identify main impedance contributors → 3D EM Simulations and Analytical Model → Accelerator I/W Model

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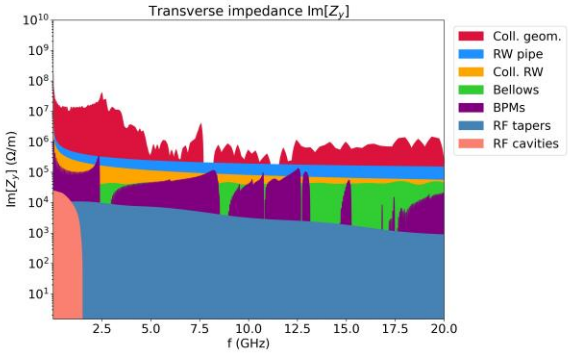

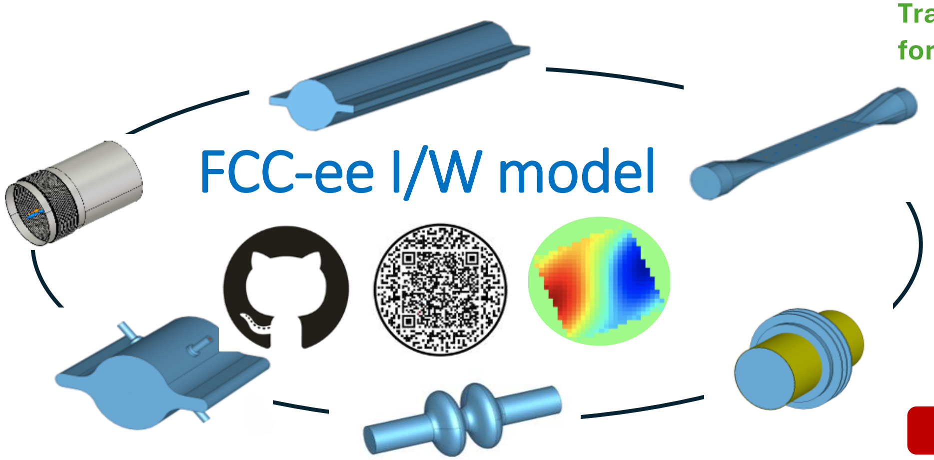

Modular and flexible

FCC-ee main ring impedance model

Identify main impedance contributors

3D EM Simulations and Analytical Model

Accelerator I/W Model

Beam Dynamics Simulations

Xsuite

FCC-ee main ring impedance model

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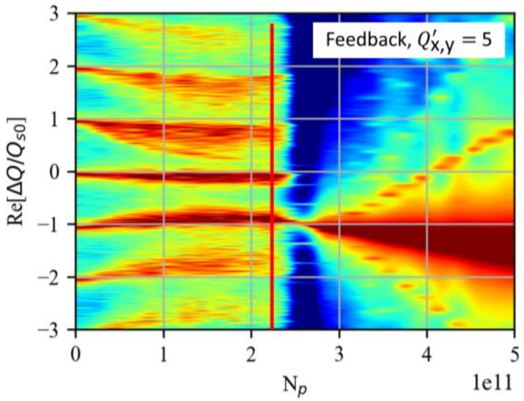
Beam Dynamics Simulations

Output:
Assessment of beam stability

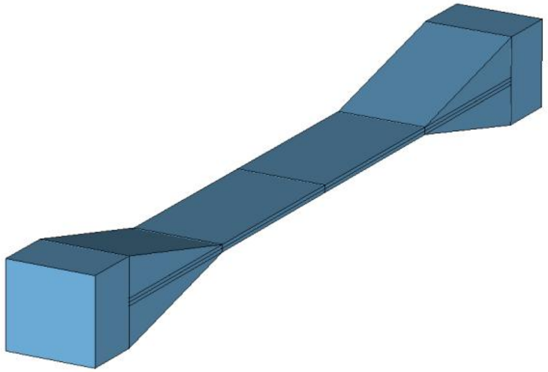


Xsuite

Collimation system: study process

Collimators were simulated in CST Studio Suite, initially using a simplified model ➔ step-by-step approach.

Schematic design



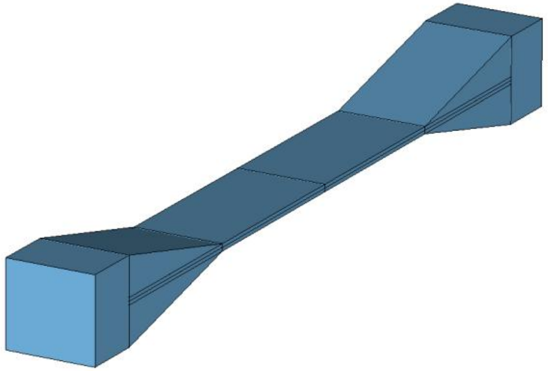
Despite its simplicity the model accurately reproduces the actual **jaw lengths** and **apertures** and effectively highlights critical parameters that can be optimized to mitigate impedance

By enabling the isolation of geometric effects, this model served as a baseline for next refinements

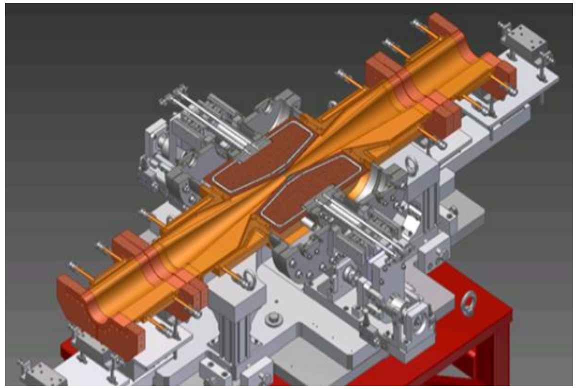
Collimation system: study process

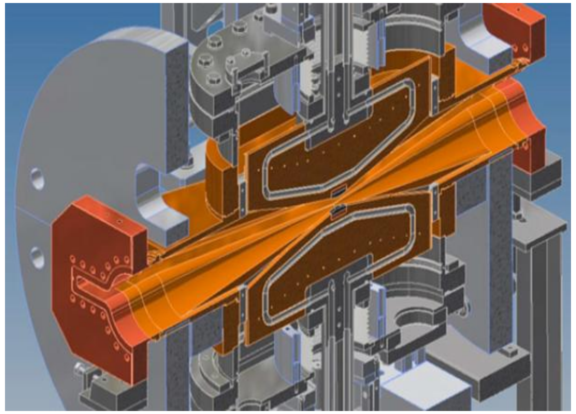
Design based on collimators for SuperKEKB.

Schematic design | Super KEKB design



3S SIMULIA
CST STUDIO SUITE

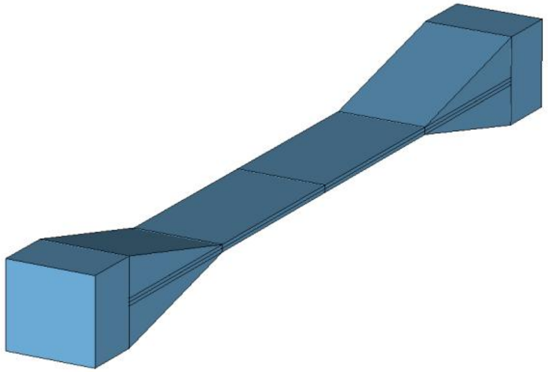




Collimation system: study process

Design based on collimators for SuperKEKB.

Schematic design | Winglets design



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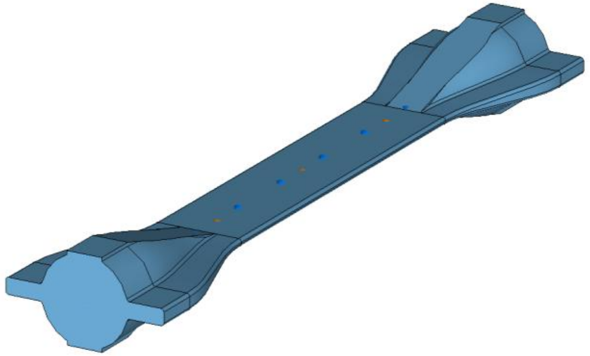

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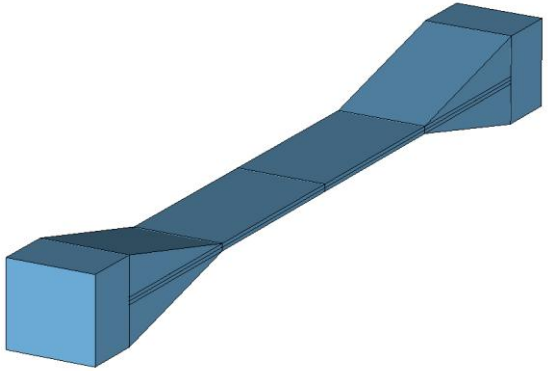
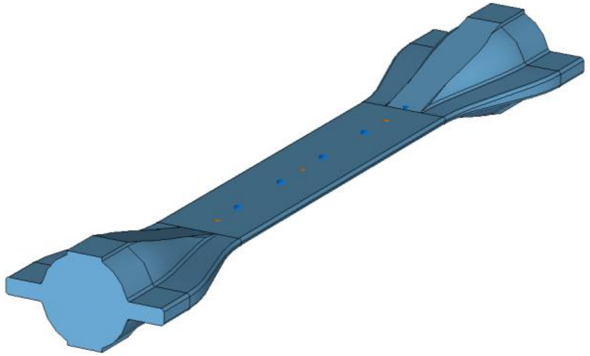
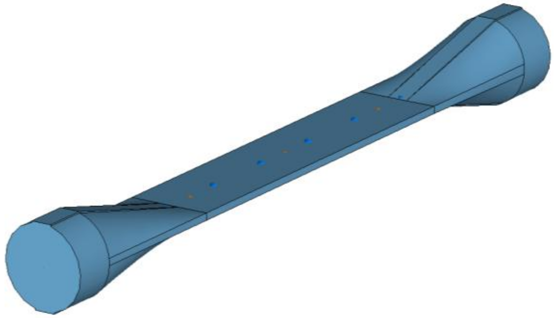
Collimation system: study process

Non- winglets design with round section.

Schematic design → Winglets design → Non-winglets design







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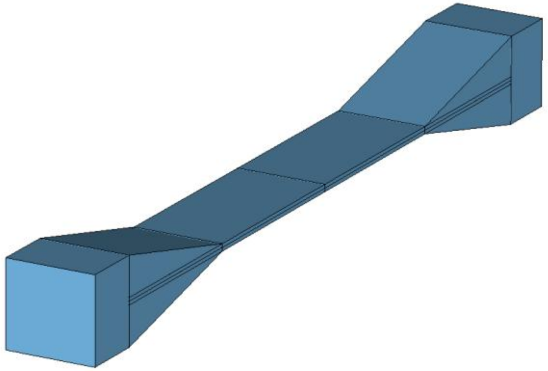
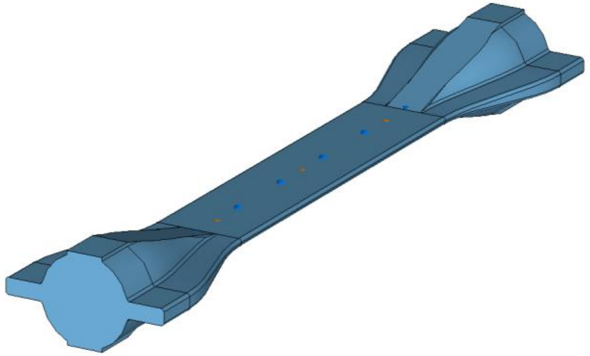
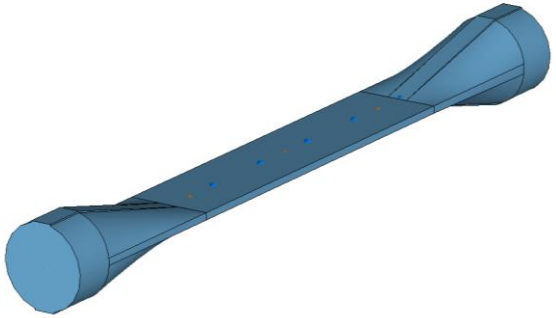
Collimation system: study process

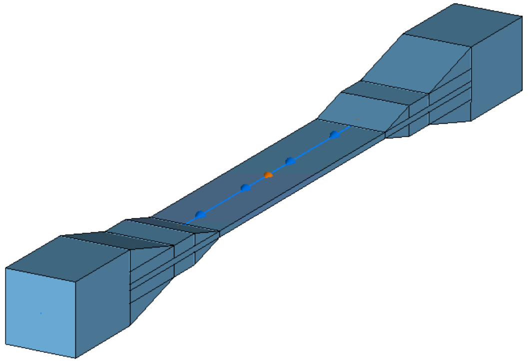
Final proposed design without winglets and step taper.

Schematic design | Winglets design | Non-winglets design | Step-taper design





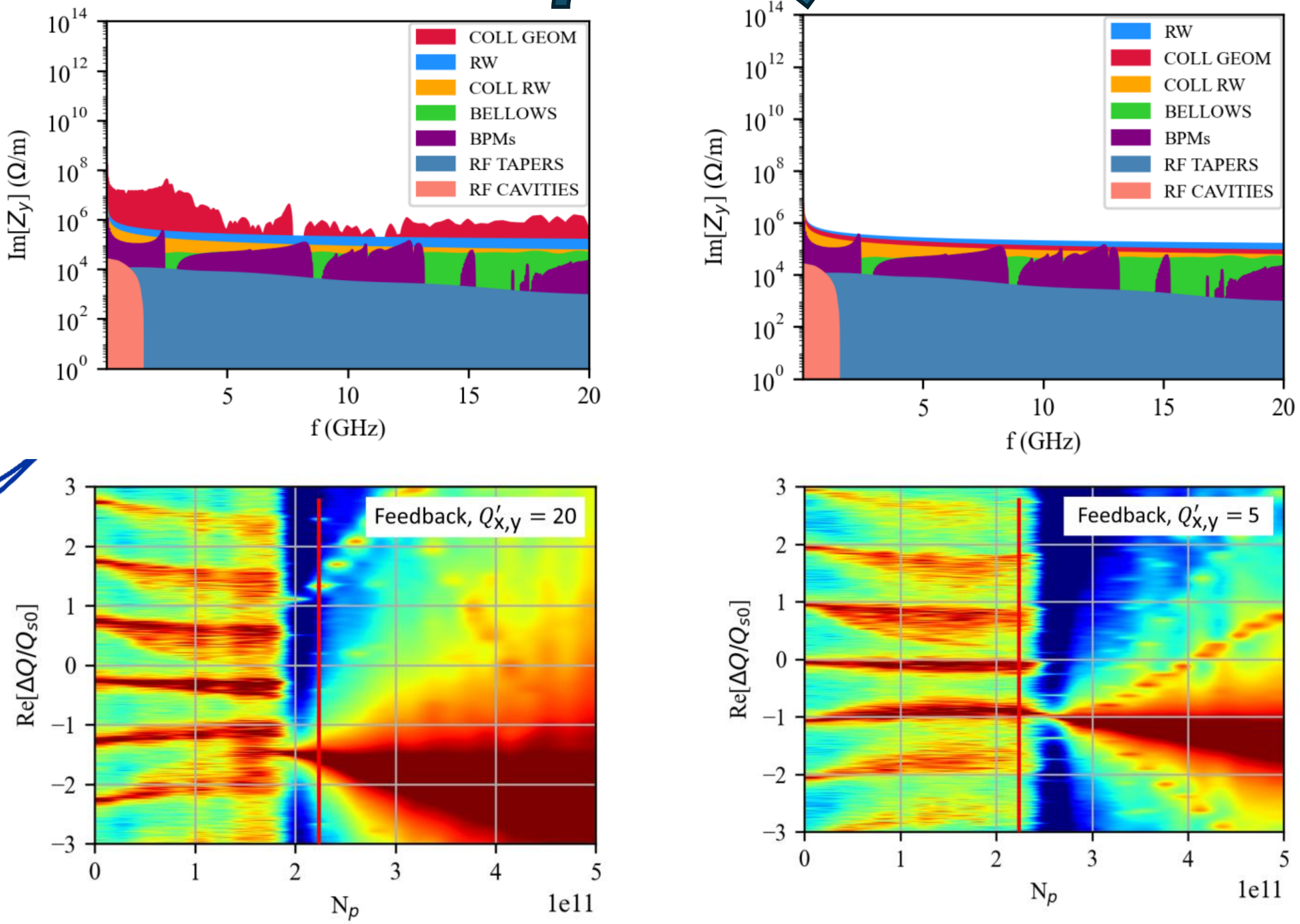




Criticality of the collimation system

Collimator geometrical impedance optimization

Beam dynamics simulations



Beam dynamics simulations

Unstable

Close to stability limit

Criticality of the collimation system

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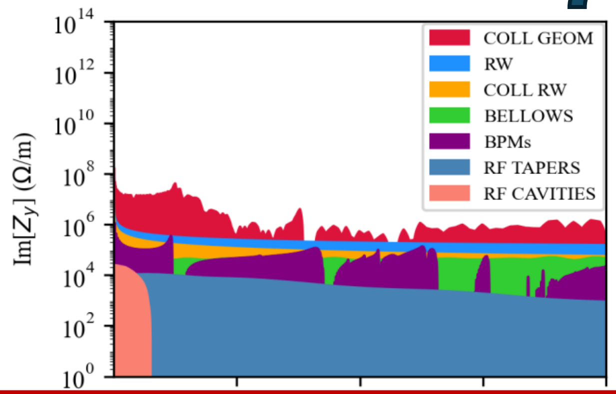
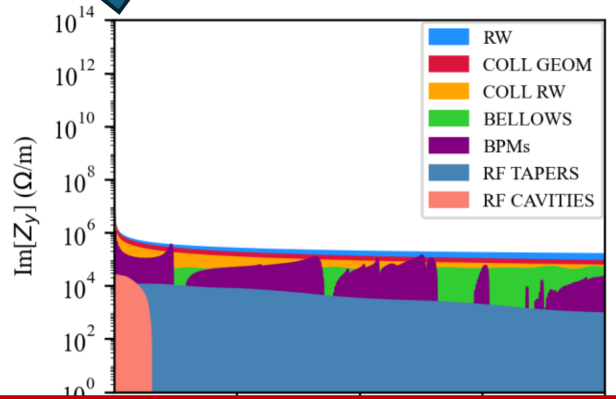
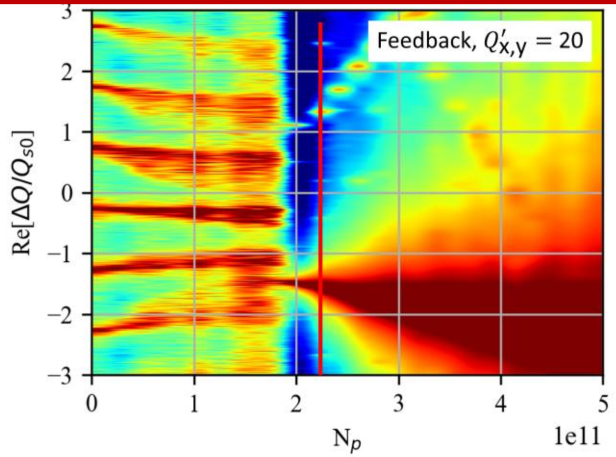


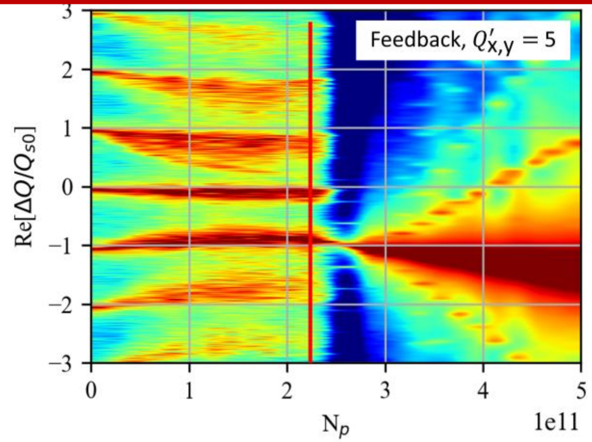


Beam dyna imulations

Further mitigation is essential to ensure robust beam stability



Unstable



Close to stability limit

Conclusion

- **Impedance/Wake model development for critical design decisions:**
  - The extremely **short bunch length** makes impedance and wakefield simulations highly **challenging**.
  - Ensured **model flexibility** to facilitate impedance and wakefield updates in optics, material choices, coating thickness, geometries, and new machine elements.
  - Enabled **impedance assessments** of different scenarios.

- **Criticality of the collimation system:**
  - A step-by-step approach is being adopted to explore computational limits and propose optimized impedance solutions.
  - Collimators geometrical impedance:
    - **Optimization strategy** → taper optimization.
      - Solutions developed in collaboration with the design and collimation groups to address spatial and mechanical constraints.
  - Collimators RW impedance:
    - Comparison between different optics layouts.
    - **Optimization strategy** → optics designed to maximize the collimator aperture and favour materials with high electrical conductivity.

Next steps and ongoing activities

- **I/W Model updates & implementation:**
  - Finalize the full **impedance database** for the **collimation system**, including impedance estimations for
  - The new operating optics version expected by September 2025. The goal is to converge on a definitive
  - Optics layout by March 2026.
  - Establish a reliable and comprehensive methodology for evaluating the **geometric impedance** contributions of collimators, ensuring accuracy across all design variants.
  - Explore novel **collimator materials** and geometries in close collaboration with the collimation technical design teams, with a focus on reducing impedance while respecting mechanical constraints.
  - Continuous **FCC-ee I/W model updates** in line with the evolving design of components, ensuring timely integration of new elements as they are defined ➔ Ensure model **flexibility.**

- **Beam dynamics simulations:**
  - Investigate beam dynamics under **non-ideal feedback systems** and propose improved feedback strategies.
  - **Multi-bunch feedback system** simulations to assess beam stability with multiple bunches.
  - Integration of **advanced feedback** features from **PyHEADTAIL multi-bunch** into **Xsuite**.

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Thank you for your attention ☺

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Full paper