Impact of Collimators' Geometric Impedance on Beam Stability in the FCC-ee Analysis and Optimization Techniques

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Outline

- Introduction
  - FCC-ee main parameters for Z configuration
  - FCC-ee main ring impedance model

- FCC-ee beam coupling impedance of the collimation system
  - Collimators geometrical impedance
    - Optimization strategies
  - Collimators RW impedance
    - Comparison between different optics

- Conclusion and next steps

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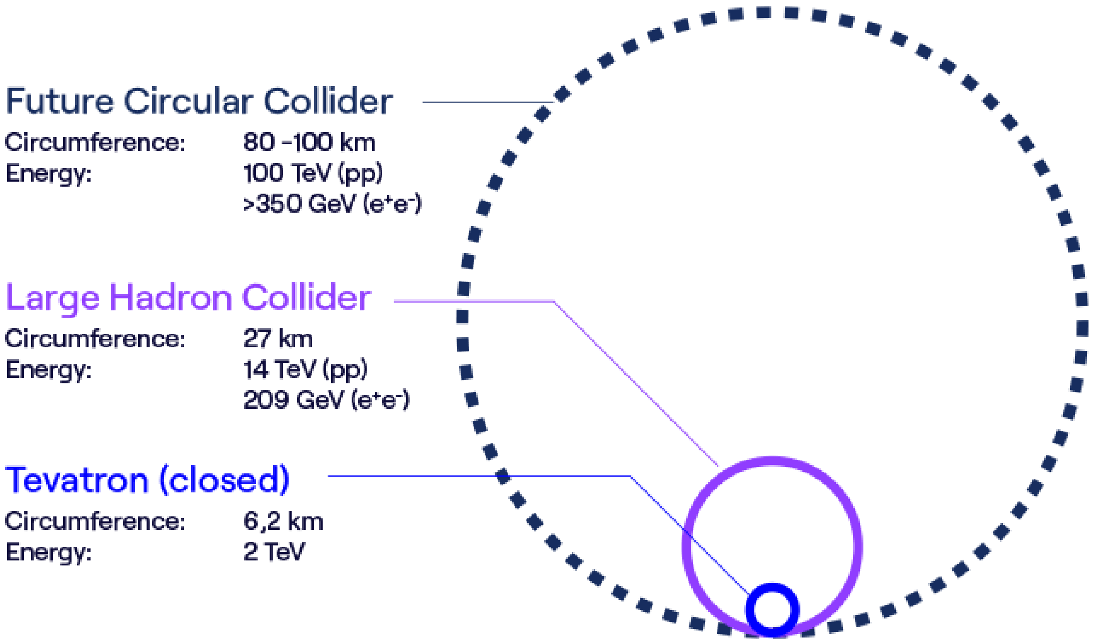
FCC-ee main parameters for Z configuration

Parameter	Value
Circumference (km)	90.658816
Beam energy (GeV)	45.6
Bunch population (10^{11})	2.18
RF frequency (MHz)	400
RF voltage (MV)	88.5
Energy loss per turn (GeV)	0.0391
Longitudinal dumping time (turns)	1158
Momentum compaction factor 10^{-6}	28.6
Horizontal tune/IP	54.5395
Vertical tune/IP	55.55
Synchrotron tune	0.0288
Emittance Hor (nm)/Vert (pm)	0.71/2.1
Bunch length (mm) (SR/BS)*	5.15/15.2
Energy spread (%) (SR/BS)*	0.039/0.115
Piwinsky angle (BS)*	25.8
ξ_x/ξ_y	0.023/0.098
β* Hor (m)/Vert (mm)	0.11/0.7
Luminosity/IP (10^{34}/cm^{2}s)	144

*SR: synchrotron radiation, BS: beamstrahlung



Necessity of having a highly flexible model to account for all changes during the feasibility study development phase

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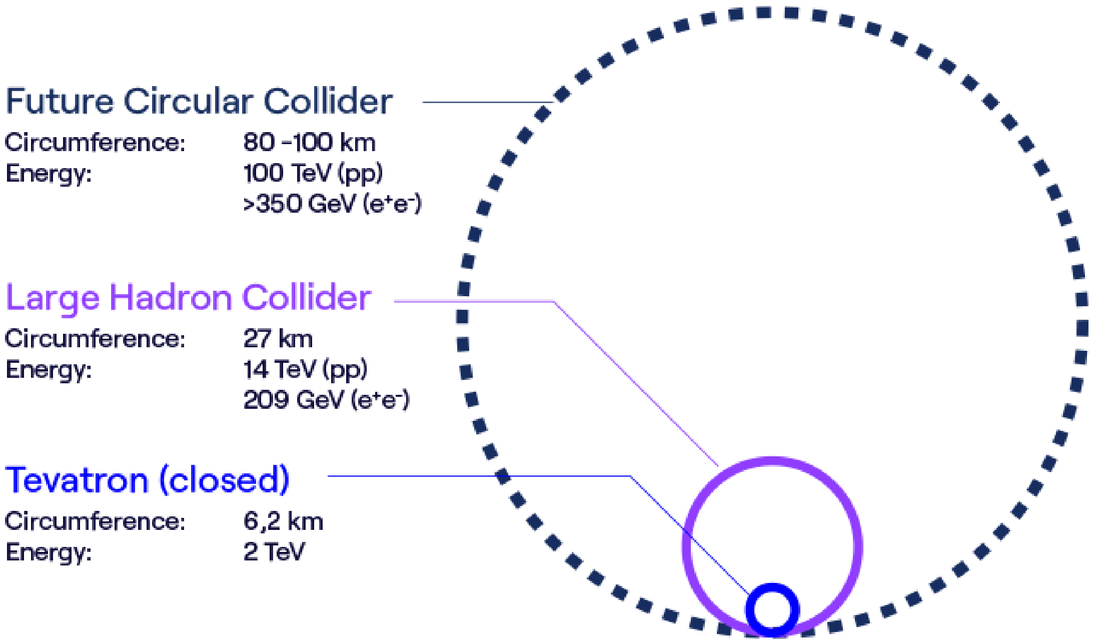
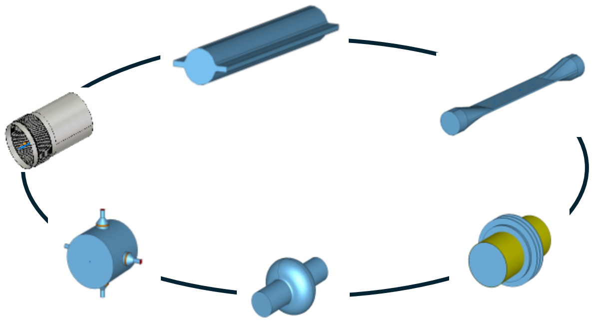


Necessity of having a highly flexible model to account for all changes during the feasibility study development phase

FCC-ee main ring impedance model

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



SIMULIA CST STUDIO SUITE

IRIS / IW2D · GitLab

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

FCC-ee main ring impedance model

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

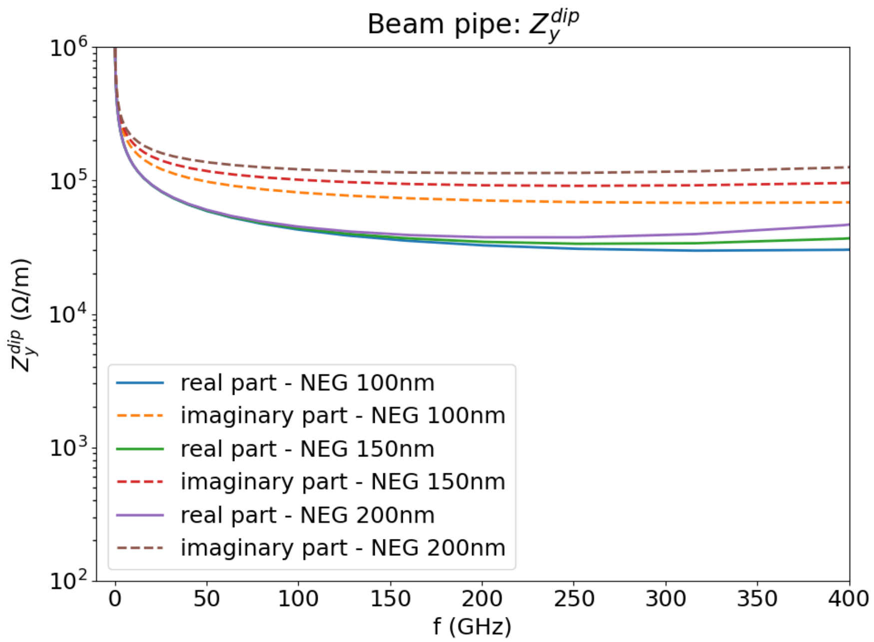
FCC-ee I/W model

[ImpedanCEI/fcc_ee_IW_model: Impedance/Wake model of the Future Circular Collider (FCC)]

Highly flexible I/W model

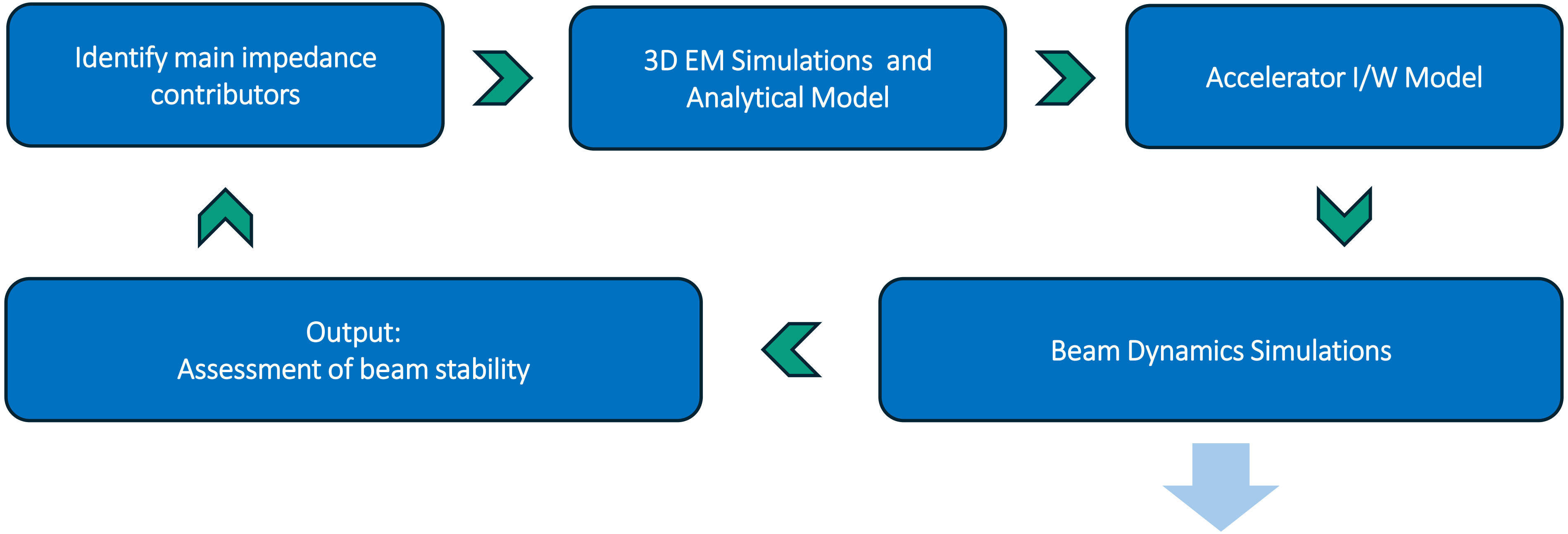
Identify main impedance contributors → 3D EM Simulations and Analytical Model → Accelerator I/W Model

Flexible & modular model



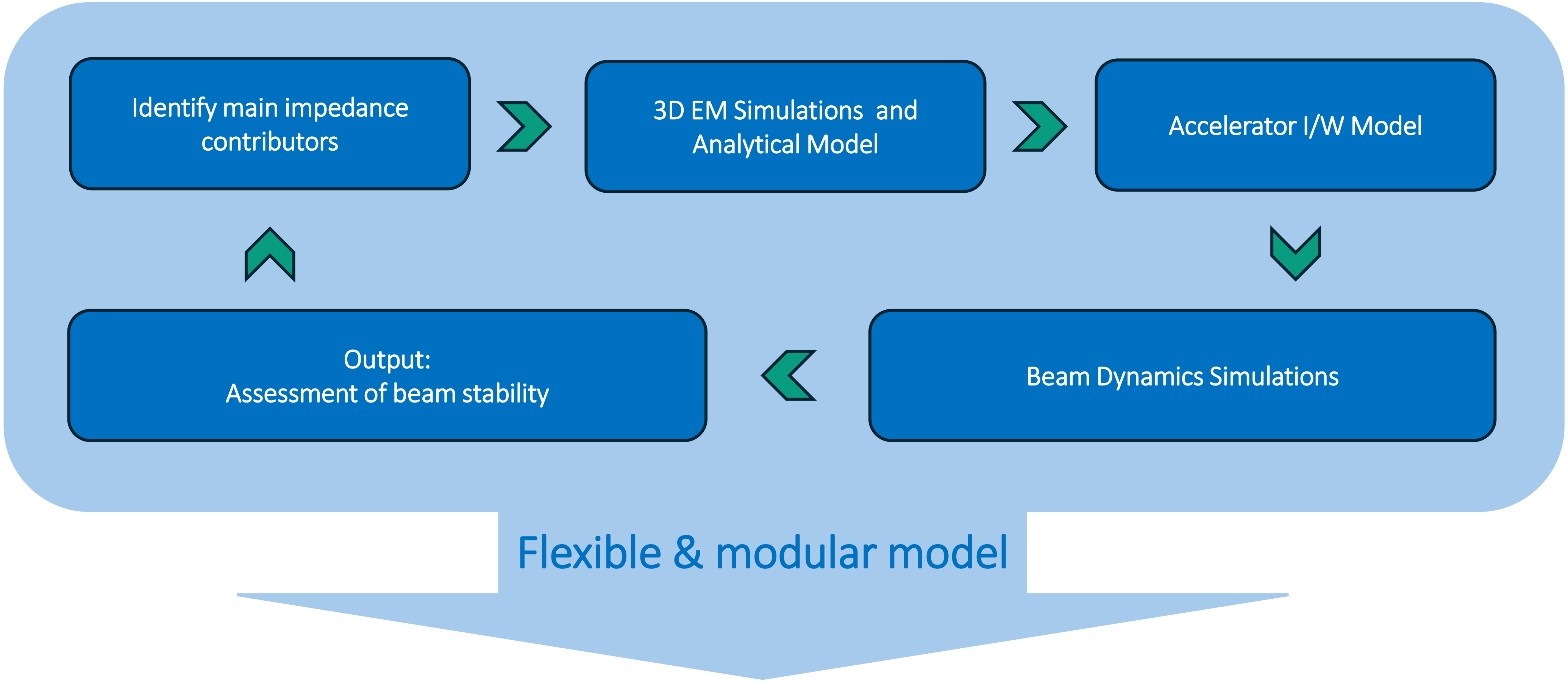
Thanks to its flexibility, the developed model integrates seamlessly with IW2D. Variations in material properties or coating thickness—such as changes to the NEG coating of the beam pipe—can be readily incorporated, enabling rapid evaluation of their impact on the overall impedance.

FCC-ee main ring impedance model



Xsuite

FCC-ee main ring impedance model



Constant Model Optimization

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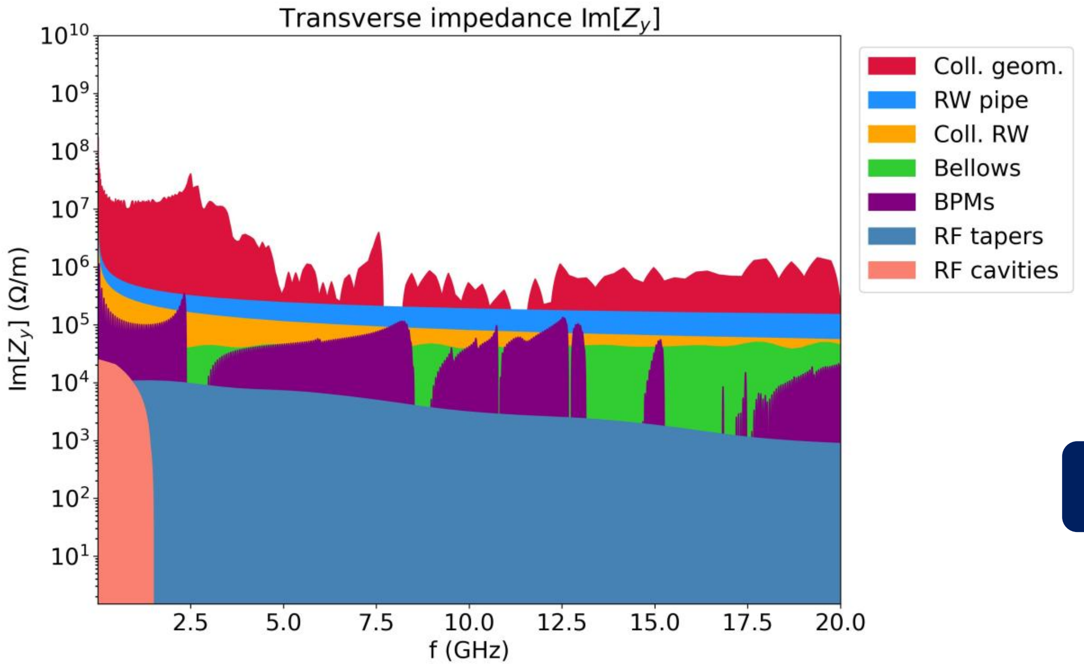
Criticality of the collimation system

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

FCC-ee I/W model

The visualization of certain parameters, such as the imaginary part of the y-dipolar impedance of various contributors, enables the identification of the primary impedance sources.



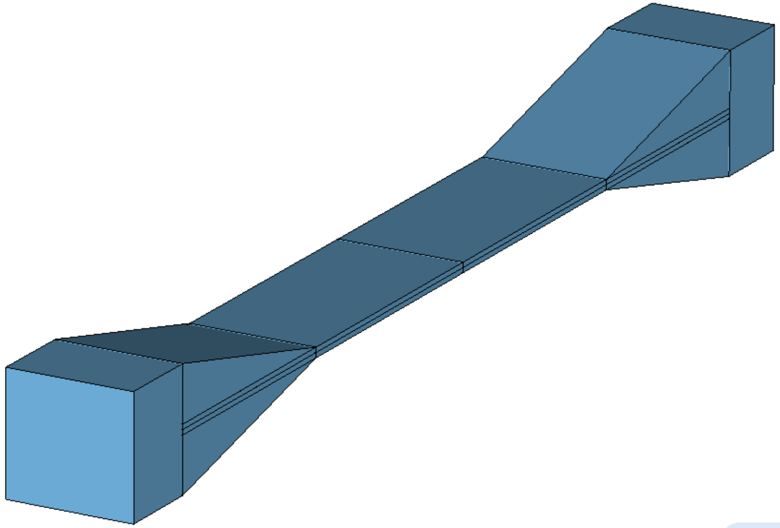
Collimation optics:

FCCee_z_v23_coll_TCTs

Collimation system: study process

Collimators were simulated in CST Studio Suite, initially using a simplified model to isolate geometric and resistive wall dependencies.

Schematic design



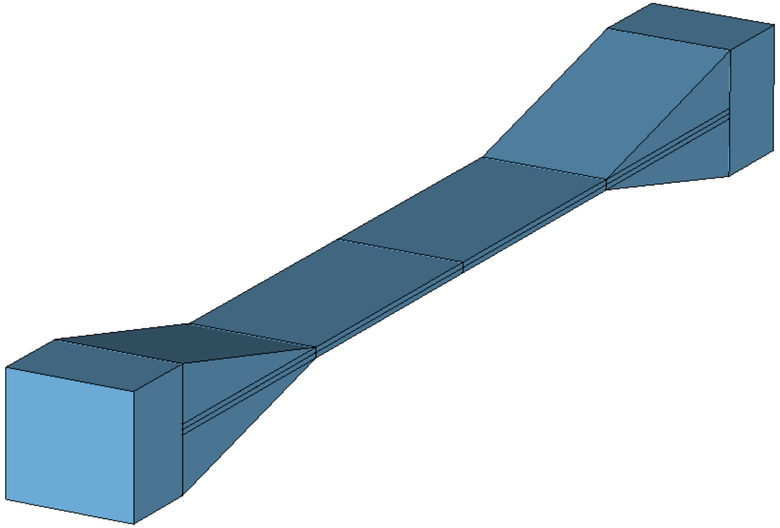
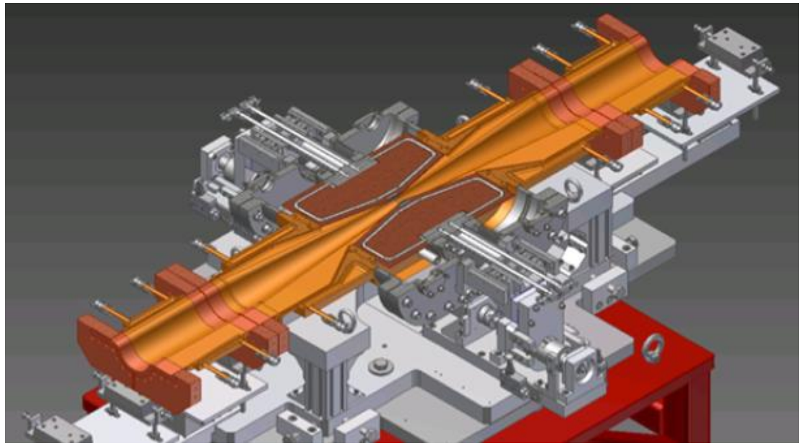
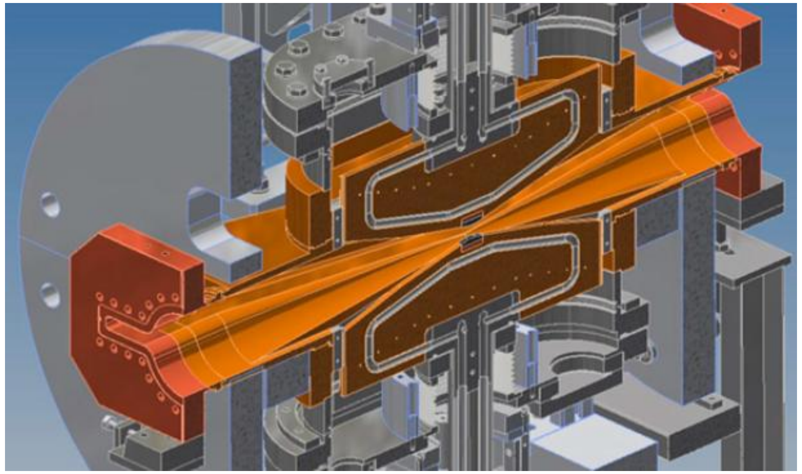
While previous models accounted only for the resistive wall (RW) contribution, this study includes both resistive and geometric effects, enabling a more comprehensive understanding of the system's impact on beam stability.

The model accurately reproduces the actual **jaw lengths** and **apertures** and effectively highlights critical parameters that can be optimized to mitigate impedance.
A **linear taper** with an angle of **15 degrees** was initially proposed.

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.

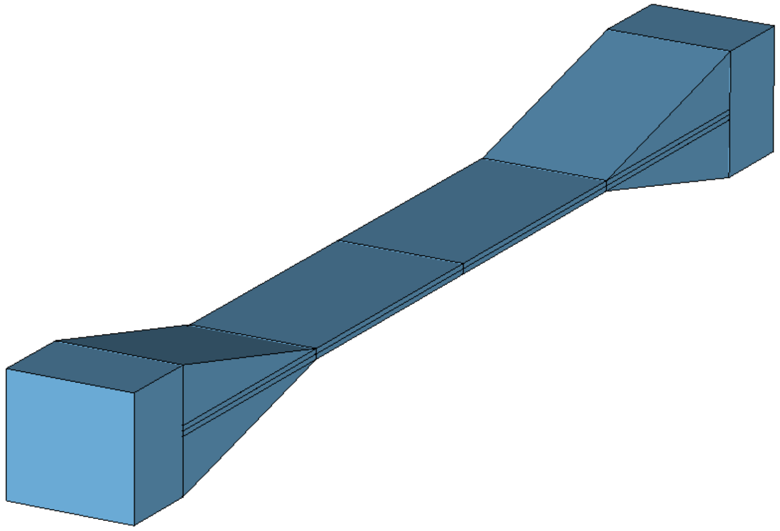
Schematic design	SuperKEKB design
	 

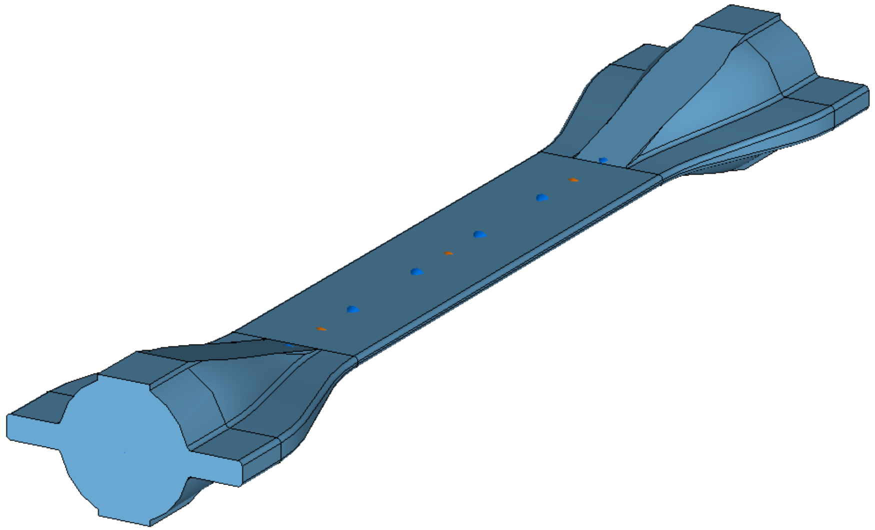
Courtesy of Regis Seidenbinder

Collimation system: study process

Design based on collimators for SuperKEKB, with circular pipe and winglets.

Schematic design | **Winglets design**

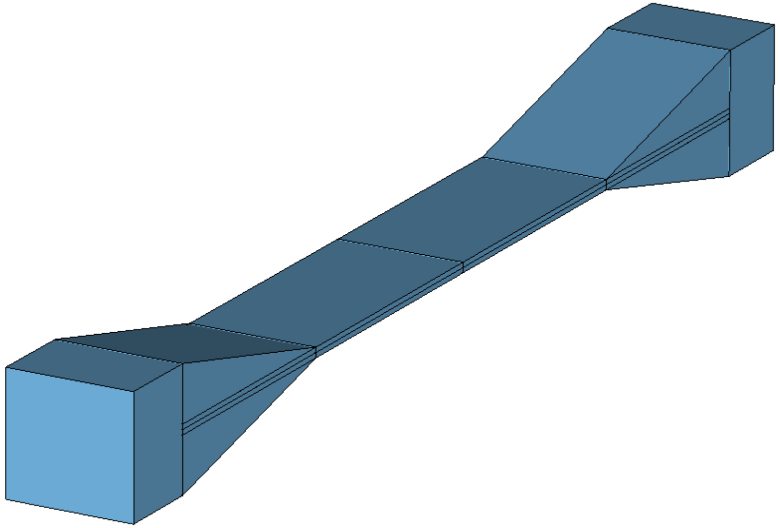


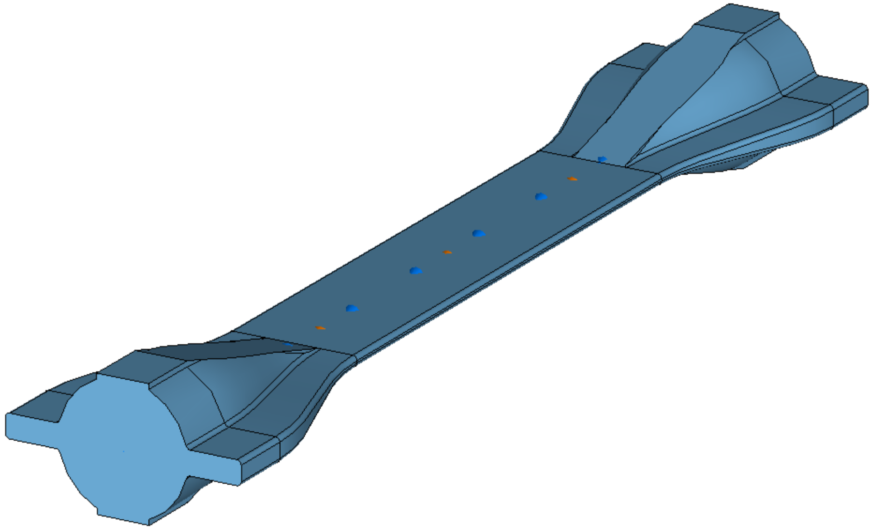


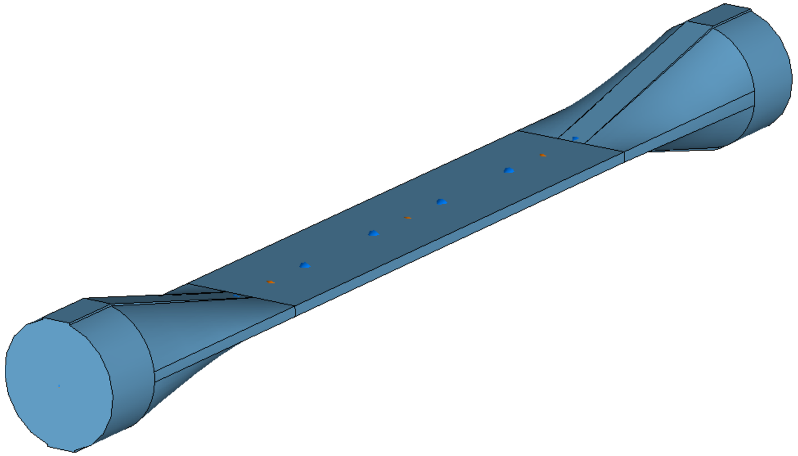
Collimation system: study process

Final proposed design with circular pipe without winglets at the collimator injection.

Schematic design | Winglets design | Non-winglets design

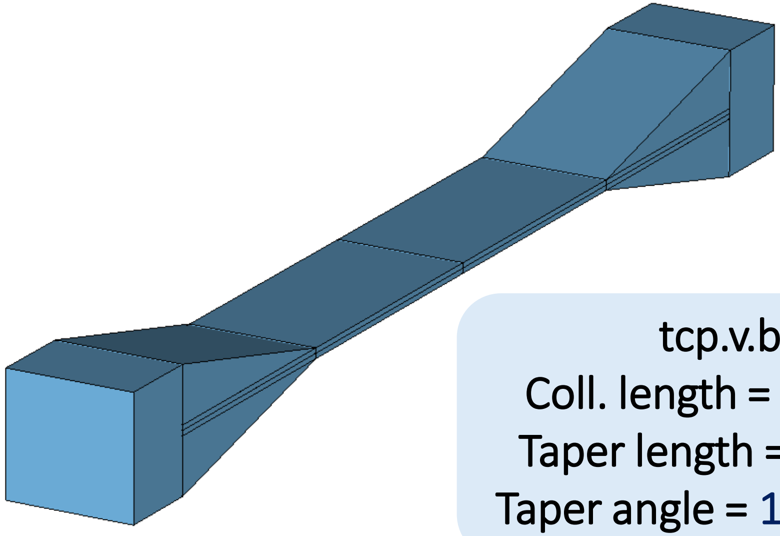




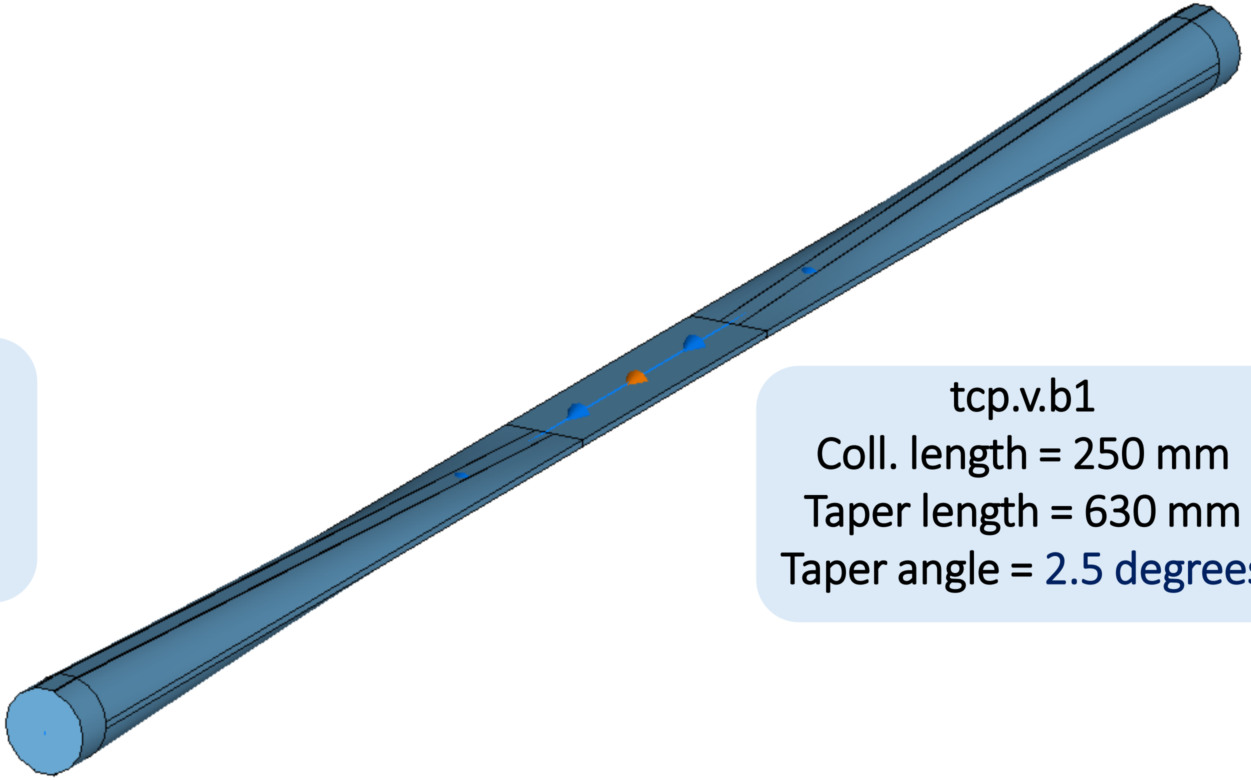


Optimization strategies

Since the geometrical contribution of the collimators has been identified as the **primary source of impedance**, an **optimization** of the **taper angle** for **all vertical collimators** has been proposed, reducing it from 15 degrees to 2.5 degrees. The most recent optimization refers to latest collimators design.



tcp.v.b1
Coll. length = 250 mm
Taper length = 110mm
Taper angle = 15 degrees



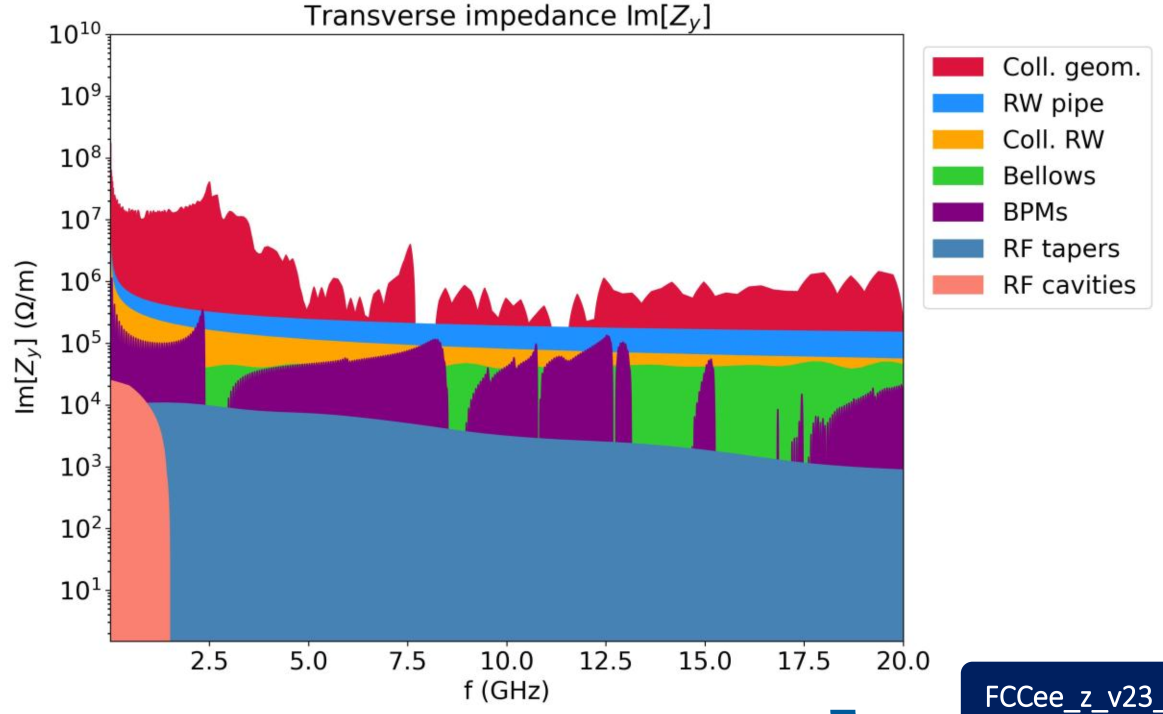
tcp.v.b1
Coll. length = 250 mm
Taper length = 630 mm
Taper angle = 2.5 degrees

It is worth noting that the achievable taper angle could be limited by spatial and mechanical constraints

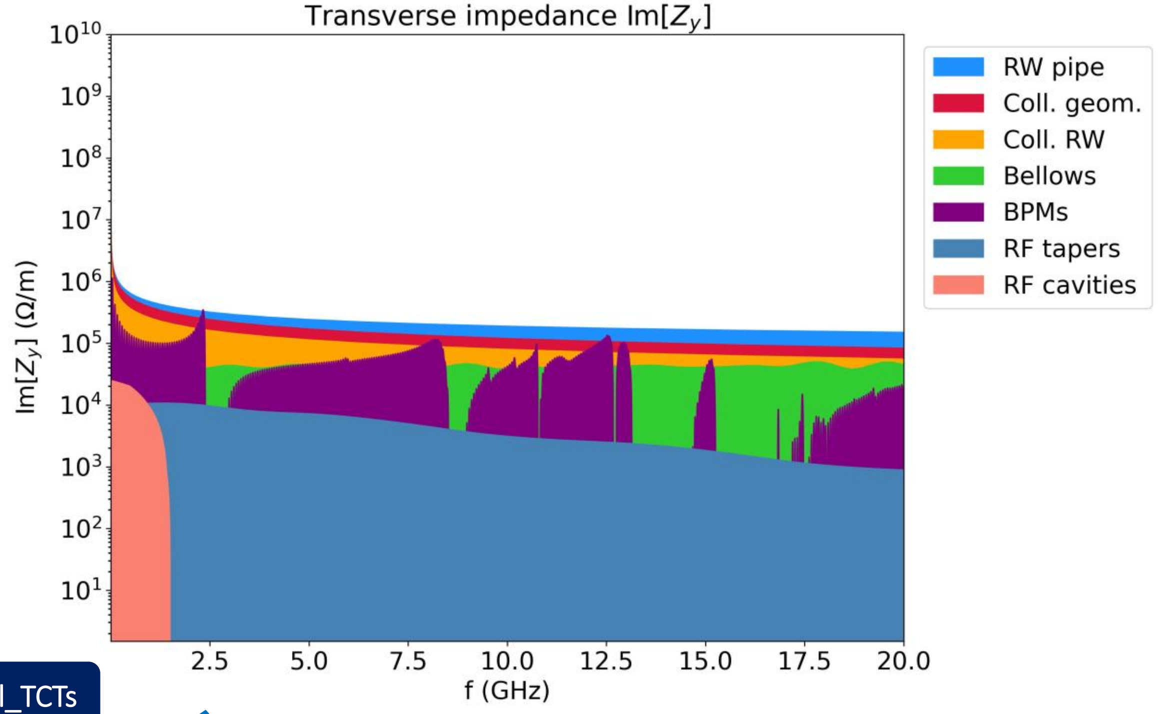
Geometrical impedance mitigation

Thanks to the **optimization** of the **taper angle** for **all vertical collimators** by reducing it from 15 degrees to 2.5 degrees, the **y-transverse impedance drastically reduces**.

Horizontal and vertical collimator taper angle of 15 degrees



Horizontal collimator taper angle of 15 degrees and vertical taper angle of 2.5 degrees



FCCee_z_v23_coll_TCTs

Optimization

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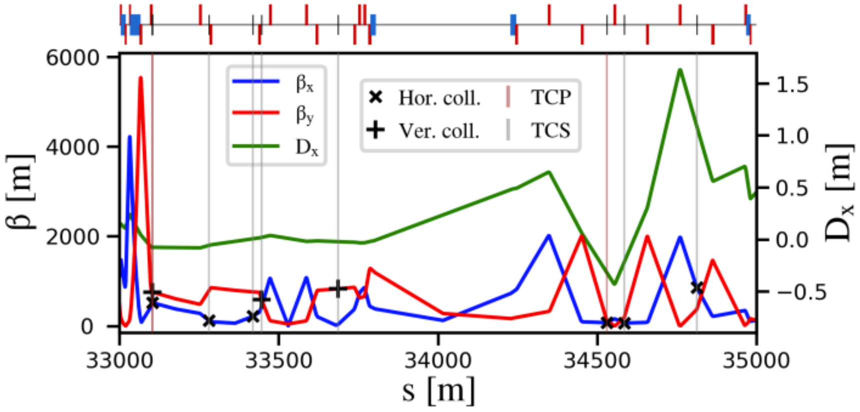
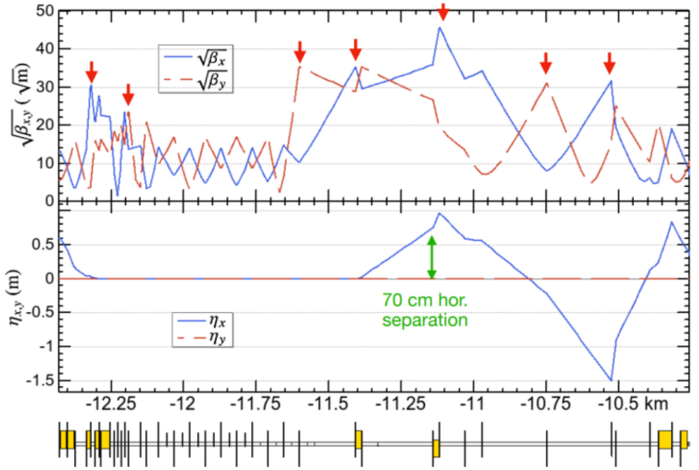
Comparison between different optics

Different optics have been analyzed:

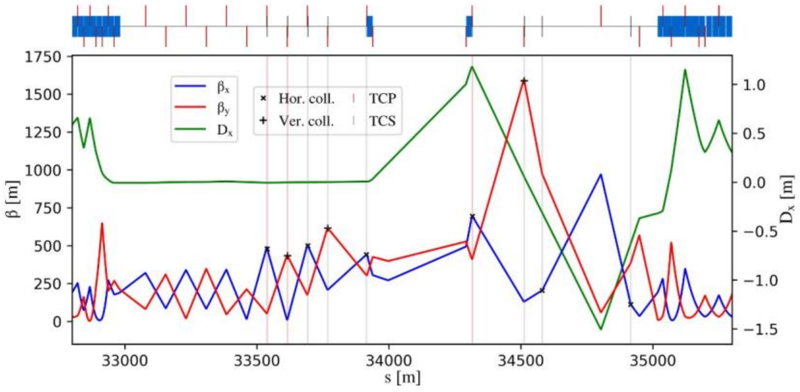
v23	V24.4	V25.2



K. Oide: FCCWeek_Optics_Oide_230606



K. Oide: Optics_Oide_241106



K. Oide: Optics_Oide_bx*:techi_250424

Collimation optics: v23

Collimator parameters from the version 23 of the collimation layout optics. The current layout consists of **17 beam halo collimators** - 3 primary, 6 secondary, and 8 tertiary units- and **24 synchrotron radiation (SR)** collimators. Among these, the main contributors to the overall impedance are listed below.

Name	Length (m)	gap/2 (mm)	Material	β_x (m)	β_y (m)
tcp.h.b1	0.25	6.7	MoGr	517.98	755.84
tcp.v.b1	**0.25**	**2.5**	**MoGr**	**519.09**	**756.98**
tcs.h1.b1	0.3	3.8	Mo	117.58	789.74
tcs.v1.b1	0.3	2.5	Mo	421.47	587.39
tcs.h2.b1	0.3	5.1	Mo	214.69	759.20
tcs.v2.b1	0.3	3.0	Mo	32.80	827.50
tcp.hp.b1	0.25	4.2	MoGr	72.05	125.94
tcs.hp1.b1	0.3	4.6	Mo	64.12	186.88
tcs.hp2.b1	0.3	16.7	Mo	855.10	368.74
tcr.h.wl.2.b1	0.1	17	W	2056.83	8840.68
-	-	-	-	-	-
-	-	-	-	-	-
tcr.h.c2.1.b1	0.1	16	W	2099.51	5012.40

tcp: primary, tcs: secondary, tcr: synchrotron radiation, h: horizontal, v: vertical, $\sigma_{MoGr} = 10^6\ S/m$, $\sigma_{Mo} = 1.8\ 10^7\ S/m$, $\sigma_W = 1.8\ 10^7\ S/m$. . Table courtesy of Giacomo Broggi.

Due to **small half-gaps** and **large beta functions**, primary collimators contribute significantly to transverse RW impedance, with collimator tcp.v.b1 identified to be the most critical.

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

Collimation optics: v24.4

Collimator parameters from version 24.4 of the collimation layout optics, which includes **17 beam halo collimators** and **24 synchrotron radiation (SR)** collimators. Particular attention is given to changes in the **vertical primary collimator** tcp.v.b1, which plays a critical role in the overall impedance of the collimation system.

Name	Length (m)	gap/2 (mm)	Material	β_x (m)	β_y (m)
tcp.h.b1	0.25	10.4	MoGr	911.81	34.32
tcp.v.b1	**0.25**	**1.7**	**MoGr**	**188.47**	**532.53**
tcs.h1.b1	0.3	5.0	Mo	185.29	35.39
tcs.h2.b1	0.3	5.0	Mo	183.71	102.12
tcs.v1.b1	0.3	1.6	Mo	50.78	278.68
tcs.v2.b1	0.3	1.6	Mo	24.68	262.12
tcp.hp.b1	0.25	18.4	MoGr	994.99	218.02
tcs.hp1.b1	0.3	5.5	Mo	74.63	285.37
tcs.hp2.b1	0.3	2.9	Mo	21.22	298.16
tcr.h.wl.2.b1	0.1	21.7	Inermet180	3036.07	4953.05
-	-	-	-	-	-
-	-	-	-	-	-
tcr.h.c2.1.b1	0.1	16.96	Inermet180	1851.88	5017.33

tcp: primary, tcs: secondary, tcr: synchrotron radiation, h: horizontal, v: vertical, , $\sigma_{MoGr} = 10^6\ S/m$, $\sigma_{Mo} = 1.8\ 10^7\ S/m$, $\sigma_{inermet180} = 1.05\ 10^7\ S/m$. Table courtesy of Giacomo Broggi.

Compared to v23 for tcp.v.b1, there was a decrease in the **half-gap**:
2.5 mm ➔ 1.7 mm

Decrease of β_y:
756.98 m ➔ 352.53 m

$$Z_\perp(f) \propto 1/gap^3$$

$$Z_\perp(f) \propto \beta$$

Collimation optics: v25.2

Collimator parameters from version 25.2 of the collimation layout optics, which includes **17 beam halo collimators** and **24 synchrotron radiation (SR)** collimators. Importance to highlight the changes on the **vertical primary collimator** tcp.v.b1, which plays a critical role in the overall impedance of the collimation system.

Name	Length (m)	gap/2 (mm)	Material	β_x (m)	β_y (m)
tcp.h.b1	0.25	5.8	MoGr	511.92	54.50
tcp.v.b1	**0.25**	**1.4**	**MoGr**	**12.16**	**432.13**
tcs.h2.b1	0.3	6.5	Mo	513.94	182.99
tcs.v1.b1	0.3	2.2	Mo	219.74	620.70
tcs.h1.b1	0.3	6.2	Mo	467.70	309.59
tcp.hp.b1	0.25	12.5	MoGr	654.03	413.61
tcs.v2.b1	0.3	3.6	Mo	127.59	1575.71
tcs.hp1.b1	0.3	11.0	Mo	209.69	965.22
tcs.hp2.b1	0.3	8.3	Mo	118.34	390.65
tcr.h.wl.2.b1	0.1	20.4	Inermet180	4253.95	5717.45
-	-	-	-	-	-
-	-	-	-	-	-
tcr.h.c2.1.b1	0.1	18.0	Inermet180	3323.15	5366.42

tcp: primary, tcs: secondary, tcr: synchrotron radiation, h: horizontal, v: vertical, , $\sigma_{MoGr} = 10^6\ S/m$, $\sigma_{Mo} = 1.8\ 10^7\ S/m$, $\sigma_{inermet180} = 1.05\ 10^7\ S/m$. Table courtesy of Giacomo Broggi.

Compared to v23 for tcp.v.b1, there was a decrease in the **half-gap**:
2.5 mm ➔ 1.4 mm

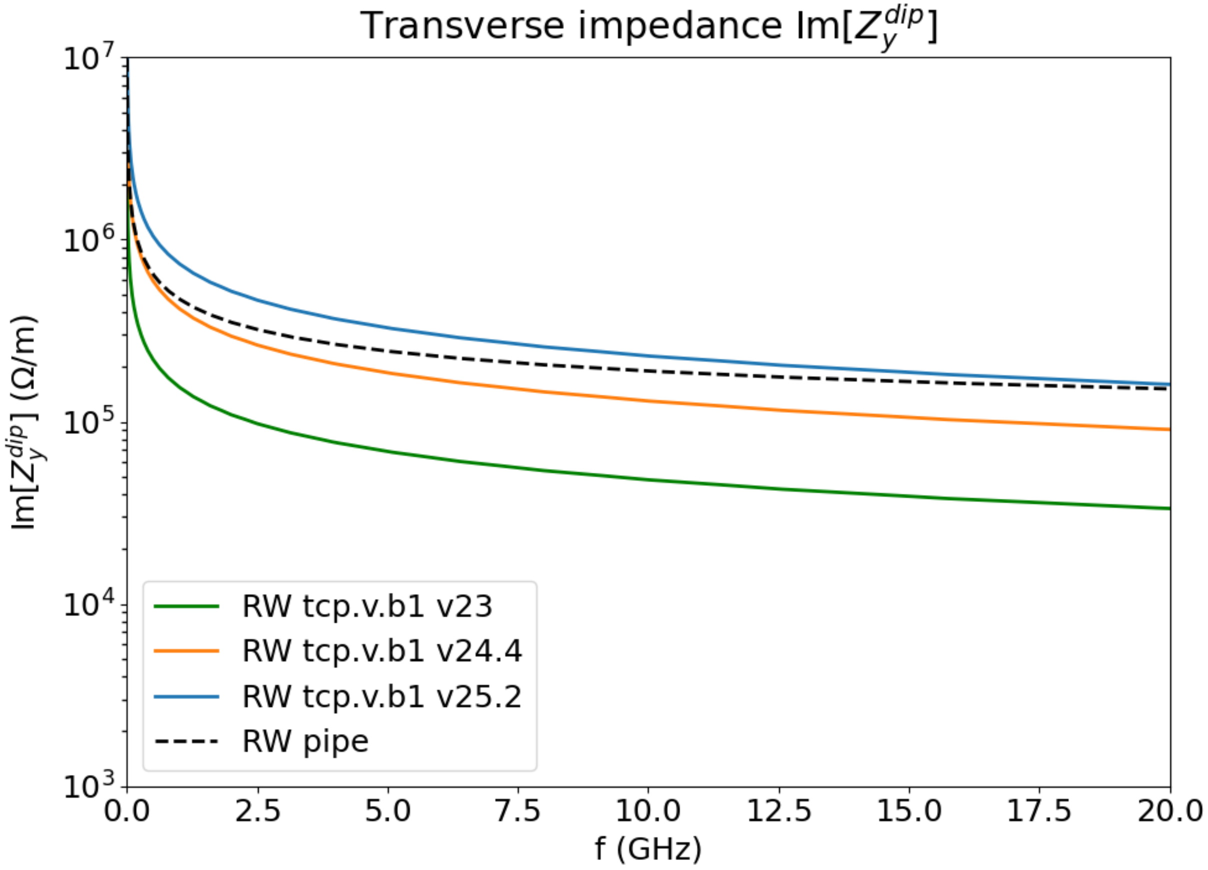
Decrease of β_y:
756.98 m ➔ 325.49 m

$$Z_\perp(f) \propto 1/gap^3$$

$$Z_\perp(f) \propto \beta$$

Comparison between different optics

To highlight the impact of the new collimation optics, the **RW impedance** of the **vertical collimator** tcp.v.b1 under different optics is compared with that of the **circular copper pipe**, with **30 mm radius** and **150 nm NEG coating**. The plot presents the imaginary part of the vertical dipolar impedance.



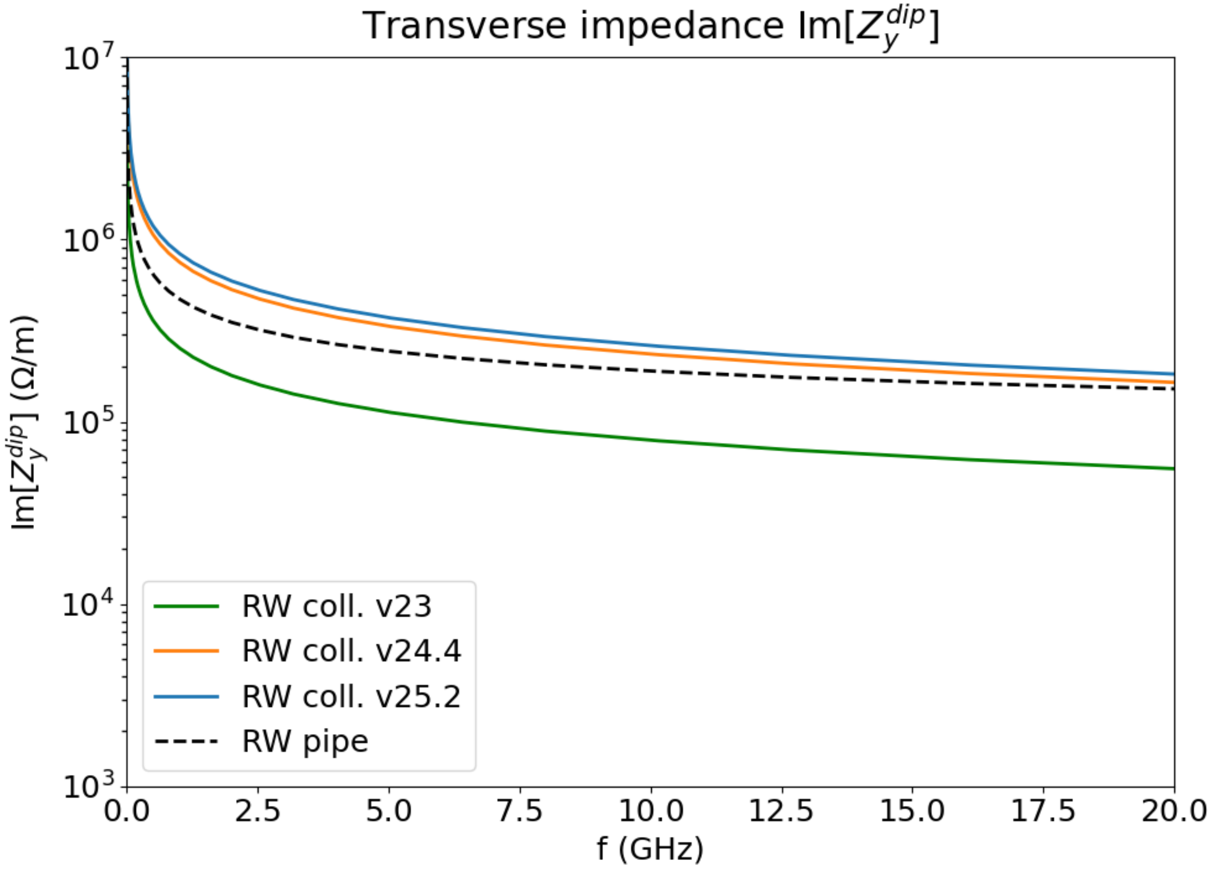
Decrease in **half-gap** for tcp.v.b1:
2.5 mm ➔ 1.7 mm ➔ 1.4 mm

$$Z_\perp(f) \propto 1/gap^3$$

$$Z_\perp(f) \propto \beta$$

Comparison between different optics

Imaginary part of the vertical transverse dipolar impedance: **total RW contribution** from all collimators, comparing optics versions 23, 24.4, and 25.2, along with the **RW impedance of the beam pipe** (considering a circular copper pipe with 30 mm radius and 150 nm NEG coating).

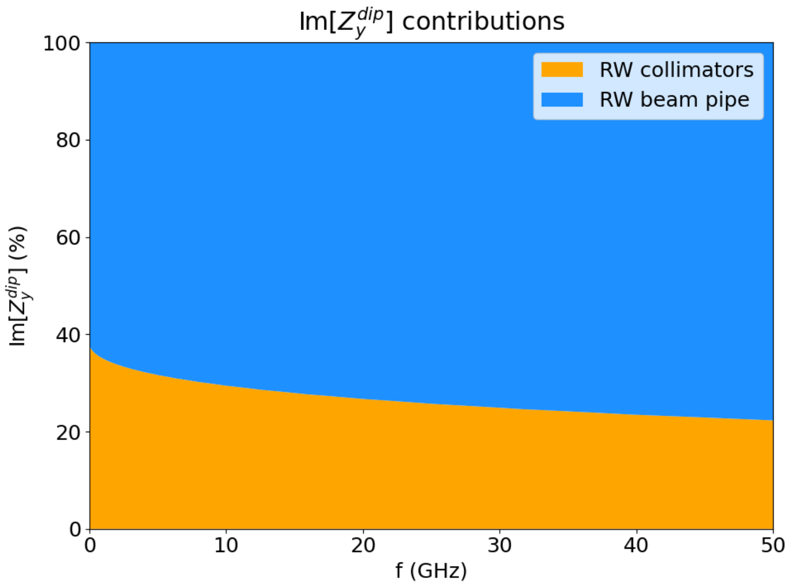


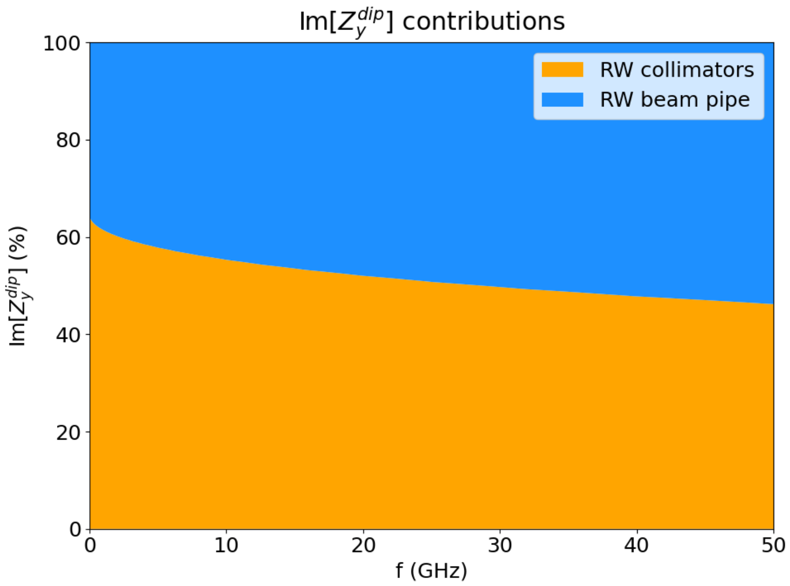
Collimator RW impedance exceeds beam pipe RW in **v24.4** and **v25.2**

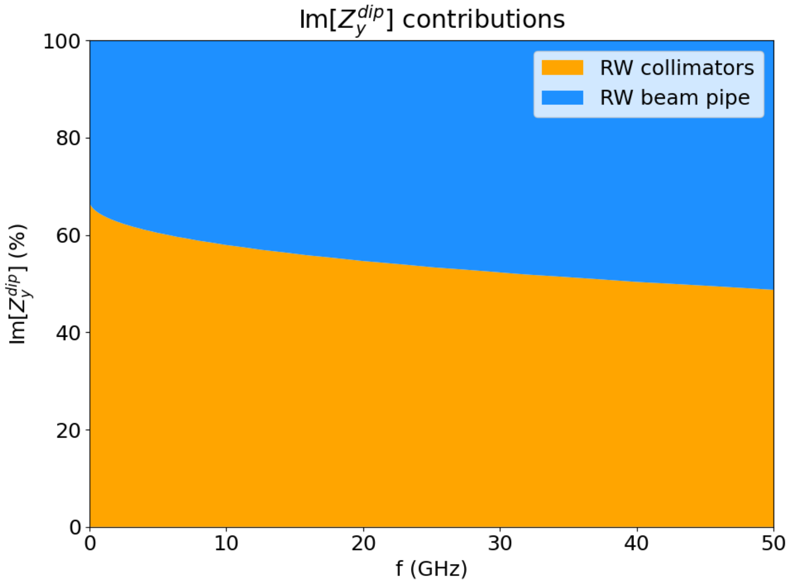
Comparison between different optics

Estimation of impedance considering the **RW contributions** from the **beam pipe** and **collimators**, with an analysis of collimators based on different optics layouts.

v23	V24.4	V25.2







Already with v23, the beam operates close to the stability limit, requiring the combined action of an **ideal bunch-by-bunch feedback system over 4-turns** and **positive chromaticity** (see **M. Migliorati:** 2025_05_20_FCC-IS_week.pdf).

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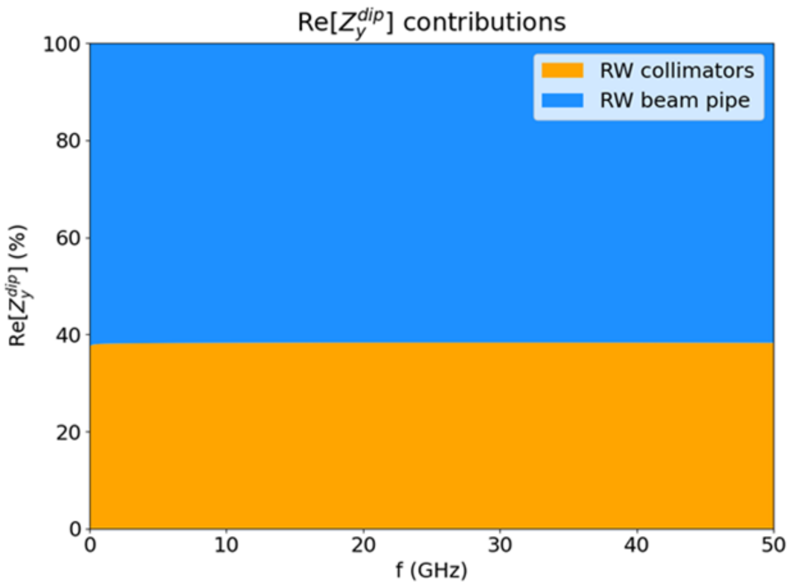

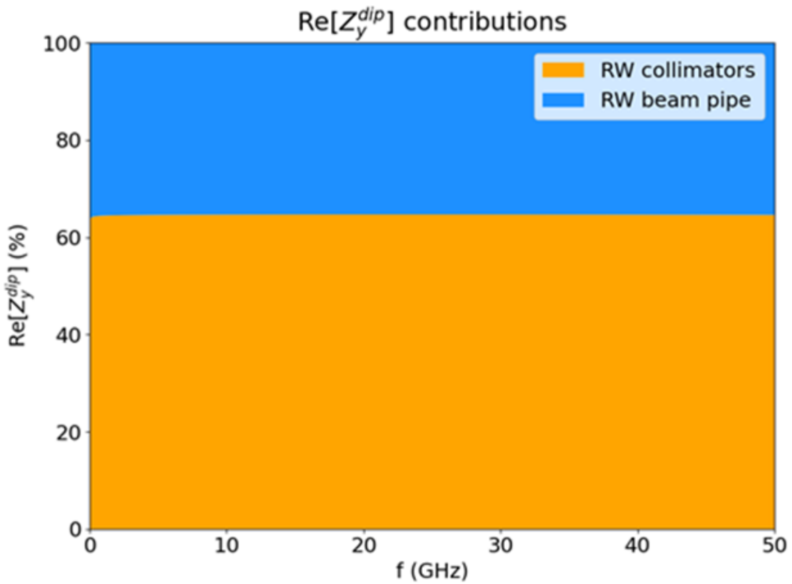

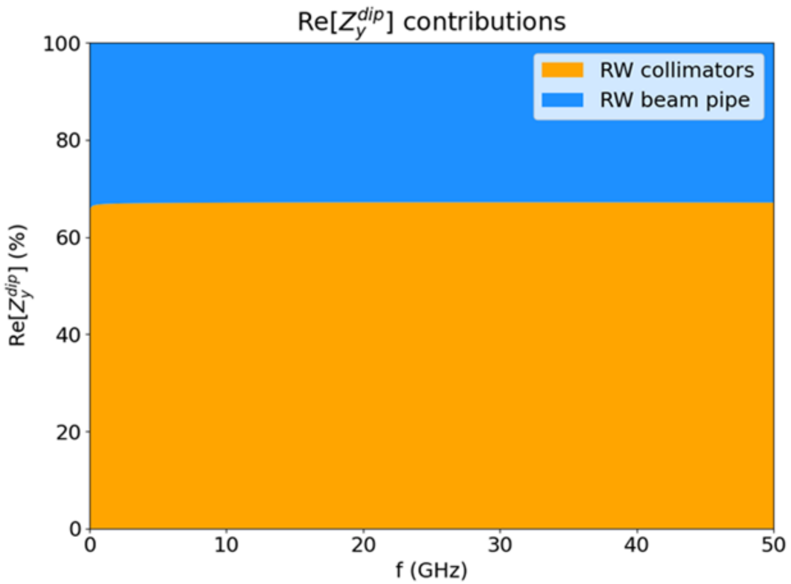

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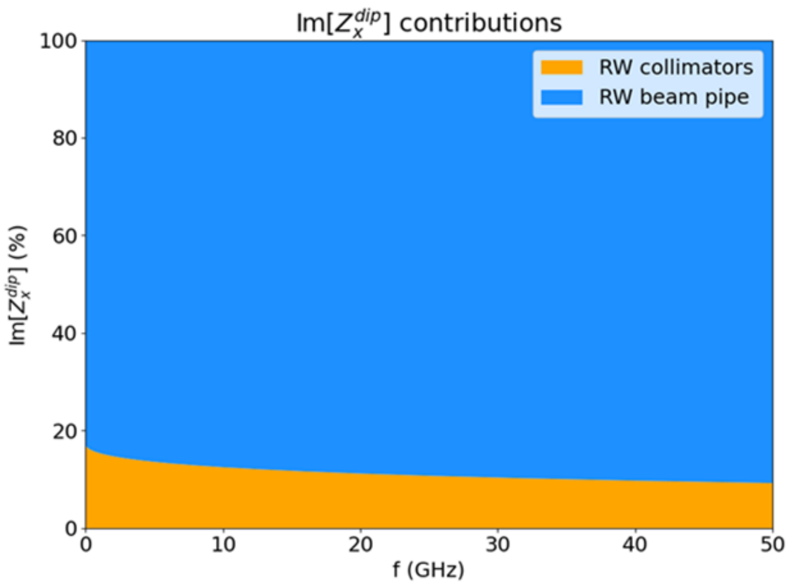
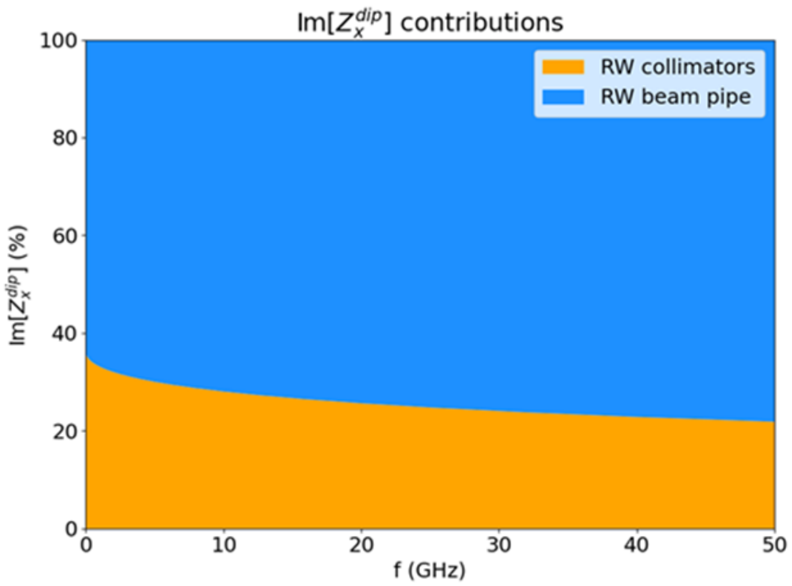
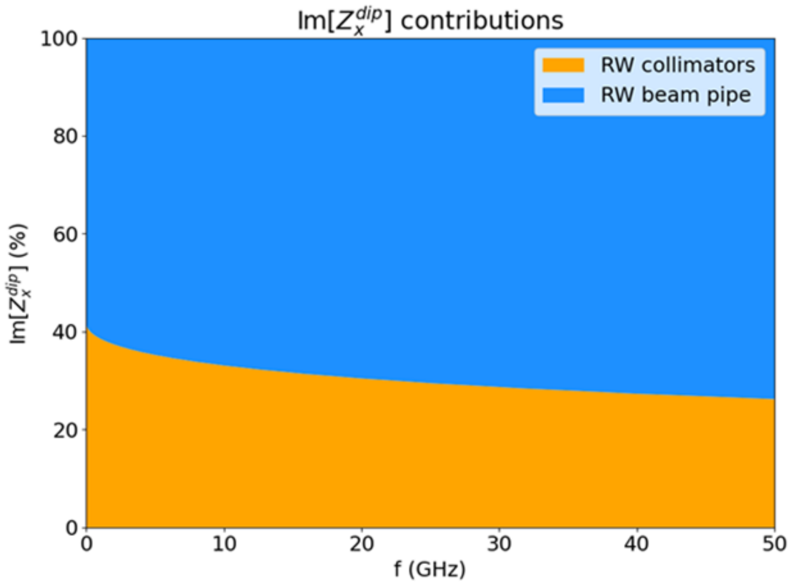




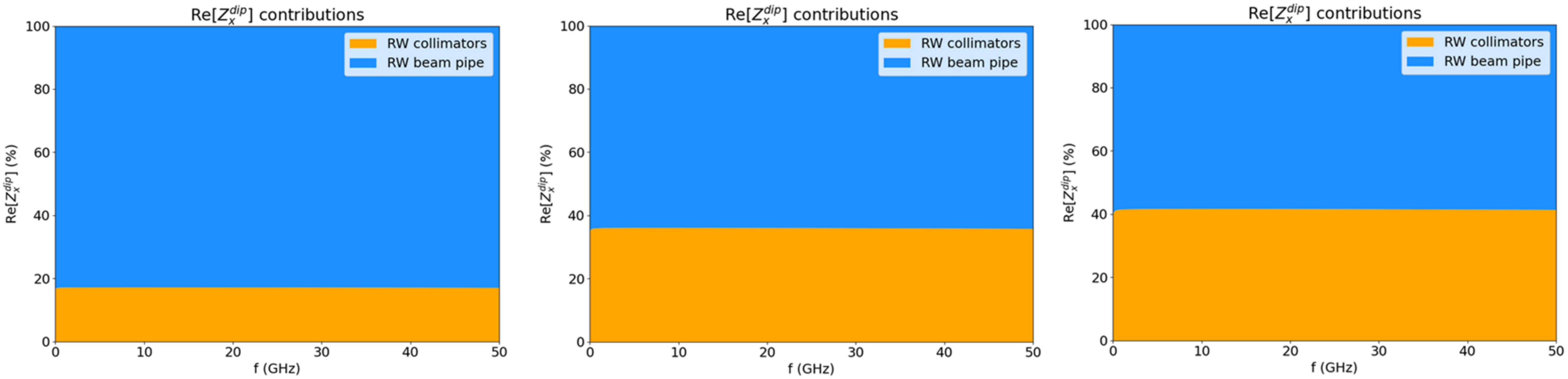


Already with v23, the beam operates close to the stability limit, requiring the combined action of an **ideal bunch-by-bunch feedback system over 4-turns** and **positive chromaticity** (see **M. Migliorati:** 2025_05_20_FCC-IS_week.pdf).

Comparison between different optics

Estimation of impedance considering the **RW contributions** from the **beam pipe** and **collimators**, with an analysis of collimators based on different optics layouts.

v23	V24.4	V25.2



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Outline

- Introduction
  - FCC-ee main parameters for Z configuration
  - FCC-ee main ring impedance model
- FCC-ee beam coupling impedance of the collimation system
  - Collimators geometrical impedance
    - Optimization strategies
  - Collimators RW impedance
    - Comparison between different optics
- Conclusion and next steps

Status updates: tools, models, and resources

- Simulations made on Xsuite
- FCC-ee Impedance Model available on GitHub
- Impedance budget space (common to booster and collider) on CERN gitlab
- Calculations made on several computing clusters : LXPLUS (CERN), FEYNMAN (CEA), and with dedicated computing resources on Jean-Zay (IDRIS) and CC IN2P3
- Dedicated chat spaces for the high energy booster and the collective effects studies on mattermost

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 favor materials with high electrical conductivity.

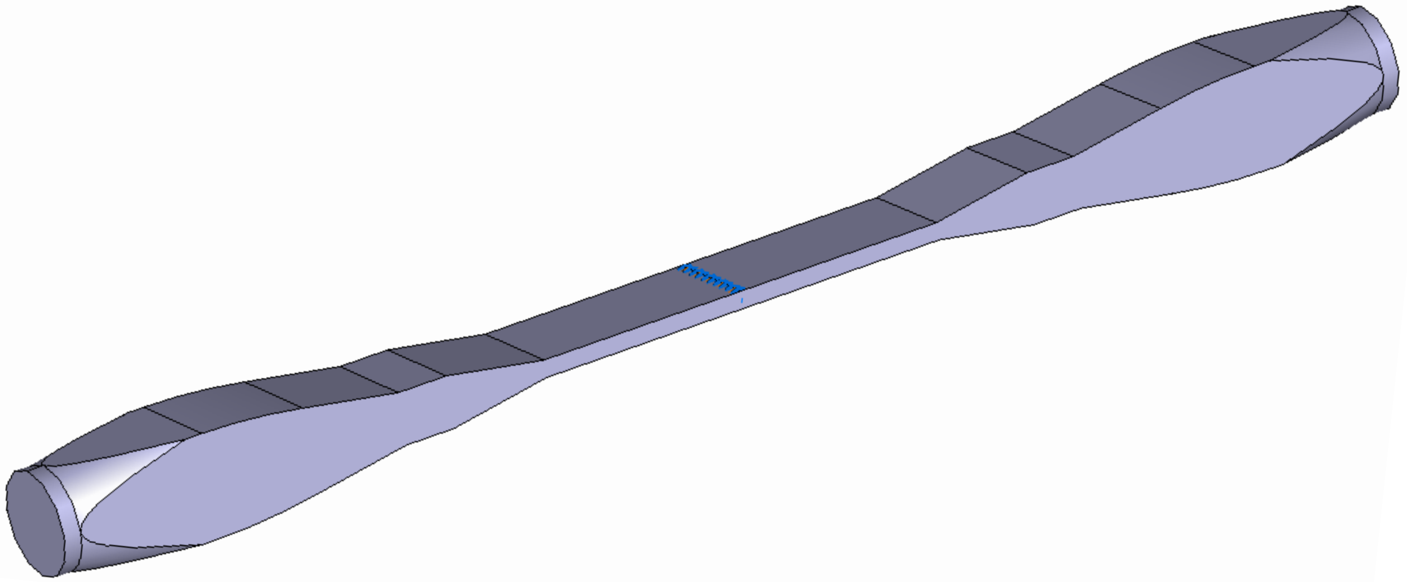
Ongoing activities: example

Proposed taper section design for collimators

Features:
- 9.4° taper (1:6 ratio) with circle-to-square transition
- Small flats at ±10 mm from jaws for BPMs
- Configured for 5 mm half-gap (adjustable)

Advantages:
- Simplified mechanical design: flexibility needed in only one direction
- More robust RF fingers
- Enhanced mechanical reliability

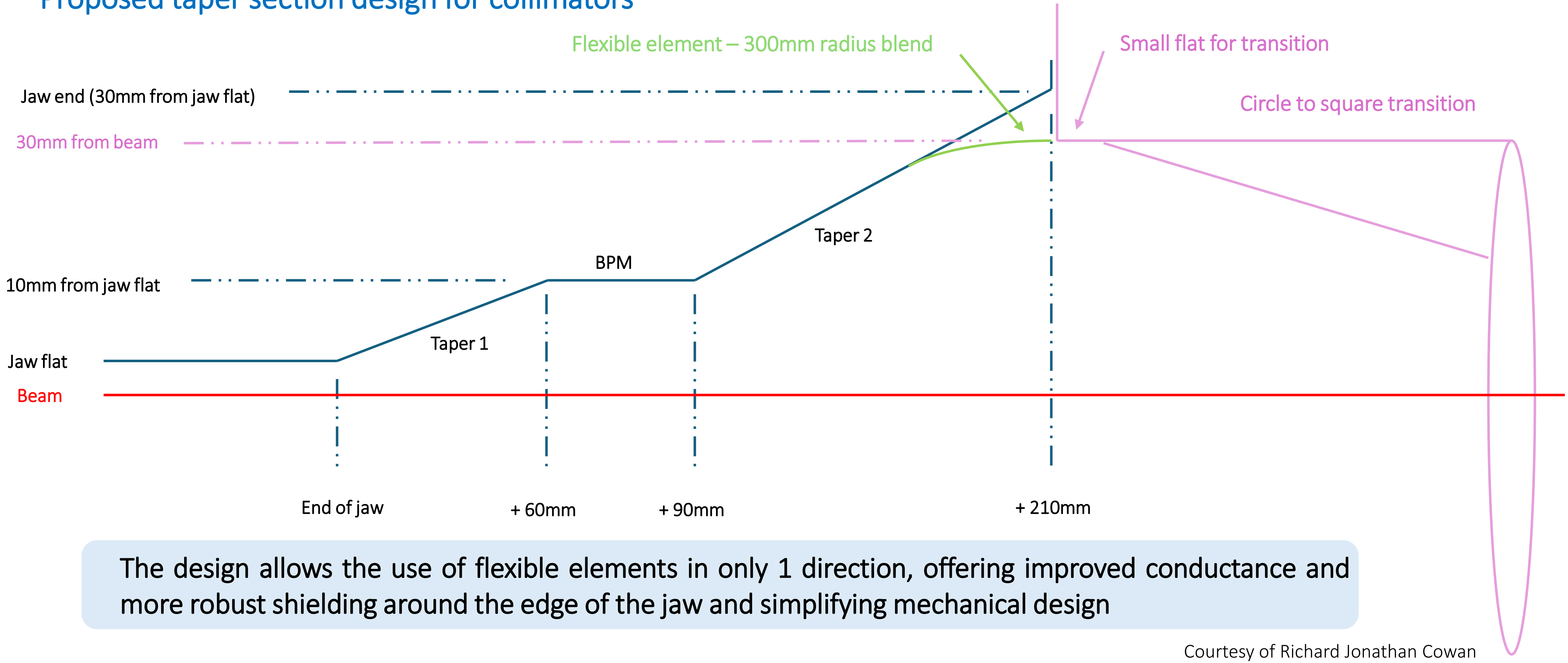
Status:
- Impedance evaluation in progress
- Taper length: 180 mm each side (excluding BPM)
- Lengths adjustable; taper is not a limiting factor unless angle < 2.5°



Courtesy of Richard Jonathan Cowan

Ongoing activities: example

Proposed taper section design for collimators



The design allows the use of flexible elements in only 1 direction, offering improved conductance and more robust shielding around the edge of the jaw and simplifying mechanical design

Courtesy of Richard Jonathan Cowan

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Thank you for your attention ☺

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