

EFFECT OF FCC-ee* COLLIMATOR IMPEDANCE ON BEAM STABILITY: DESIGN AND OPTIMIZATION STRATEGY

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Abstract

Operating at 45.6 GeV with high beam current, low emittances, and long damping times, the FCC-ee low-energy collider configuration is particularly sensitive to collective effects and impedance-induced beam instabilities. Controlling these effects requires a continuously refined impedance model to guide design choices and to establish reliable instability thresholds. Recent studies identify the collimation system as a dominant contributor to the total machine impedance, with geometric effects playing a key role in beam stability. Within this framework, a flexible, modular, and comprehensive impedance model enables targeted optimization and systematic stability assessments. The total impedance model includes the beam pipe, collimators, RF cavities, bellows, tapers, and beam position monitors. This work presents the latest FCC-ee impedance model with a full evaluation of collimator impedance, addressing current limitations related to the challenging simulation regime. It provides an in-depth analysis of the contribution of collimators to beam stability, comparing different optics configurations, novel materials, and advanced design solutions, as well as highlighting ongoing progress in impedance modelling, intensity threshold evaluation, and instability mitigation.

INTRODUCTION

In the FCC-ee Z operation mode (45.6 GeV), the combination of high beam current, low emittances, and long damping times makes the machine particularly sensitive to impedance-driven collective effects [1]. In this regime, an accurate impedance model is essential to predict instability thresholds and guide design choices. Relevant prior work is presented in [2–8].

Recent studies identify the collimation system as a dominant contributor to the total impedance [2, 3]. While resistive wall effects are well understood [9, 10], the geometric impedance of realistic collimators remains challenging to accurately quantify.

In this work, the FCC-ee impedance model is extended to include a comprehensive set of collimator impedances derived from full 3D electromagnetic simulations, providing a comprehensive framework to capture both geometric and resistive effects, as well as additional features such as surface

roughness. This enables a realistic evaluation of their impact on beam stability.

Several mitigation strategies are investigated, including taper optimization, collimator length reduction, and material improvements, providing guidance for the design of the FCC-ee collimation system.

IMPEDANCE MODEL FRAMEWORK

The impedance model describes the cumulative electromagnetic interaction between the beam and the surrounding accelerator structures, including vacuum chambers, RF systems, diagnostics, and protection devices such as collimators [11]. Each element contributes to the overall impedance spectrum and can drive beam instabilities.

The analysis focuses on the FCC-ee Z operation mode using the latest Local Chromaticity Correction (LCC) optics [12]. The main parameters are listed in Table 1.

Table 1: FCC-ee Parameters of the FCC-ee Z Configuration for the Version 106 of the LCC Optics [12]

Parameter	Value
Beam energy E (GeV)	45.6
Circumference C (m)	90644.816
Arc-cell setup	52°/45°
Momentum compaction factor α_c (10^{-6})	28.6
Energy Loss per turn W_0 (GeV)	0.035
Beam Intensity N (10^{12} particles)	2424
Bunch Intensity N_b (10^{11} particles)	2.02
Number of Bunches	12000
Horiz. β -function at IP β_x^* (cm)	9
Vert. β -function at IP β_y^* (mm)	0.7
Hor. emittance ε_x (nm)	0.70
Target vert. emittance in collision ε_y (pm)	1.40
Transverse tune Q_x / Q_y	194.16 / 170.20
Chromaticity Q'_x / Q'_y	5 / 5
Harmonic number h at 400 MHz	121200
Total RF voltage of 400/800 MHz (GV)	0.09/0
Synchrotron tune Q_s	0.031
RF momentum acceptance (%)	1.3
Bunch length σ_z (non coll./coll.) (mm)	5.1 / 16.7
Rel. mom. spr. σ_p (non coll./coll.) (10^{-3})	0.39 / 1.34
Long. damping time τ_z (turns)	1297
Beam-beam parameter ξ_x / ξ_y (10^{-3})	1.4 / 80
Luminosity \mathcal{L} (1×10^{34} s ⁻¹ /cm ²)	150

The model is implemented in a modular framework based on PyWIT/Xwakes, integrated in Xsuite [13, 14], allowing

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consistent integration of analytical and numerical impedance contributions.

The total transverse impedance is computed as:

$$Z_{\perp}(f) = \sum_i Z_{\perp}^i(f) \cdot \frac{\beta_{\perp}^i}{\langle \beta_{\perp} \rangle} \quad (1)$$

where β_{\perp}^i is the beta function at the location of the i^{th} element and $\langle \beta_{\perp} \rangle$ is the average beta function over the ring. This formulation ensures the correct scaling of impedance contributions with the optics functions.

In FCC-ee, the beam pipe contribution is dominated by resistive-wall effects and is modeled as a circular copper chamber of 30 mm radius coated with Non-Evaporable Getter (NEG). The effect of lateral winglets, designed to absorb synchrotron radiation, is included in the model via Yokoya form factors [9, 15, 16].

The resistive wall model of the circular beam pipe has been obtained with the code IW2D [17], while complex elements, such as collimators, are described using 3D electromagnetic simulations (CST Studio Suite [18]).

The total impedance model also includes tapers, 10 000 beam position monitors (BPMs), 10 000 bellows, and 132 double-cell 400 MHz RF cavities. The modular structure of the model allows continuous updates throughout the FCC-ee design evolution and enables systematic and consistent beam stability assessments.

3D COLLIMATOR MODELLING

The collimation system is one of the dominant sources of impedance in FCC-ee, requiring an accurate and realistic description of geometry and material properties.

Collimator impedance is evaluated using full 3D electromagnetic simulations with CST Studio Suite, capturing both geometric and resistive effects. The 3D models reproduce the key geometrical features of the devices, including jaw length, aperture, and taper transitions. This enables a realistic characterization of the impedance contribution of individual collimators.

The current LCC double-phase optics includes 41 collimators: 21 beam halo (BH) collimators - including primary (TCP), secondary (TCS), and tertiary (TCT) collimators — and 20 synchrotron radiation (SR) collimators (TCR). The main parameters of the dominant contributors are summarized in Table 2.

The resulting wakefields and impedances are integrated into the global model through the PyWIT framework. This provides a coherent and comprehensive description of the collimator contribution within the overall impedance budget.

FCC-ee IMPEDANCE BUDGET

The developed impedance model allows isolating and analyzing the contribution of individual machine elements to the total impedance. Figure 1 shows the contributions to the vertical transverse dipolar impedance, considering only the taper optimization.

Table 2: Main Parameters of BH Collimators: Length l and Gap g , and Horizontal and Vertical Beta Functions β_x and β_y

Name	l(m)	g/2(mm)	β_x (m)	β_y (m)
tct.v.1.b1	0.25	8.99	640.03	10052.91
tct.h.1.b1	0.25	8.67	621.10	10263.60
tcr.h3.1.b1	0.1	10.65	700.85	568.69
tcr.h2.1.b1	0.1	11.80	860.80	4697.84
tcr.h1.1.b1	0.1	19.92	2449.88	5171.56
tcr.v.c2.1.b1	0.1	7.81	2869.03	5269.94
tcr.h.c2.1.b1	0.1	21.69	2904.85	5278.05
tcp.h.b1	0.25	6.51	724.61	73.92
tcp.v.b1	0.25	1.93	251.54	723.09
tcs.h1.b1	0.3	6.27	450.40	461.20
tcs.v1.b1	0.3	2.21	255.20	610.10
tcp.hh.b1	0.25	4.86	404.25	90.71
tcs.hh1.b1	0.3	2.72	84.95	162.72
tcs.h2.b1	0.3	5.82	389.42	103.12
tcp.vv.b1	0.25	1.95	175.85	739.24
tcs.vv1.b1	0.3	2.41	252.47	724.25
tcs.hh2.b1	0.3	7.56	657.06	75.87
tcp.hp.b1	0.25	8.69	333.66	957.01
tcs.hp1.b1	0.3	13.76	467.36	705.02
tcs.hp2.b1	0.3	3.28	25.96	364.39

As anticipated, the collimation system dominates the impedance budget. Even with a chromaticity of $Q'_{x,y} = +5$ and an ideal bunch-by-bunch feedback system with a damping time of four turns, the current optics leads to an unstable beam configuration. Figure 2 shows the real part of the normalized tune shift of the first azimuthal coherent transverse mode as a function of bunch population. The instability threshold is $N_p = 0.6 \cdot 10^{11}$ particles per bunch, well below the nominal value of $2.02 \cdot 10^{11}$ (Table 1). Without collimators, the beam remains stable up to 4.0×10^{11} ppb, confirming their dominant impact on beam stability.

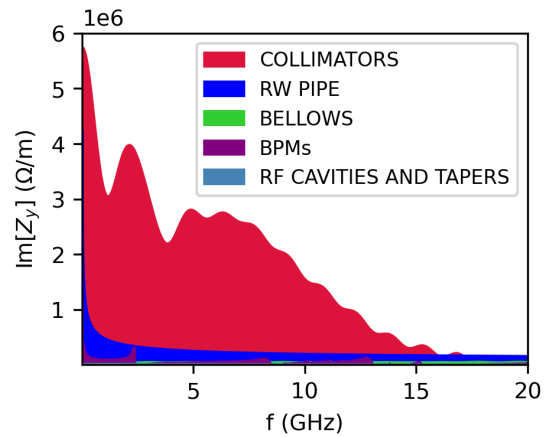


Figure 1: Imaginary vertical dipolar impedance contributions. Collimators with taper optimization only.

COLLIMATOR IMPEDANCE REDUCTION

Several mitigation strategies are investigated, including taper angle reduction [2], here extended to all collimators,

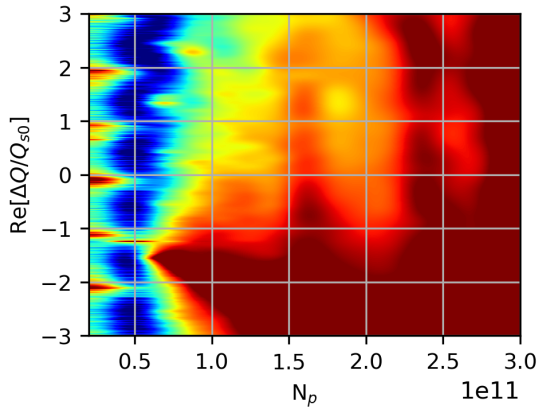


Figure 2: Real part of the normalized tune shift vs bunch population. Collimators with taper optimization only.

as well as shorter devices, higher conductivity of secondary collimators, and reduced contribution of synchrotron radiation collimators. All modifications are compatible with mechanical and integration constraints. The optimized configuration significantly reduces the transverse impedance (Fig. 3) and increases the threshold to $N_p = 1.9 \cdot 10^{11}$ ppb (Fig. 4). The impact of surface roughness (R) has also been investigated using the 3D model. While a roughness of $1 \mu\text{m}$ has a negligible effect, a roughness of $10 \mu\text{m}$ significantly reduces the stability threshold (Fig. 5). This highlights the importance of controlling surface quality.

Further optimization is ongoing to increase the stability margin. Realistic thresholds require accounting for beam-beam effects, which will further enhance beam stability [19].

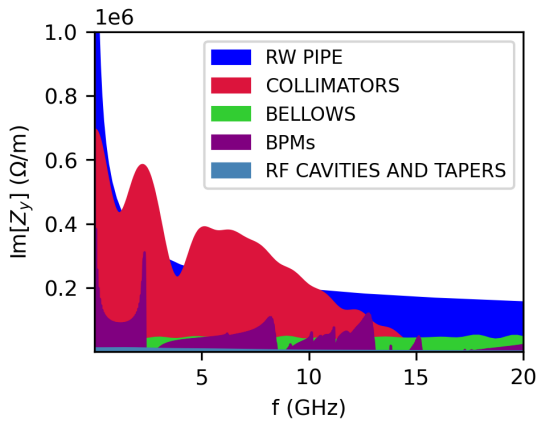


Figure 3: Imaginary vertical dipolar impedance contributions. Collimator taper, length, and material optimization.

CONCLUSION

A comprehensive impedance model of FCC-ee has been developed, combining a modular framework with full 3D electromagnetic simulations. For the first time, the collimator impedance has been evaluated using detailed 3D models, including surface roughness effects, confirming that collimators are among the dominant contributors to the total machine impedance. Several mitigation strategies have

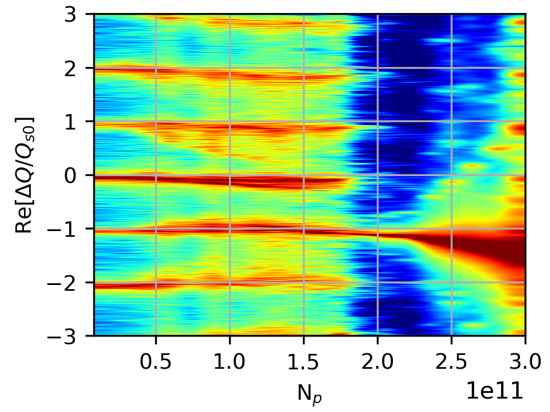


Figure 4: Real part of the normalized tune shift vs bunch population for the fully optimized collimator configuration.

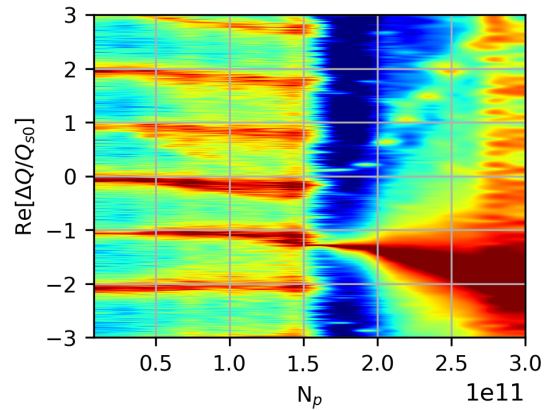


Figure 5: Real part of the normalized tune shift vs bunch population for the fully optimized collimator configuration, including a surface roughness of $R = 10 \mu\text{m}$.

been investigated, including taper angle reduction, shorter collimators, higher material conductivity, and reduced synchrotron radiation collimator contributions, providing clear design guidelines for impedance optimization while preserving device functionality.

This study highlights the importance of realistic 3D modelling for reliable impedance evaluation and guides the design of the FCC-ee collimation system. Realistic thresholds require including beam-beam effects, which, via beamstrahlung, are expected to increase the stability threshold [19,20]. Recent updates indicate that new optics configurations under study may provide additional stability margin.

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