

Abstract

The purpose of this study is to calculate the longitudinal and transverse wakefields of the FCC collimators using the electromagnetic codes ECHO3D and IW2D. We cross-checked our results using CST particle studio for long bunches, and found them to be in good agreement. The obtained results show that the collimators represent an important wake potential source for FCC-ee in the transverse plane. In particular, using the code PyHEADTAIL, we have found that the geometric contribution of the collimators' wakefield reduces significantly the transverse mode coupling instability threshold. Therefore, it is imperative to explore and implement solutions that effectively mitigate this wakefield source.

Introduction

The FCC-ee is a proposed particle physics facility to be built in the CERN area [1], featuring a circular tunnel spanning 91 kilometers to house an advanced electron-positron collider.

As part of our efforts in the project, we are actively engaged in evaluating the impedance and collective effects associated with the collider [2, 3, 4, 5]. In particular, we have focused our studies on the lowest energy machine (Z-pole) since it is considered the most critical from the collective effects point of view. As the design of the machine progresses, its devices are better defined. In this framework, we have recently found that one of the primary sources of wakefield is represented by the collimation system.

Analytical computation

Taper transition mitigates wakefield effects, especially for transverse wakefields [6, 7]. For an axisymmetric transition, the longitudinal and dipolar impedances are given by [8]:

$$Z_L^{m=0}(k) = \frac{Z_0}{2\pi} \ln \frac{a_1}{a_2} - i \frac{kZ_0}{4\pi} \int_{-\infty}^{\infty} dz (a')^2 \quad (1)$$

$$Z_T^{dipole}(k) = \frac{Z_0}{2k\pi} \left(\frac{1}{a_1^2} - \frac{1}{a_2^2} \right) - i \frac{Z_0}{2\pi} \int_{-\infty}^{\infty} dz \left(\frac{a'}{a^n} \right)^2. \quad (2)$$

Applying inverse Fourier transform to $Z_L^{m=0}(k)$ yields:

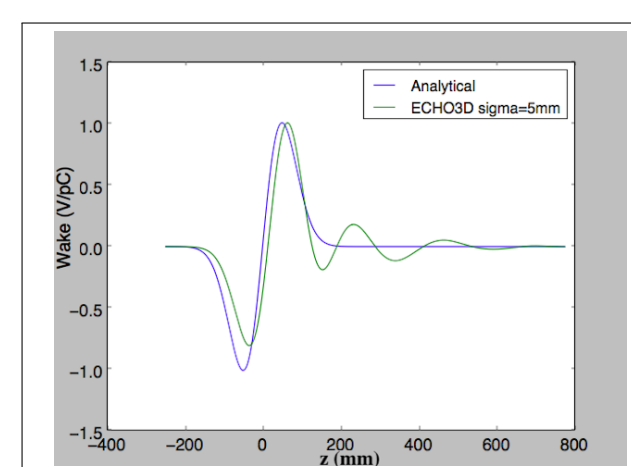
$$\omega_{||}(z) = \mathcal{F}^{-1} \left[-i \frac{kZ_0}{4\pi} \int (a')^2 dz \right] = -\frac{Z_0}{2\sqrt{2\pi}} \delta'(z) \int (a')^2 dz. \quad (3)$$

By convolving this wakefield with a Gaussian distribution $\lambda(z) = \frac{q}{\sqrt{2\pi}\sigma_z} e^{-\frac{z^2}{2\sigma_z^2}}$, we can obtain the wake potential for a given bunch length σ_z as [9]

$$W_{||} = \frac{1}{q} \int_{-\infty}^{\infty} \omega_{||}(z - z') \lambda(z') dz' = -Z_0 L a^2 \frac{z}{4\pi\sigma_z^3} e^{-\frac{z^2}{2\sigma_z^2}} \quad (4)$$

$$W_T = \frac{Z_0}{2\pi\sigma_z} e^{-\frac{z^2}{2\sigma_z^2}} \int \frac{a^2}{a^2} dz. \quad (5)$$

These equations offer valuable insights into how the taper length influences the geometric contribution to the collimator's wakefield, playing a crucial role in effectively reducing wakefield effects.



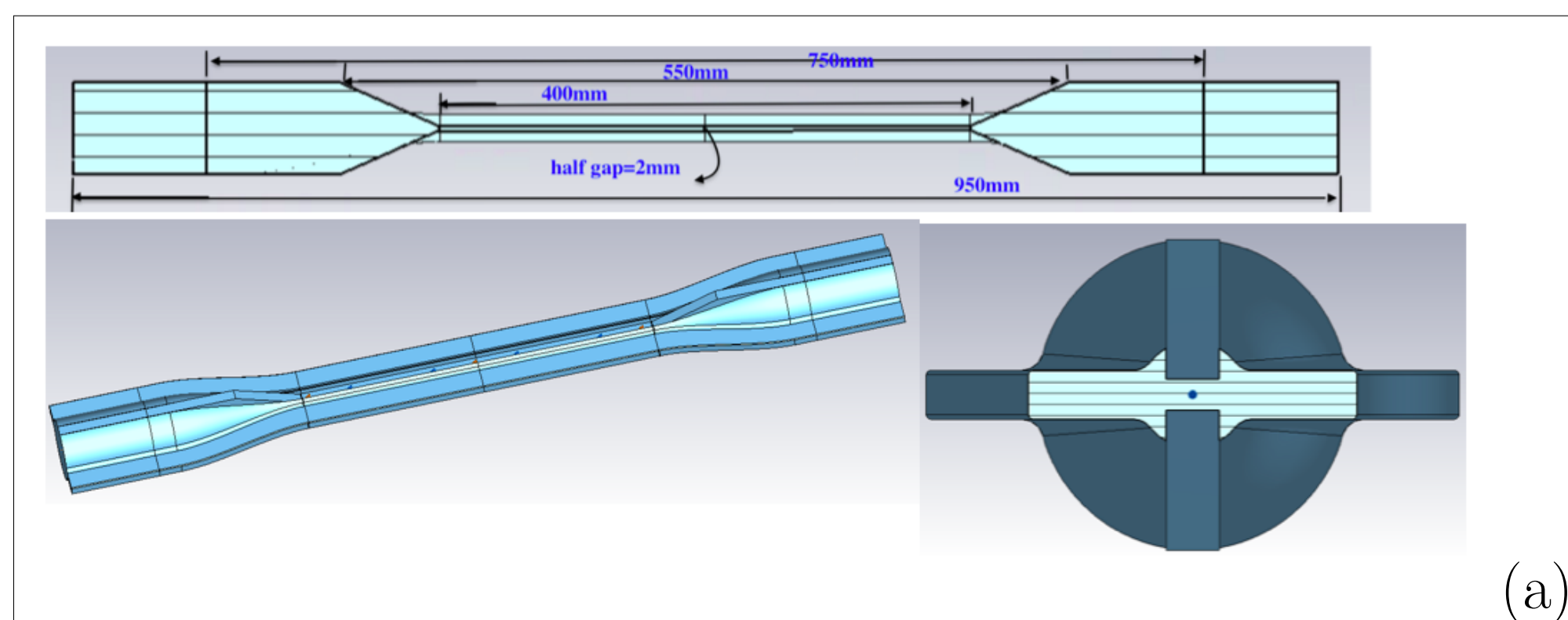
Comparison of analytical expression and numerical simulations for the wake potential of a 5 mm Gaussian bunch passing through a collimator with a half gap of 3.5 mm, using ECHO3D.

Collimator settings and the model

Summary of the collimator settings for the Z-pole and for the 4 IPs layout as shown in the following table [10]. The length of these collimators is much longer than the SuperKEKB model (0.3 - 0.4 m instead of few mm).

name	type	length [m]	half-gap [m]	material	plane	β_x [m]	β_y [m]
tcp.h.b1	primary	0.4	0.005504	MoGR	H	352.578471	113.054110
tcp.v.b1	primary	0.4	0.002332	MoGR	V	147.026106	906.282898
tcs.h1.b1	secondary	0.3	0.004162	Mo	H	144.372060	936.118623
tcs.v1.b1	secondary	0.3	0.00203	Mo	V	353.434125	509.320452
tcs.h2.b1	secondary	0.3	0.005956	Mo	H	295.623450	1419.375106
tcs.v2.b1	secondary	0.3	0.002116	Mo	V	494.235759	554.055888
tcp.hp.b1	primary	0.4	0.005755	MoGR	H	55.469637	995.306256
tcs.hp1.b1	secondary	0.3	0.01649	Mo	H	373.994993	377.277726
tcs.hp2.b1	secondary	0.3	0.011597	Mo	H	184.970621	953.229862

A proposed FCC-ee collimator model. It should be noted that the length of these collimators is much longer than the SuperKEKB model [11], ranging from 0.3 to 0.4 meters instead of just a few millimeters.



(a)

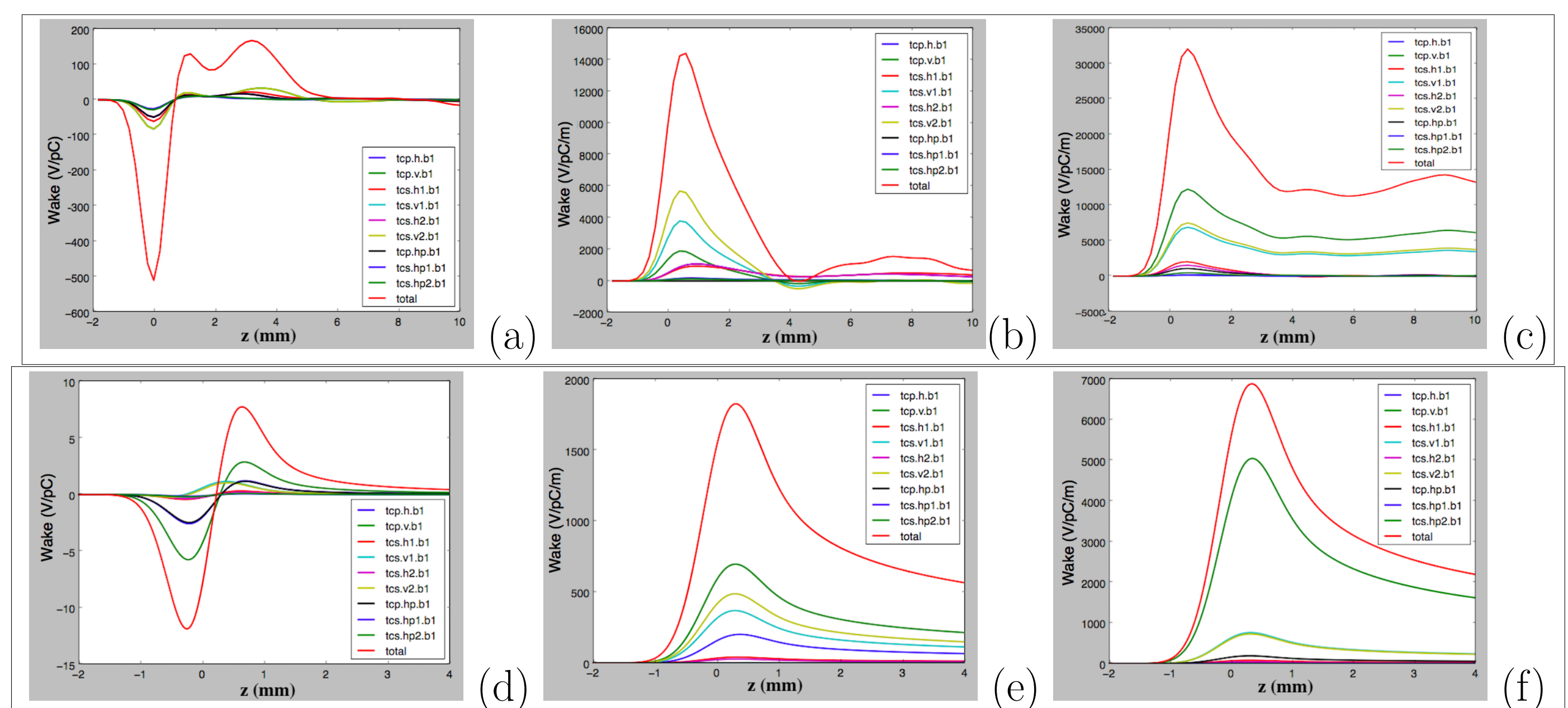
Conclusion

Collimator wakefields in FCC-ee impact beam dynamics and performance. This study focuses on wakefields from collimators designed for the Z-mode with 4 interaction points. Numerical simulations utilize CST Particle Studio and ECHO3D codes, cross-benchmarking results. Resistive wall effects are considered using the parallel plate approximation and IW2D code.

Results align well with analytical expressions and agree perfectly between CST and ECHO3D. The total wake of the collimation system is high, with the vertical dipolar wake potential comparable to other vacuum chamber components. PyHEADTAIL code simulates the impact on FCC-ee's beam dynamics, revealing lower TMCI threshold due to the collimators' wake, even with strong feedback bunch-by-bunch feedback system. Mitigation measures should address collimators' contribution to the FCC impedance/wake budget.

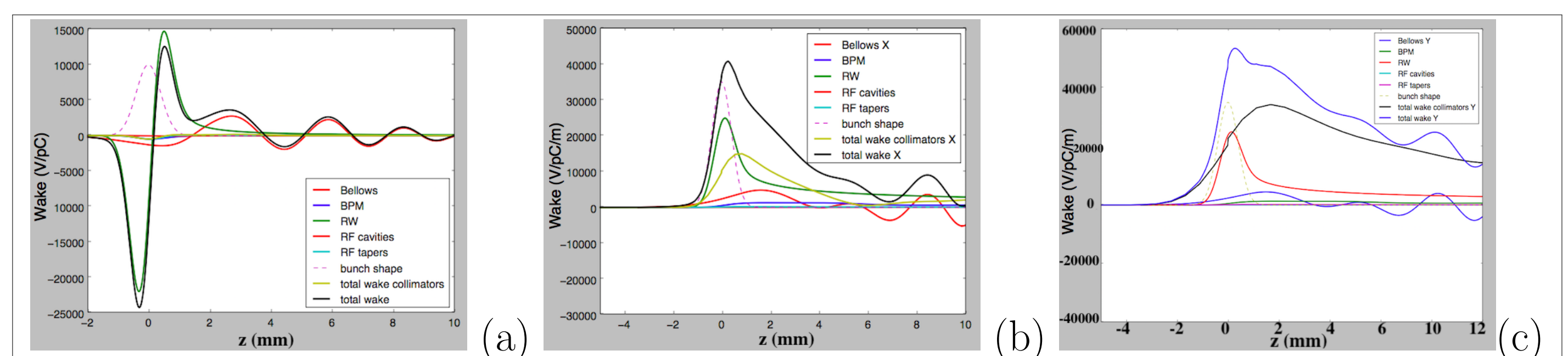
Numerical solution

The longitudinal (a), transverse horizontal dipolar (b) and transverse vertical dipolar (c) geometrical wake potential of collimators for a 0.4 mm Gaussian bunch calculated using ECHO3D. Similarly, the longitudinal (d), transverse horizontal dipolar (e) and transverse vertical dipolar (f) components of the resistive wall wake potential for the same 0.4 mm bunch computed using IW2D.



Total FCC wakefield

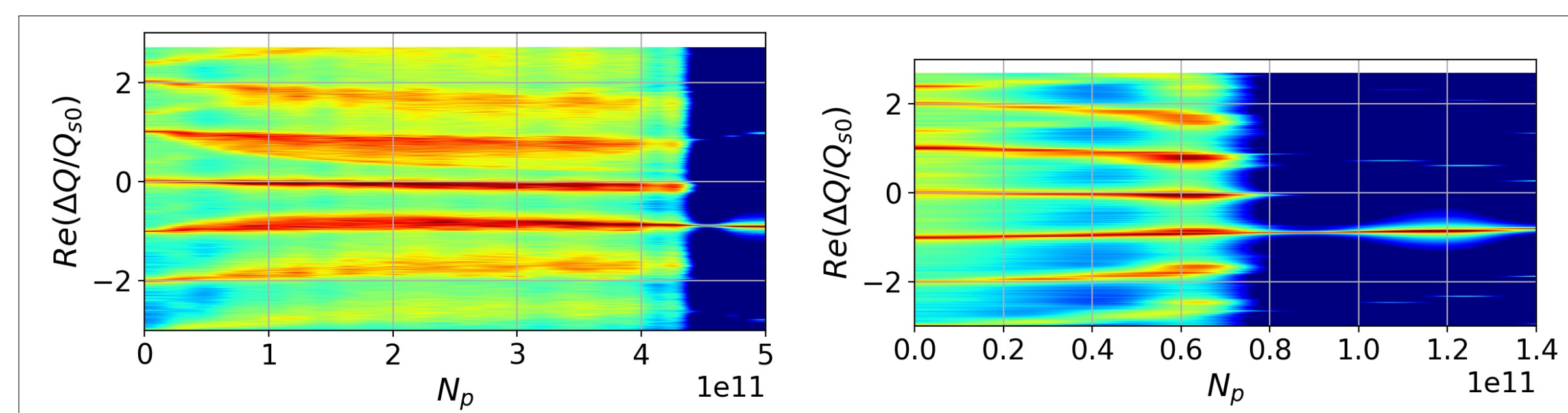
The wake potentials that have been evaluated so far consider several components, including the resistive wall, bellows, beam position monitors (BPM), and the RF system, which includes tapers connecting the cryo-modules in both longitudinal and transverse planes. These contributions are illustrated in the following figures. It is worth noting that, apart from the resistive wall and the bellows, the other devices have a negligible impact on the longitudinal wake potentials. However, in the transverse plane, the geometric contribution of collimators is almost equal to the total of all the other wakefield sources evaluated so far.



a) The total longitudinal b) horizontal dipolar and c) vertical dipolar wake potential of the FCC machine for a 0.4 mm Gaussian bunch.

Collective effects

As expected, the geometric wakefield due to the collimators reduces the threshold by a very large amount and solutions to decrease the amplitude of such wakes must be found. We are currently exploring the maximum length of tapers that can be implemented to effectively reduce the impact of the geometric wakefield. In addition, non-linear tapers [12] and non-linear collimation optics [13] can also be explored as potential methods for mitigating the effects of the geometrical impedance. With the non-linear optics solution, also the RW contribution of the collimators can be effectively reduced. These approaches may offer additional advantages over linear tapers, such as greater flexibility and control over the beam dynamics. Our investigation into this matter is ongoing.



The PyHEADTAIL simulation code analyzes the combined effects of longitudinal and transverse wakefields, particularly in the FCC-ee. Real part of the tune shift of the first azimuthal transverse coherent oscillation modes normalized by the synchrotron tune Q_{s0} as a function of bunch population without (a) and with (b) the effect of geometric wakefield of the collimators.

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