Collimator model & FCC-ee impedance model

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INFN-LNF, on behalf of FCC group

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Acknowledgements: A. Abramov, M. Boscolo, Demin Zhou and Frank Zimmermann

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- Motivation
  Why is the FCC project important?
  FCC-ee main parameters
- Main impedance sources
- Collimators
  Why Collimators are so important?
  Why do we need numerical simulations?
- How CST and ECHO3D work
  Wake fields and impedances calculations
- Wake potential calculations of Collimator (ECHO3D and CST)
- Validation of the results
  1- Comparing the results of ECHO3D with CST (long bunch)
  2- Convolution method (short bunch)
- Updated table of collimation system
- Wake potential calculations of Collimator for the updated table of collimation system
  Longitudinal, transverse dipolar and quadrupolar
- Summary

FCC-ee main parameters

- FCC-ee is a highest-luminosity Higgs and electroweak factory energy-frontier electron-positron collider spanning the energies from 45 to 183 GeV.
- This circular lepton collider allow us to study the Z, W, Higgs and top particles with high precision.
- INFN/Sapienza together with CERN, DESY and SLAC are responsible for establishing a complete impedance budget for collider, booster and evaluate single-beam collective effects for different modes of operation.

Layout	PA31-1.0			
	Z	WW	ZH	$t\hat{t}$
Circumference (km)	91.174117 km			
Beam energy (GeV)	45.6	80	120	182.5
Bunch population (10^{11})	2.53	2.91	2.04	2.64
Bunches per beam	9600	880	248	36
RF frequency (MHz)	400			400/800
RF Voltage (GV)	0.12	1.0	2.08	4.0/7.25
Energy loss per turn (GeV)	0.0391	.37	1.869	10.0
Longitudinal damping time (turns)	1167	217	64.5	18.5
Momentum compaction factor 10^{-6}	28.5		7.33	
Horizontal tune/IP	55.563		100.565	
Vertical tune/IP	55.600		98.595	
Synchrotron tune	0.0370	0.0801	0.0328	0.0826
Horizontal emittance (nm)	0.71	2.17	0.64	1.49
Verical emittance (pm)	1.42	4.34	1.29	2.98
IP number	4			
Nominal bunch length (mm) (SR/BS)*	4.37/14.5	3.55/8.01	3.34/6.0	2.02/2.95
Nominal energy spread (%) (SR/BS)*	0.039/0.130	0.069/0.154	0.103/0.185	0.157/0.229
Piwinski angle (SR/BS)*	6.35/21.1	2.56/5.78	3.62/6.50	0.79/1.15
ξ_x/ξ_y	0.004/0.152	0.011/0.125	0.014/0.131	0.096/0.151
Horizontal β^* (m)	0.15	0.2	0.3	1.0
Vertical β^* (mm)	0.8	1.0	1.0	1.6
Luminosity/IP ($10^{34}/\text{cm}^2\text{s}$)	181	17.4	7.8	1.25

*SR: syncrotron radiation, BS: beamstrahlung

Main impedance sources

Largest longitudinal impedance sources: Resistive wall, Bellows

Largest transverse impedance source: Collimators

Collimators are used in storage rings and accelerators

What are the objectives of collimators?

- To remove high amplitude particles from the transverse profile of the beam
- To reduce the uncontrolled beam loss from the lost particles originating from beam tails
- Act as shielding for the remainder of the accelerator structures by minimizing the production and leakage of secondary radiation

Collimator issues

- Being close to the beam orbit they may introduce large impedance
- This impedance perturbs the beam motion downstream of the collimator
- Longitudinal wakefields → change the energy distribution and lengthen the bunch
- Transverse wakefields → increase the beam emittance, shift the betatron tune and decrease beam life time

In order to estimate the impact of these effects, the geometric and resistive wall wakefields must be investigated.

Why do we need numerical simulations?

From Maxwell's equations (equation for the high frequency impedance of tapered transitions)

$$(\nabla^2 + \partial_{zz} - c^{-2}\partial_{tt})\mathbf{E} = 4\pi\nabla\rho + \frac{4\pi}{c^2}\partial_t \mathbf{j} \quad (1)$$

Solution: None

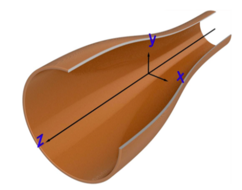
From Maxwell's equations (equation for the low frequency impedance of tapered transitions)

$$(\nabla^2 + \partial_{zz})\mathbf{E} = 4\pi\nabla\rho \quad (2)$$

Solution by Stupakov (by considering the two-dimensional Poisson equations with Dirichlet boundary conditions):

$$Z_{\parallel}^{d} = -\frac{2x_1 x}{c}\left(\frac{1}{a_1^2} - \frac{1}{a_2^2}\right) - 2ix_1 x\frac{k}{c}\int \frac{(a')^2}{a^2}dz \quad (3)$$

$$Z_{\perp}^{d} = \frac{2x_1}{\omega}\left(\frac{1}{a_1^2} - \frac{1}{a_2^2}\right) - 2\frac{ix_1}{c}\int \frac{(a')^2}{a^2}dz \quad (4)$$

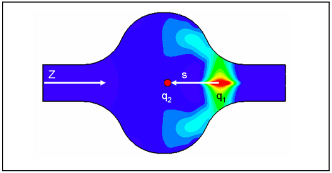


Geometry of a round transition.

How CST (Wakefield Solver) works? (Wakefields and impedances calculations)

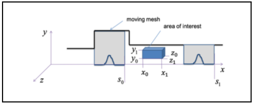
- The wakefield solver calculates the wake-potentials for a given structure from electromagnetic fields.
- Wakefield problems are driven by a bunch of charged particles, which is passing the observed structure parallel to a main coordinate axis.
- These particles cause electromagnetic fields, which are calculated with a time domain solver.
- The Fourier transform is normed such that the unitarity is given or Parseval's identity is fulfilled:

$$\int_{-\infty}^{\infty} |c(t)^2 dt = \int_{0}^{\infty} |C(\omega)^2 d\omega \qquad (5)$$

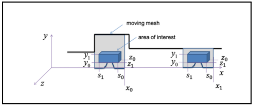


How ECHO3D works? (Wakefields calculations)

- Code ECHO3D calculates in time domain the electromagnetic fields generated by an electron bunch passing through arbitrary three dimensional chamber.
- The structure can consist of several materials with different permeabilities and permittivities.
- The bunch form is a Gaussian pencil bunch.
- Moving mesh (Field monitor of type s-time OR Field monitor of type x-time)



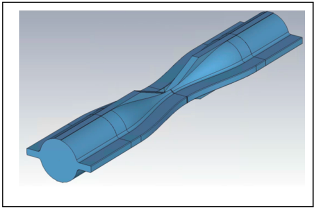
(Field monitor of type s-time)

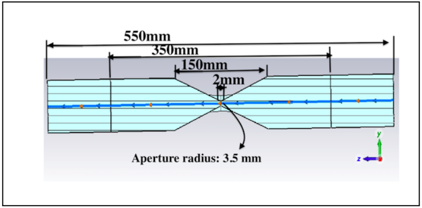


(Field monitor of type x-time)

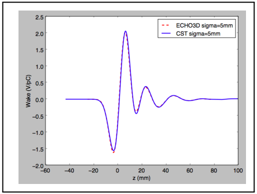
Wake potential

Collimator original shape (SuperKEKB model, thanks to Takuya Ishibashi) proposed by Mauro Migliorati



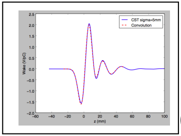


Geometric longitudinal wake potential of a 5 mm Gaussian bunch (ECHO3D Vs. CST)



(a)

Convolution vs CST (suggested by Mauro Migliorati)



(b)

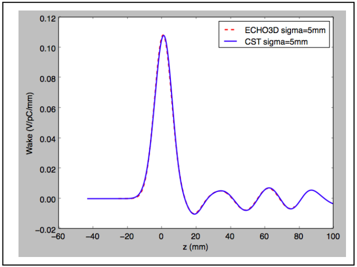
Longitudinal wake potential of a distribution

$$W_{||} = -\frac{U(z)}{qe} = \frac{1}{q}\int_{-\infty}^{\infty} \omega_{||}(z'-z)\lambda(z')dz' \quad (6)$$

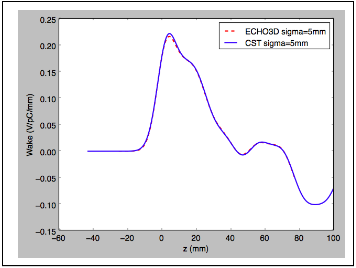
where $q = \int_{-\infty}^{\infty} \lambda(z)dz$

Geometric transverse dipolar wake potential of a 5 mm Gaussian bunch (ECHO3D Vs. CST) and its convolution

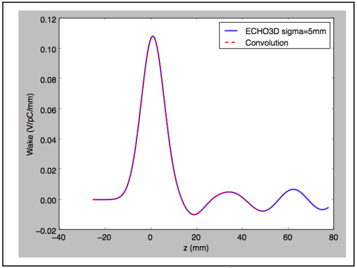
The transverse wake is due to the excitation of dipole modes. These modes are excited by the dipole momentum of the beam.



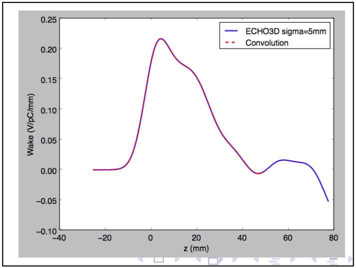
(D_x)



(D_y)



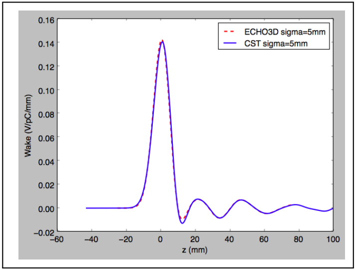
(D_x)



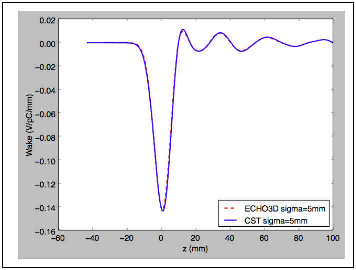
(D_y)

Quadrupolar Wake Potential

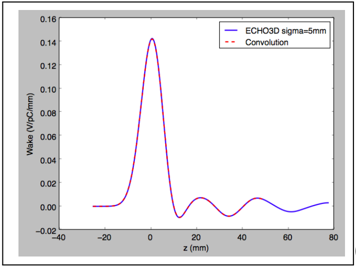
Geometric transverse quadrupolar wake potential of a 5 mm Gaussian bunch (ECHO3D Vs. CST) and its convolution



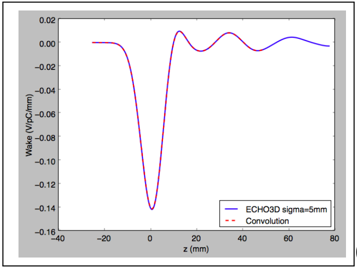
(Q_x)



(Q_y)

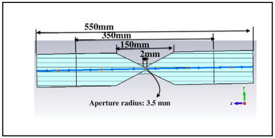


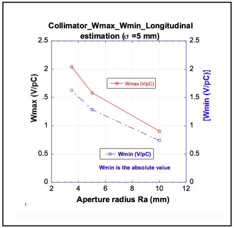
(Q_x)

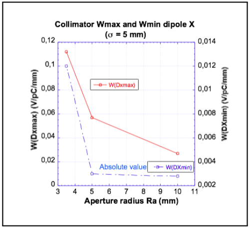


(Q_y)

Collimator optimization







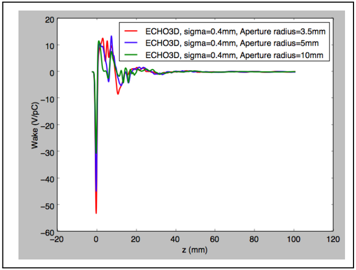
Longitudinal, transverse dipolar and quadrupolar wake potentials of a 5 mm Gaussian bunch (ECHO3D) for different aperture radii of the collimator (3.5mm, 5mm, 10mm)

R_a [mm]	[max,min] $W_L{}^*$	[max,min] $(W_{Dx})^{**}$	[max,min] $(W_{Dy})^{**}$	[max,min] $(W_{Qx})^{**}$	[max,min] $(W_{Qy})^{**}$
3.5	[2.045,-1,623]	[0.112,-0.012]	[0.224,-0.101]	[0.141,-0.014]	[0.014,-0.141]
5	[1.587,-1.282]	[0.057,0.003]	[0.123,0.002]	[0.088,0.013]	[0.013,-0.088]
10	[0.903,-0.749]	[0.027,-0.0028]	[0.289,0.014]	[0.010,0.002]	[0.002,-0.010]

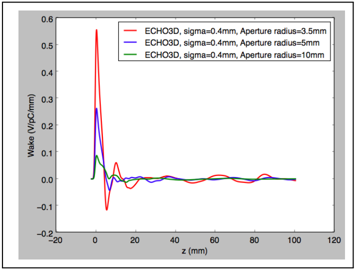
* [V/pC]
**[V/pC/mm]
R_a: Aperture radius

Wake Potential $\sigma = 0.4mm$

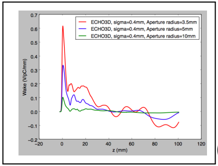
Echo3d: it takes 4 hours for every simulation.
CST: there is no enough resources to do such simulations for the short bunches



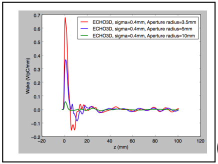
(L)



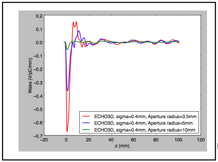
(D_x)



(D_y)



(Q_x)



(Q_y)

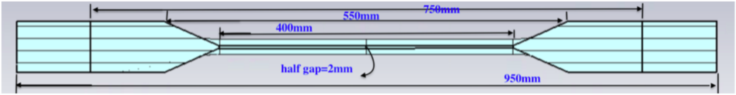
Summary of the collimator settings for the Z mode and for the 4 IP layout. The table includes both betatron and off-momentum collimators. The synchrotron collimators and masks upstream the IP are not included in the table. The length of these collimators is much longer than the SuperKEKB model (0.3 - 0.4 m instead of few mm))

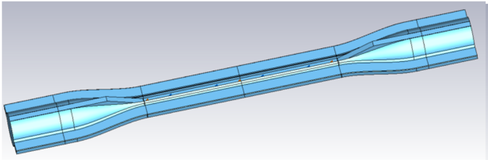
Updated table of collimation system

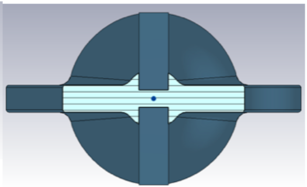
name	type	length[m]	nsigma	half-gap[m]	material	plane	angle[deg]	offset_x[m]	offset_y[m]	beta_x[m]	beta_y[m]
tcp.h.bl	primary	0.4	11.0	0.005504	MoGR	H	0.0	0.0	0.0	352.578471	113.054110
tcp.v.bl	primary	0.4	65.0	0.002332	MoGR	V	90.0	0.0	0.0	147.026106	906.282898
tcs.h1.bl	secondary	0.3	13.0	0.004162	Mo	H	0.0	0.0	0.0	144.372060	936.118623
tcs.v1.bl	secondary	0.3	75.5	0.00203	Mo	V	90.0	0.0	0.0	353.434125	509.320452
tcs.h2.bl	secondary	0.3	13.0	0.005956	Mo	H	0.0	0.0	0.0	295.623450	1419.375106
tcs.v2.bl	secondary	0.3	75.5	0.002118	Mo	V	90.0	0.0	0.0	494.235759	554.055888
tcp.hp.bl	primary	0.4	29.0	0.005755	MoGR	H	0.0	0.0	0.0	55.469637	995.306256
tcs.hp1.bl	secondary	0.3	32.0	0.01649	Mo	H	0.0	0.0	0.0	373.994993	377.277726
tcs.hp2.bl	secondary	0.3	32.0	0.011597	Mo	H	0.0	0.0	0.0	184.970621	953.229862

Collimator optimization

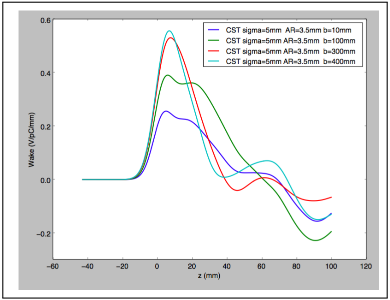
The length of these collimators is much longer than the SuperKEKB model (0.3 - 0.4 m instead of few mm)

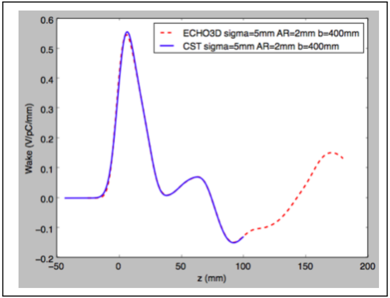






Geometric wakefield of collimators

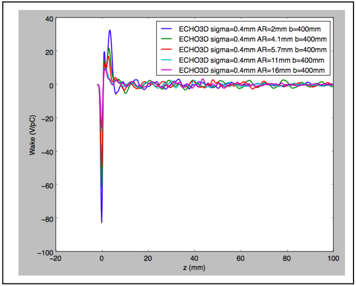




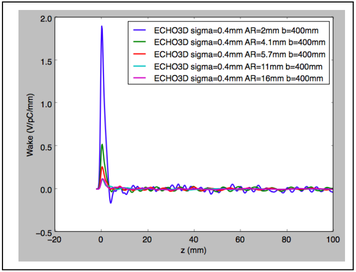
From 300 mm to 400 mm the wake potential is almost the same. For the wake potential of a 0.4 mm Gaussian bunch we have used ECHO3D (too high number of mesh cells was required by CST)

Collimator optimization

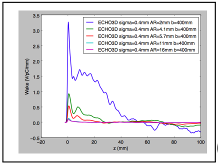
Wake potential calculations for different aperture radii of the collimators using Echo3d



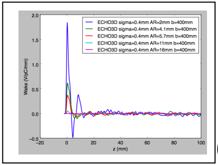
(L)



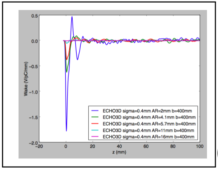
(D_x)



(D_y)

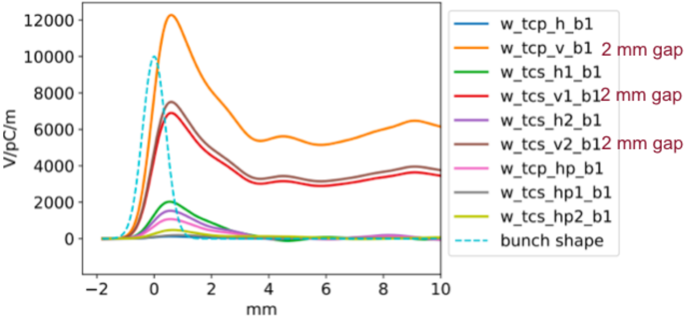


(Q_x)



(Q_y)

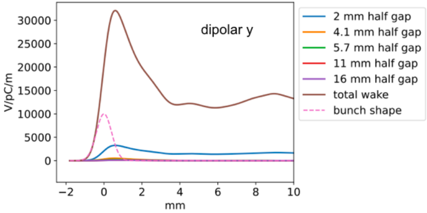
Transverse dipolar wake potential of 0.4 mm Gaussian bunch

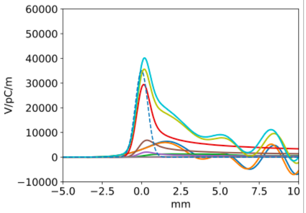


The highest contribution to the geometric wakefield is due to the vertical collimators with 2 mm half gap. At least in this case we should increase the length of the tapers.

Collimator optimization

Transverse dipolar wake potential of 0.4 mm Gaussian bunch



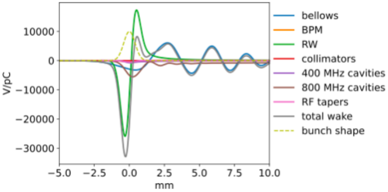


The geometric wakefield of the collimators with the model that we have adopted is too high. We need to reduce this contribution. How long the tapers can be?

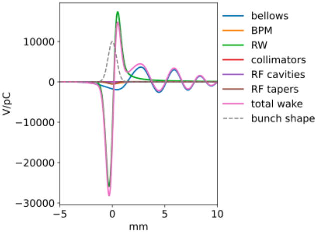
Collimator optimization

Longitudinal wake potential of 0.4 mm Gaussian bunch

New wake (longitudinal)



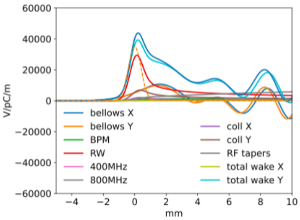
Standard Z-pole wake (longitudinal)



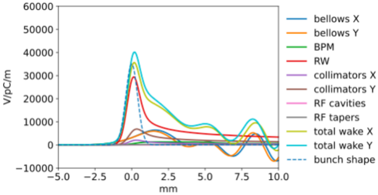
Collimator optimization

Transverse dipolar wake potential of 0.4 mm Gaussian bunch

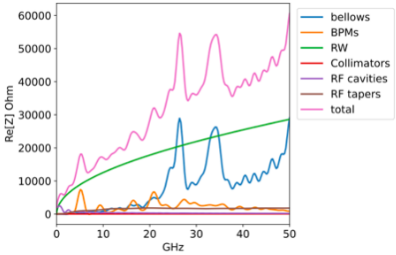
New wake (transverse dipolar)

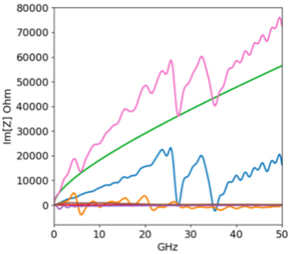


Standard Z-pole wake (transverse dipolar)

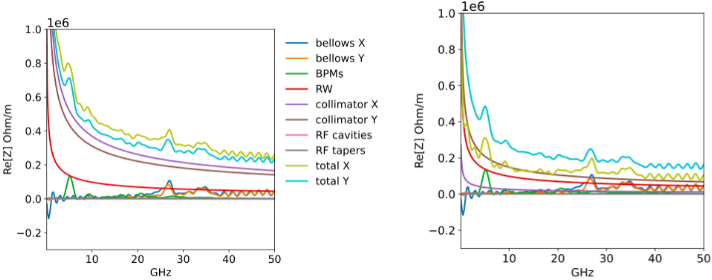


Total impedance: longitudinal





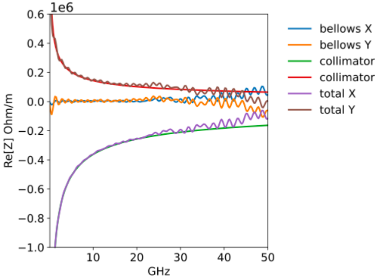
Total impedance: transverse dipolar

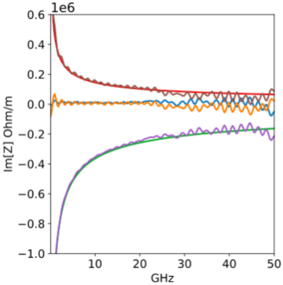


initial table

updated table

Total impedance: transverse quadrupolar





- We calculated the wake potential of the FCC collimators (ECHO3D and CST) and validated the results
- We will continue the work for the evaluation, reduction and optimization of the impedances of the main machine elements (e. g. bellows, collimators system)
- Analytical method to calculate wake potential for short bunch from long one by using the operation inverse to convolution (deconvolution method)

Thanks for your attention