Collimator model & FCC-ee impedance model

Mostafa Behtouei

INFN-LNF, on behalf of FCC group

E. Carideo, M. Migliorati, B. Spataro and M. Zobov

Acknowledgements: M. Boscolo, D. De Arcangelis, A. Abramov and all the collimation group

November 2022

- Motivation
  Why is the FCC project important?
  FCC-ee main parameters
- Main impedance sources
  Resistive wall, Bellows, Collimators
- Collimators
  Why Collimators are so important?
  Why do we need numerical simulations?
- How CST works (Wakefield Solver Overview)
  Wake fields and impedances calculations
- How ECHO3D works? (Wakefields 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)
- Preliminary and updated tables of collimation system
- Total impedance
  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}/cm^{2}s)	181	17.4	7.8	1.25

*SR: syncrotron radiation, BS: beamstrahlung

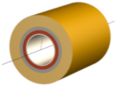
Main impedance sources

Main impedance sources (so far)

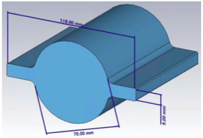
Resistive wall : It is the largest impedance source for FCC-ee evaluated so far. NEG coating is needed to mitigate the electron cloud build-up in the positron machine and for pumping reasons in both rings.

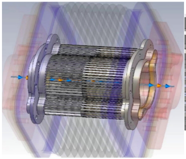
Bellows: They represent the second highest impedance source so far. We have used an upper pessimistic estimate of 20000 bellows

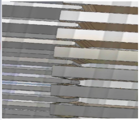
Collimators: Being close to the beam orbit they may introduce large impedance

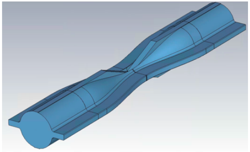


IRON	$\Delta = \infty$	$\rho = 6.89 \cdot 10^{-7} \Omega m$
DIELECTRIC	$\Delta = 6\,mm$	$\rho = 10^{-15} \Omega m$
COPPER	$\Delta = 2\,mm$	$\rho = 1.66 \cdot 10^{-8} \Omega m$
NEG	$\Delta = 150\,nm$	$\rho = 10^{-6} \Omega m$









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)

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

Solution: None

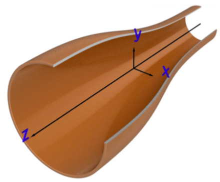
From Maxwell's equations (equation for the low frequency impedance of tapered transitions)

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

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

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

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

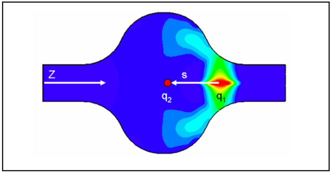


Geometry of a round transition.

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

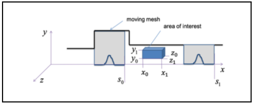
- The wakefield solver calculates the wake-potentials for a given structure from electromagnetic fields.
- Wakefield problems are driven by a bunch of charged particles, which is passing the observed structure parallel to a main coordinate axis.
- These particles cause electromagnetic fields, which are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

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

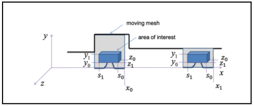


How ECHO3D works? (Wakefields calculations)

- 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)

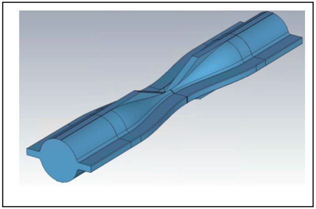


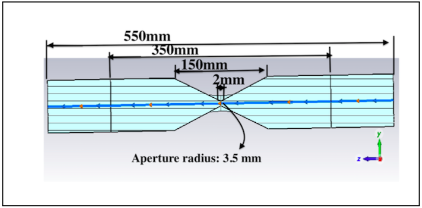
(Field monitor of type s-time)



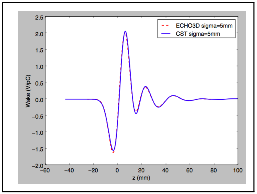
(Field monitor of type x-time)

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



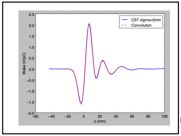


Geometric longitudinal wake potential of a 5 mm Gaussian bunch (ECHO3D Vs. CST)



(a)

Convolution vs CST (suggested by Mauro Migliorati)



(b)

Longitudinal wake potential of a distribution

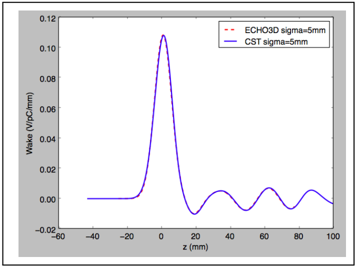
$$W_{||} = -\frac{U(z)}{qe} = \frac{1}{q}\int_{-\infty}^{\infty} \omega_{||}(z'-z)\lambda(z')dz' \quad (6)$$

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

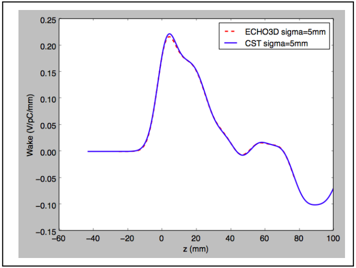
Dipole Wake Potential

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

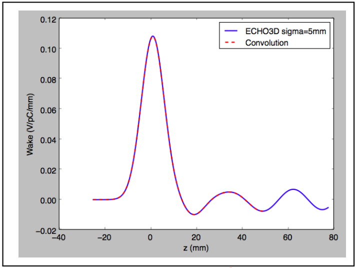
The transverse wake is due to the excitation of dipole modes. These modes are excited by the dipole momentum of the beam.



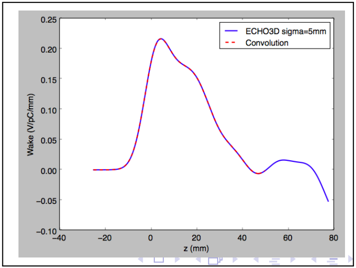
(D_x)



(D_y)

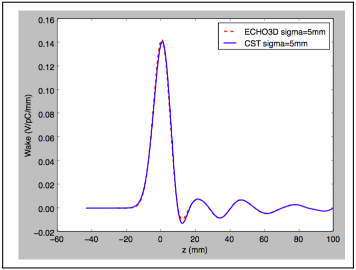


(D_x)

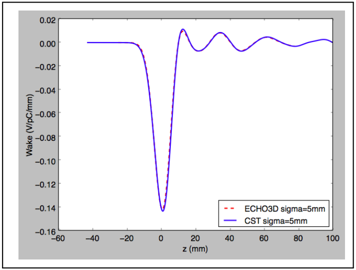


(D_y)

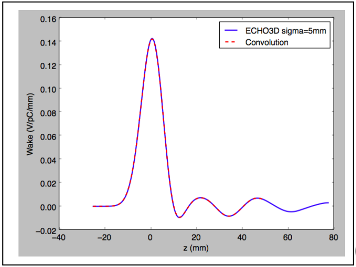
Geometric transverse quadrupolar wake potential of a 5 mm Gaussian bunch (ECHO3D Vs. CST) and its convolution



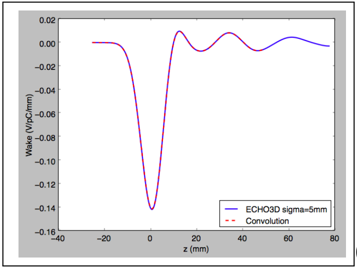
(Q_x)



(Q_y)

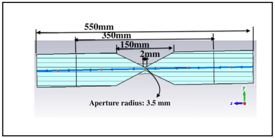


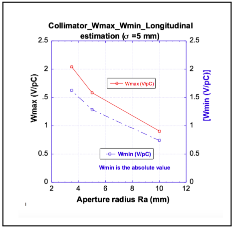
(Q_x)

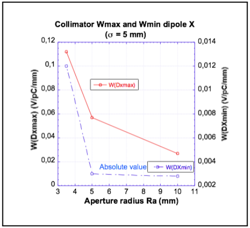


(Q_y)

Collimator optimization







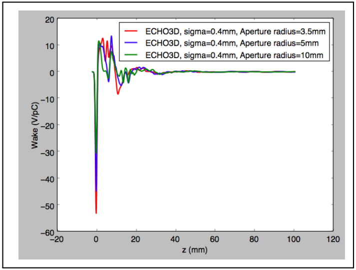
Longitudinal, transverse dipolar and quadrupolar wake potentials of a 5 mm Gaussian bunch (ECHO3D) for different aperture radii of the collimator (3.5mm, 5mm, 10mm)

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]

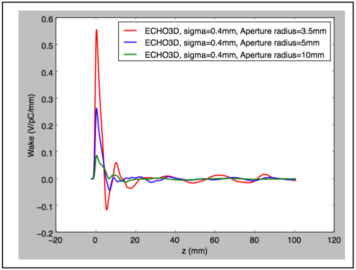
* [V/pC]
**[V/pC/mm]
R_a: Aperture radius

Wake Potential $\sigma = 0.4mm$

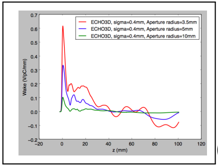
Echo3d: it takes 4 hours for every simulation.
CST: there is no enough resources to do such simulations for the short bunches



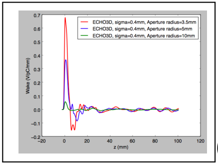
(L)



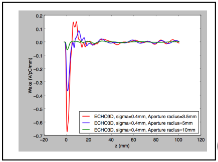
(D_x)



(D_y)

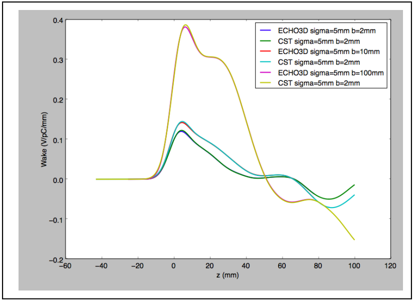


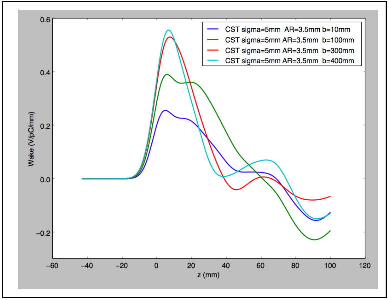
(Q_x)



(Q_y)

Transverse dipolar wake potentials of a 5 mm Gaussian bunch (ECHO3D) for different aperture lengthes of the collimator (2mm, 10mm, 100mm)





Collimation system

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))

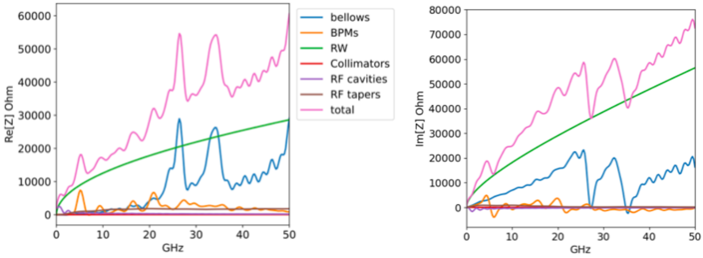
Preliminary table of collimation system

#collimator	type	length[m]	half-gap[m]	material	plane	offset_x[m]	offset_y[m]	beta_x [m]	beta_y [m]
tcp.h.bl	primary	0.4	0.005504	MoGR	H	0.0	0.0	352.578471410311295	113.054109500623440
tcp.v.bl	primary	0.4	0.000992	MoGR	V	0.0	0.0	329.331023390820064	163.921790515995099
tcs.h1.bl	secondary	0.3	0.004162	Mo	H	0.0	0.0	144.372060225234833	936.118623285785816
tcs.v1.bl	secondary	0.3	0.002159	Mo	V	0.0	0.0	406.501047352056446	576.026918367956227
tcs.h2.bl	secondary	0.3	0.005956	Mo	H	0.0	0.0	295.623449812136869	1419.37510613787344
tcs.v2.bl	secondary	0.3	0.000974	Mo	V	0.0	0.0	736.253284828415531	117.301450420286400
tcp.hp.bl	primary	0.4	0.005755	MoGR	H	0.0	0.0	55.469636601816113	995.306256172161511
tcs.hp1.bl	secondary	0.3	0.01649	Mo	H	0.0	0.0	373.994993388812532	377.277726493928981
tcs.hp2.bl	secondary	0.3	0.011597	Mo	H	0.0	0.0	184.970621310328227	953.229862066088458

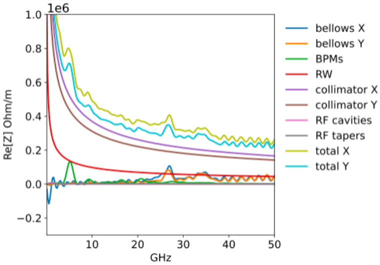
Updated table of collimation system

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

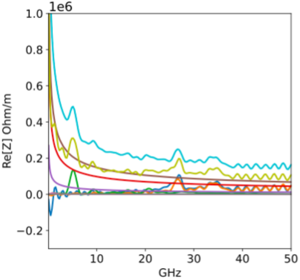
Total impedance: longitudinal



Total impedance: transverse dipolar

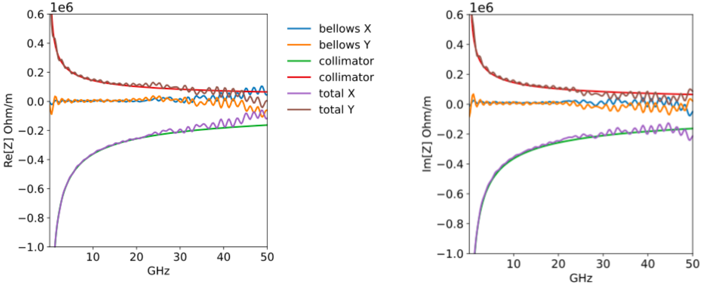


initial table

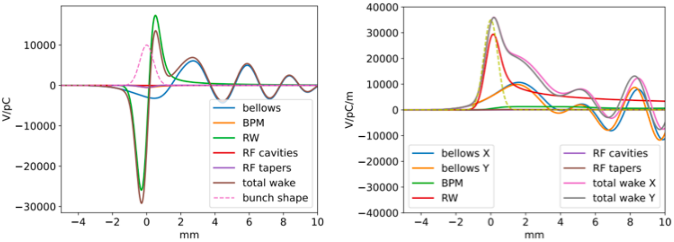


updated table

Total impedance: transverse quadrupolar



Wake potential of 0.4 mm Gaussian bunch



- We calculated the wake potential of the FCC collimators (ECHO3D and CST) and validated the results
- We calculated the total impedance of the machine elements (longitudinal, transverse dipolar and quadrupolar)
- 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