FCC-ee Collective Effects

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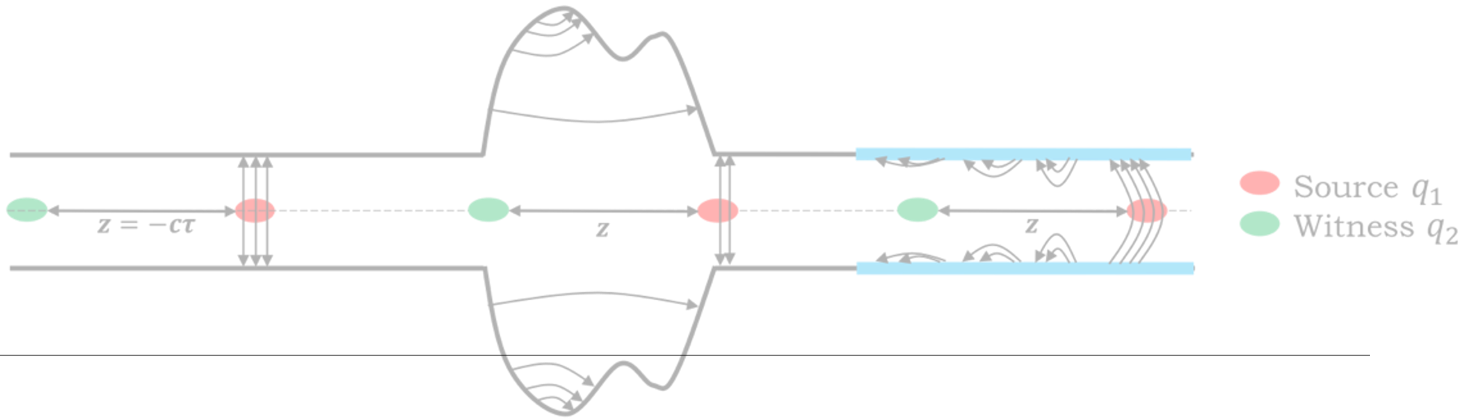
FCC-ee main parameters

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

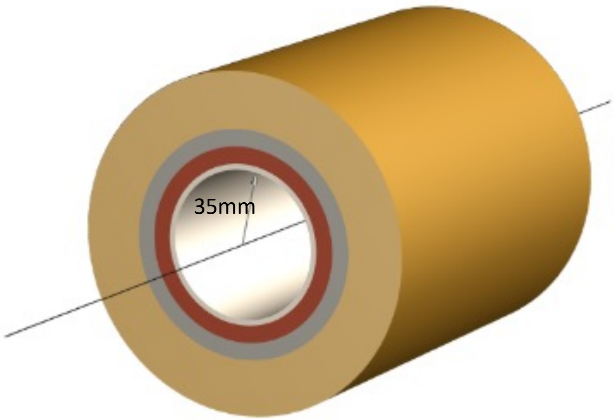
*SR: syncrotron radiation, BS: beamstrahlung

Resistive wall



- The interaction of the beam with the environment can produce **wakefields** (**impedances** in the frequency domain) that induce **instabilities**
  - The resistive wall impedance is produced by the finite conductivity of the pipe walls. The presence of the coating affects the RW impedance, increasing its imaginary part.
  - Since the resistive wall impedance is proportional to C, its contribution to the total machine impedance increases linearly with the machine length.
  - The main difference between FCC-ee and other colliders is its large circumference ≈ 91.17 km
  - By increasing the machine length the contribution of the RW impedance assumes more and more importance with respect to other elements

In FCC-ee, RW represents the main source of wakefields

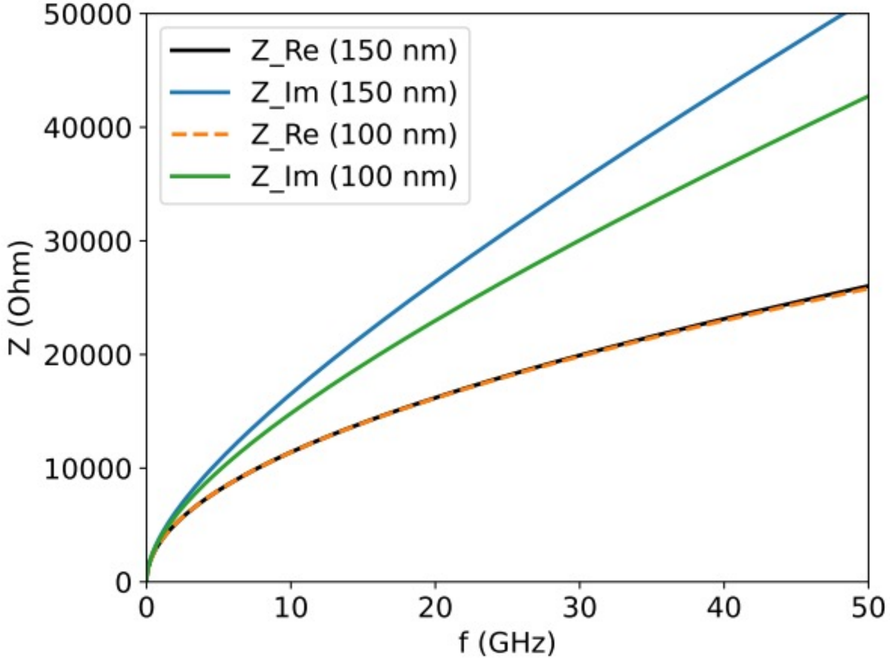


IRON	$\Delta = \infty$	$\rho = 6.89 \cdot 10^{-7}\Omega m$
DIELECTRIC	$\Delta = 6\ mm$	$\rho = 10^{-15}\Omega m$
COPPER	$\Delta = 2\ mm$	$\rho = 1.66 \cdot 10^{-8}\Omega m$
NEG	$\Delta = 150\ nm$	$\rho = 10^{-6}\Omega m$

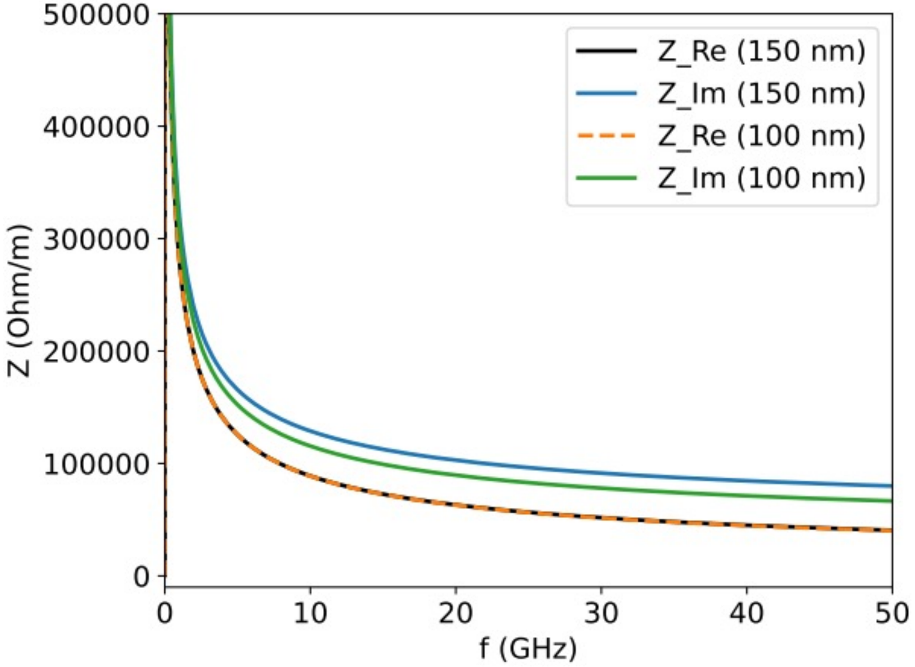
NEG coating is needed to mitigate the electron cloud build-up in the positron machine and for pumping reasons in both rings.

IW2D results for a circular pipe. We estimated a factor 1.1 for winglets contribution

Longitudinal Impedance

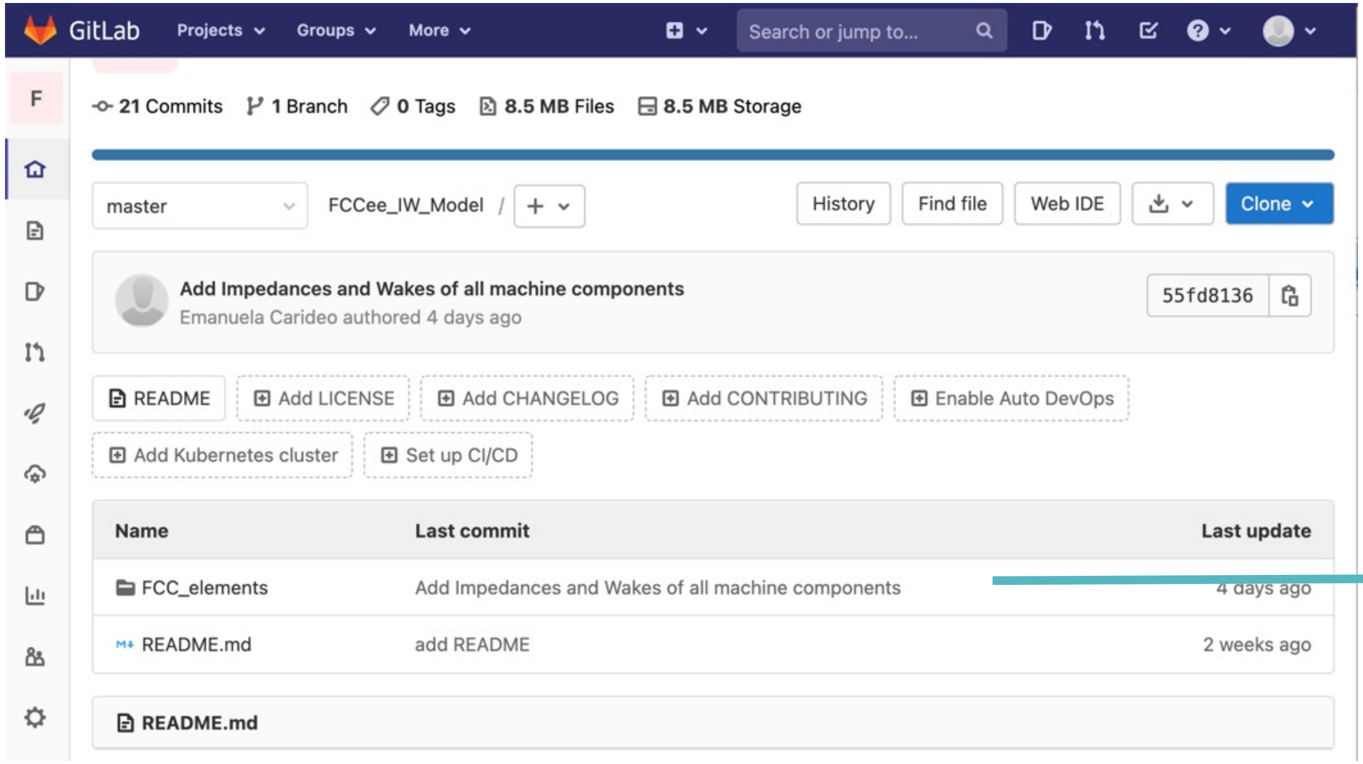


Transverse Impedance



Wake and impedance repository for FCC-ee: https://gitlab.cern.ch/ecarideo/FCCee_IW_Model

A repository, or Git project, encompasses the entire collection of files and folders associated with a project. Working in repositories keeps development projects organized and organized and protected.

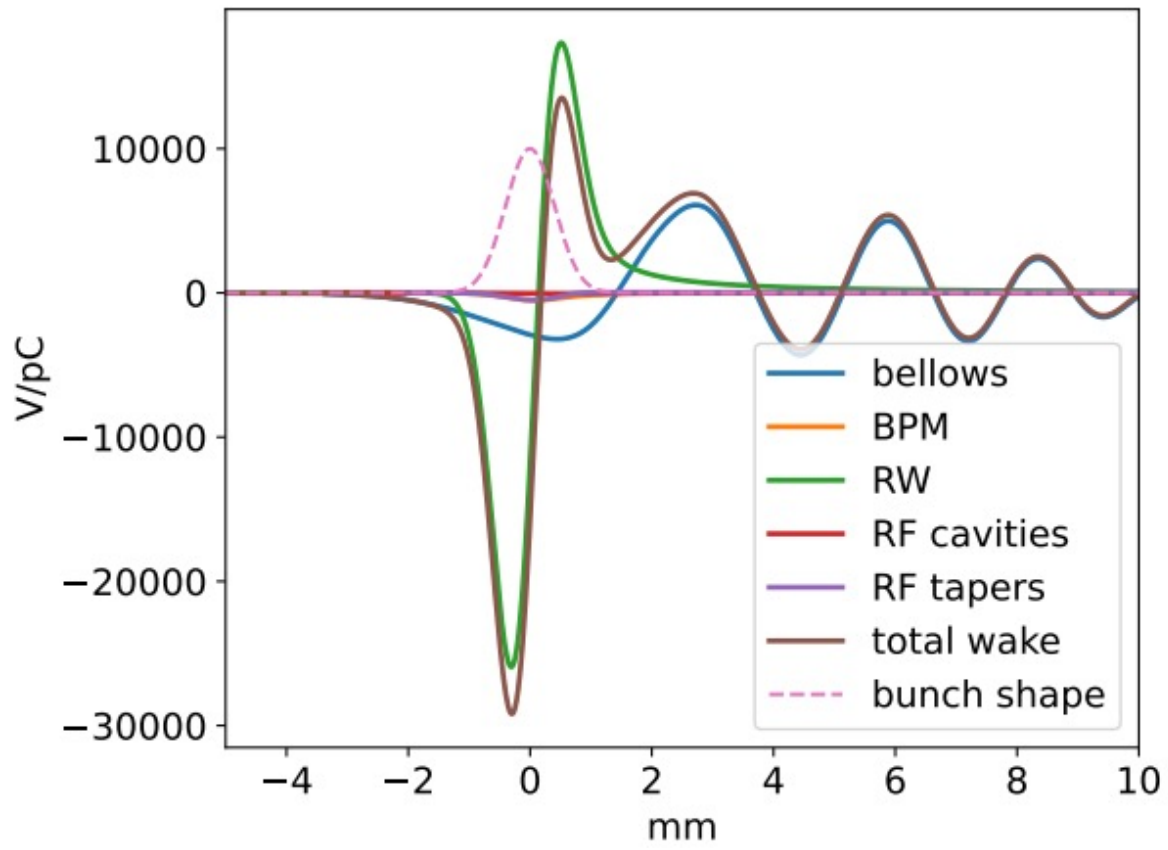


The Repository also provides more opportunities for project transparency and collaboration, working together to build the best possible final product.

How is it developed?

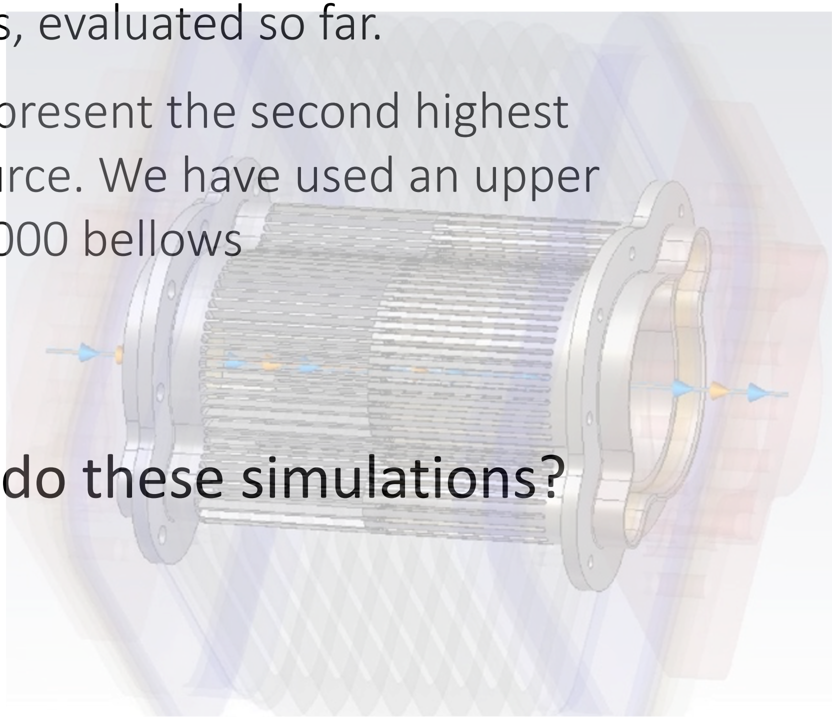
In this folder there are some of FCC-ee components and for each machine components the calculated impedance and wake

Impedance Sources: CST and IW2D simulations



Longitudinal wake potentials for a Gaussian bunch with nominal bunch length due to the main FCC-ee components, evaluated so far.

The bellows represent the second highest impedance source. We have used an upper estimate of 20000 bellows

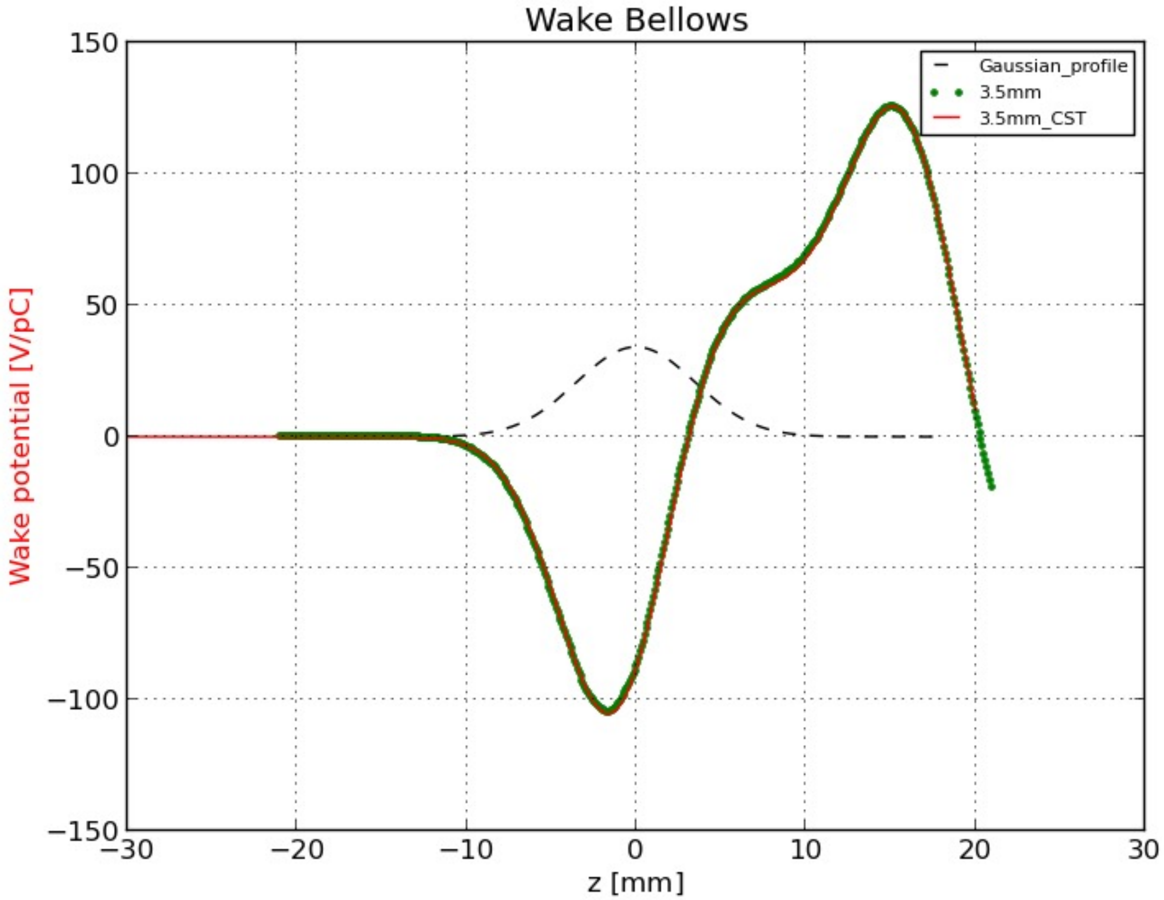


How did we do these simulations?

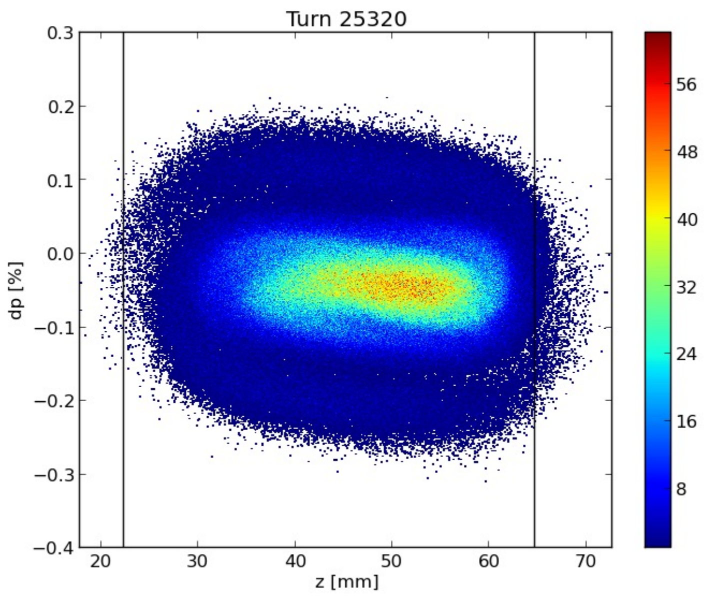
Method to calculate the Wake Potential by software simulation

Comparison of the wake potential of 3.5 mm bunch length between PyHT and CST: Bellows

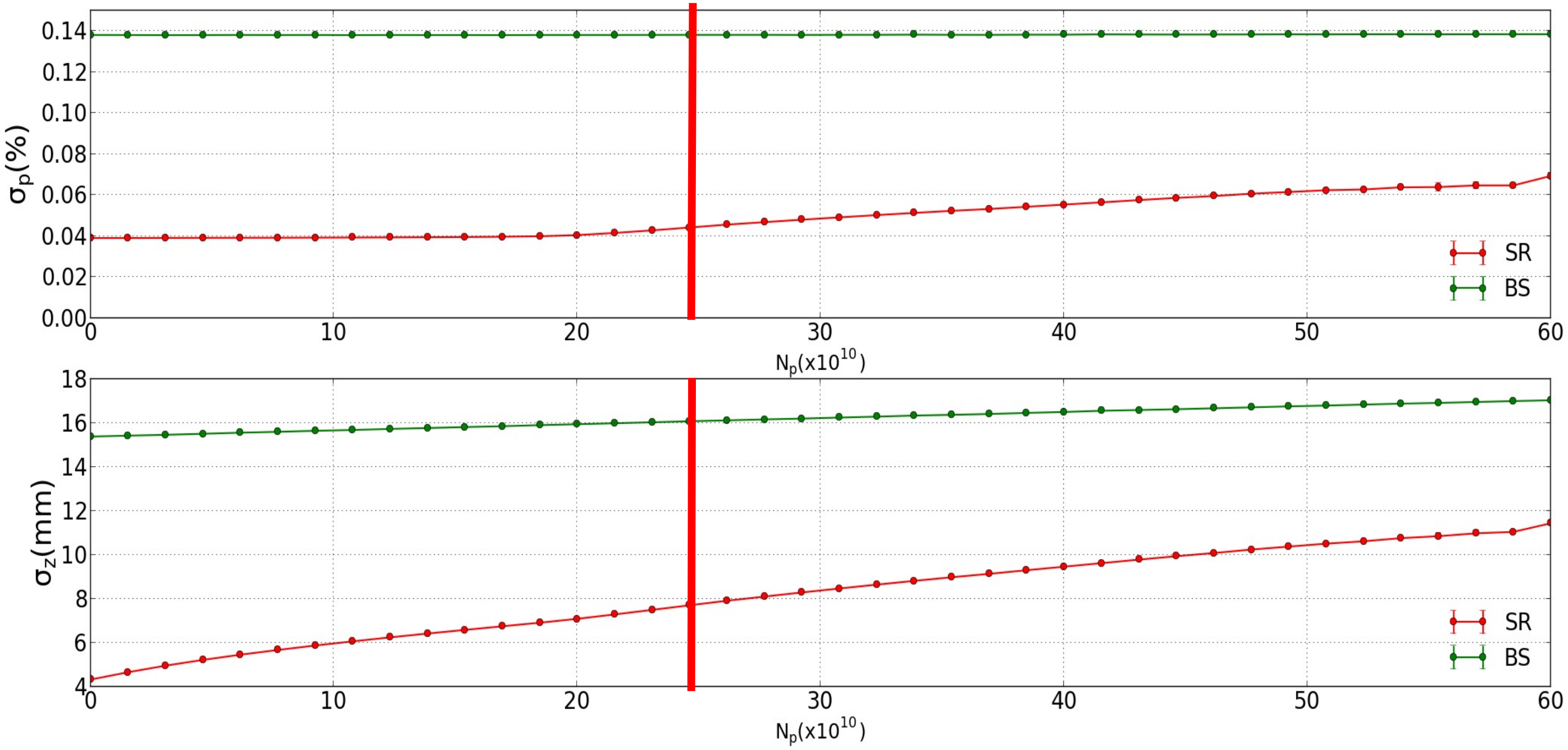
Wake potential for a Bellow of a 3.5 mm Gaussian bunch obtained directly by CST (red curve) and with the convolution by using the wake potential of 0.4 mm Gaussian bunch (green dots).



LONGITUDINAL DYNAMICS



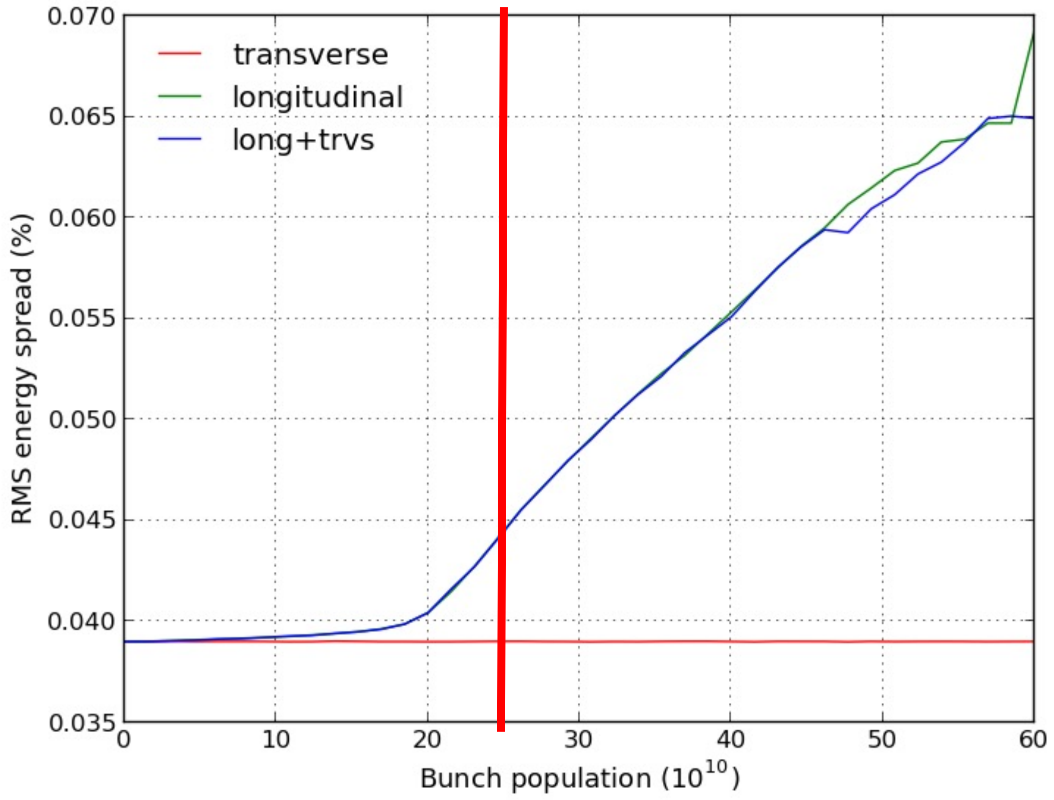
Longitudinal phase space

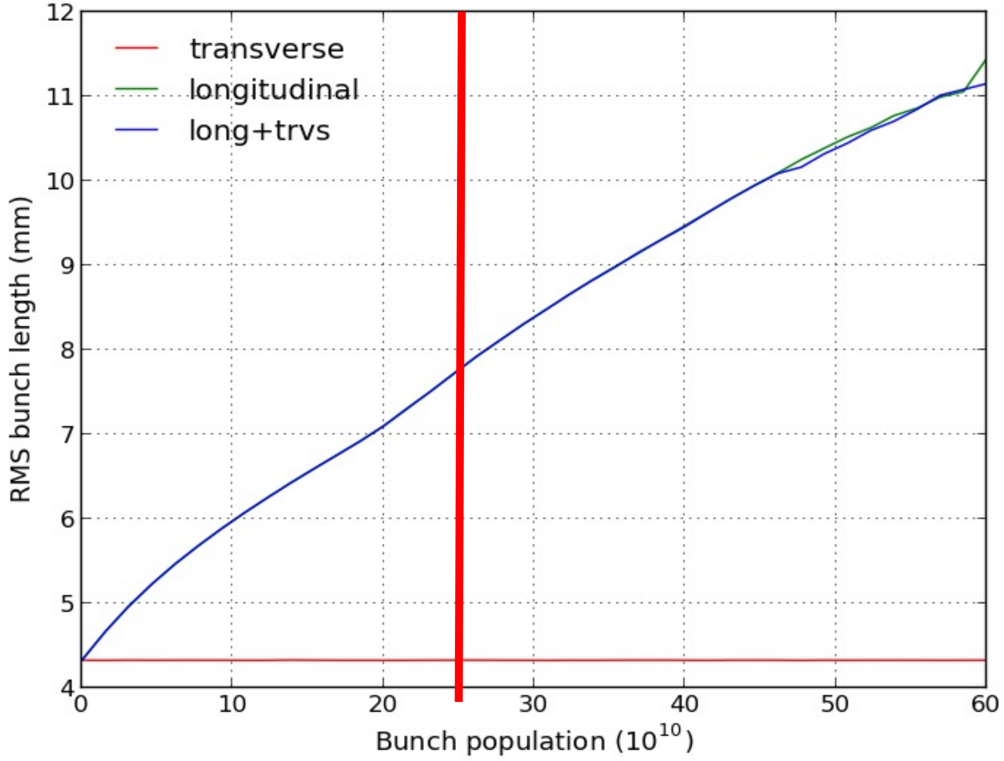


Bunch length (bottom) and RMS energy spread (top) as a function of bunch population in the case with (BS) and without (SR) beamstrahlung, which is considered here independent of the longitudinal impedance.

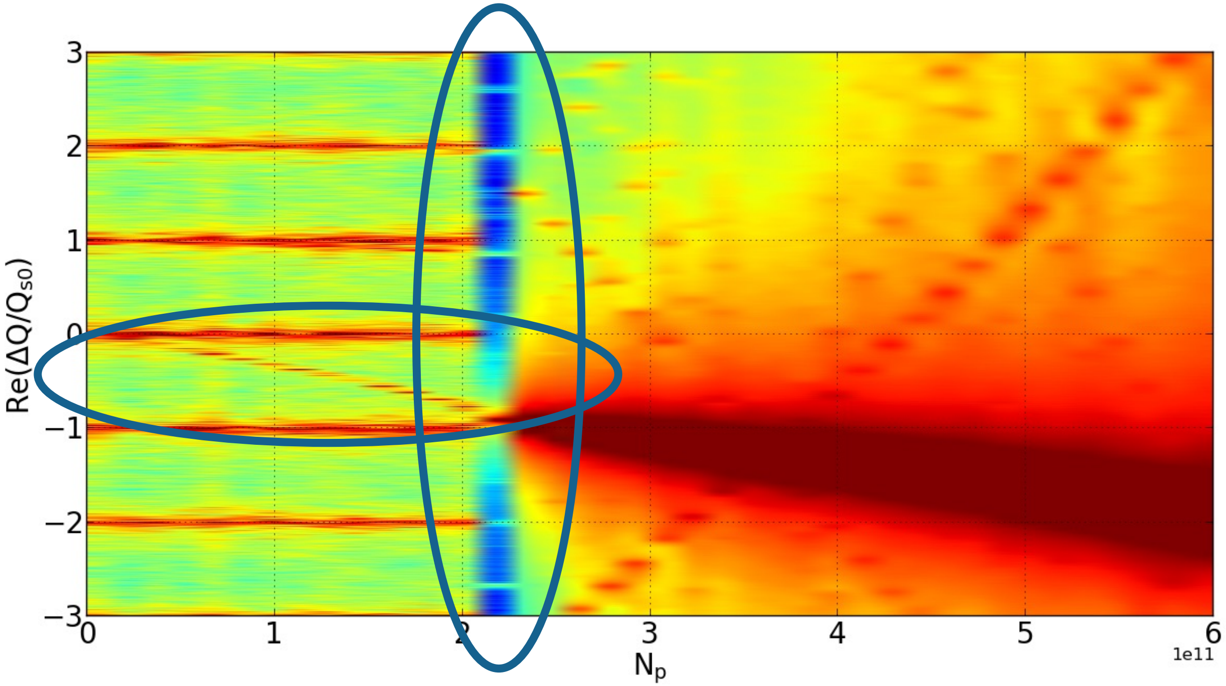
Bunch length and energy spread for considered cases

- The transverse impedance almost does not affect the longitudinal dynamics





FUTURE CIRCULAR COLLIDER



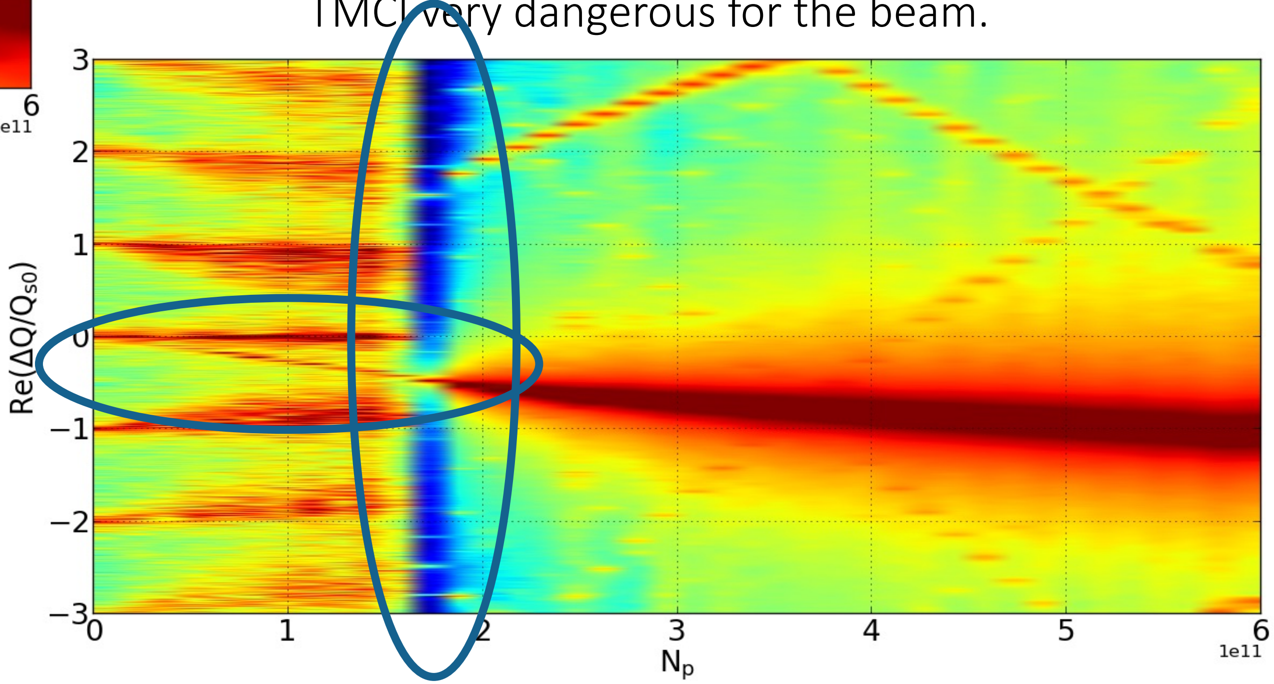
Transverse Dynamics

SR: Bunch length of 4.37 mm

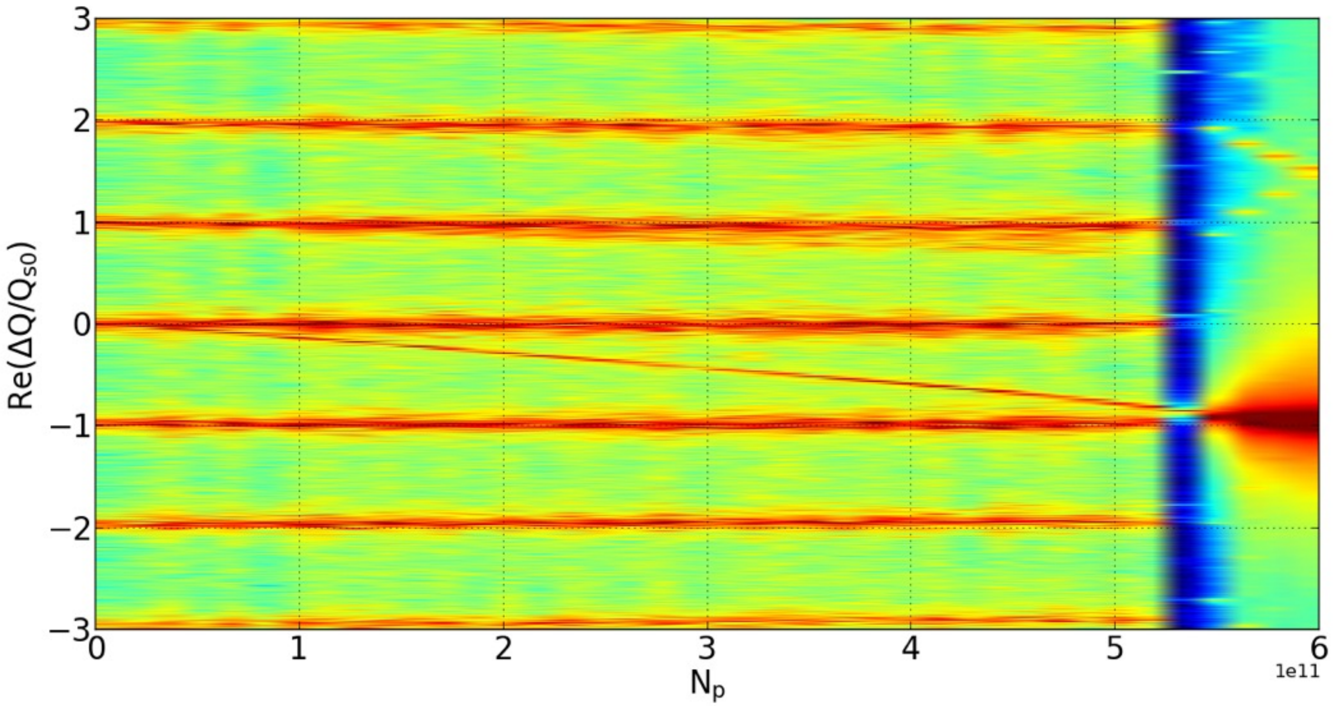
The TMCI, **Transverse Mode Coupling Instability,** occurs when the frequencies of two neighboring coherent oscillation modes merge together. Above the transverse instability threshold the bunch is lost and this makes the TMCI very dangerous for the beam.

On the top, real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without beamstrahlung, by considering only the transverse RW impedance produced by a NEG film with 150 nm thickness given by IW2D.

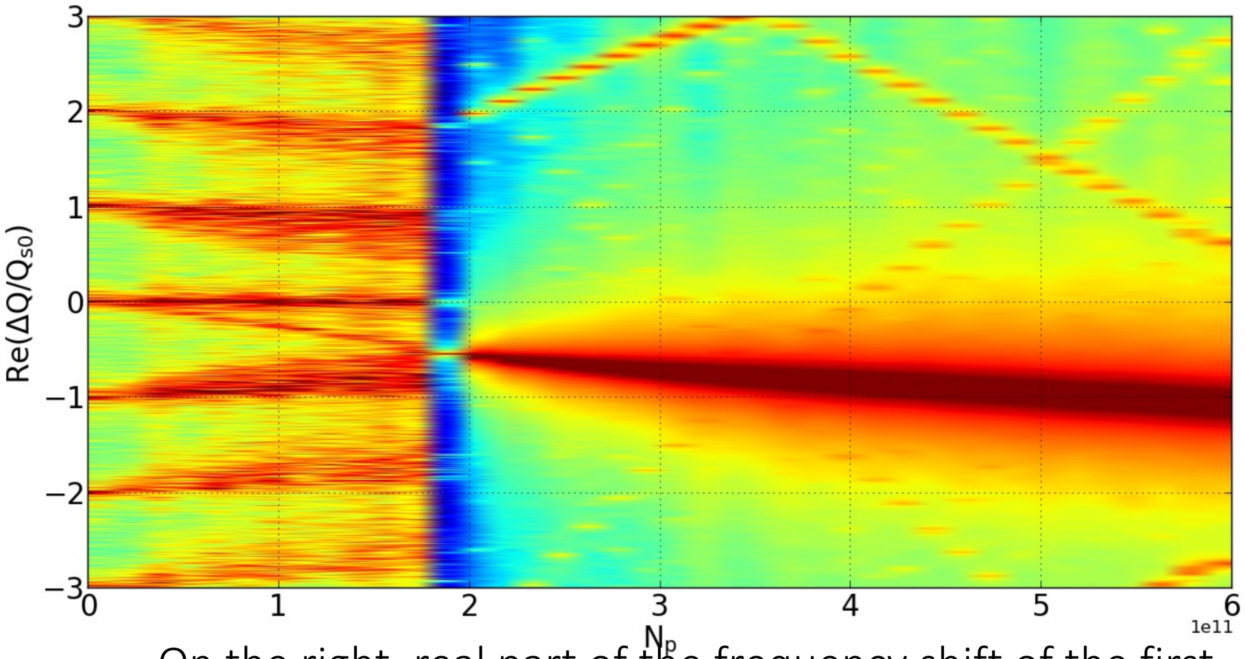
On the right, real part of the coherent tune shift as a function of intensity considering both longitudinal and transverse wakefield, by using PyHEADTAIL.



TMCI: longitudinal and transverse wake with a bunch length of 14.5 mm (BS)

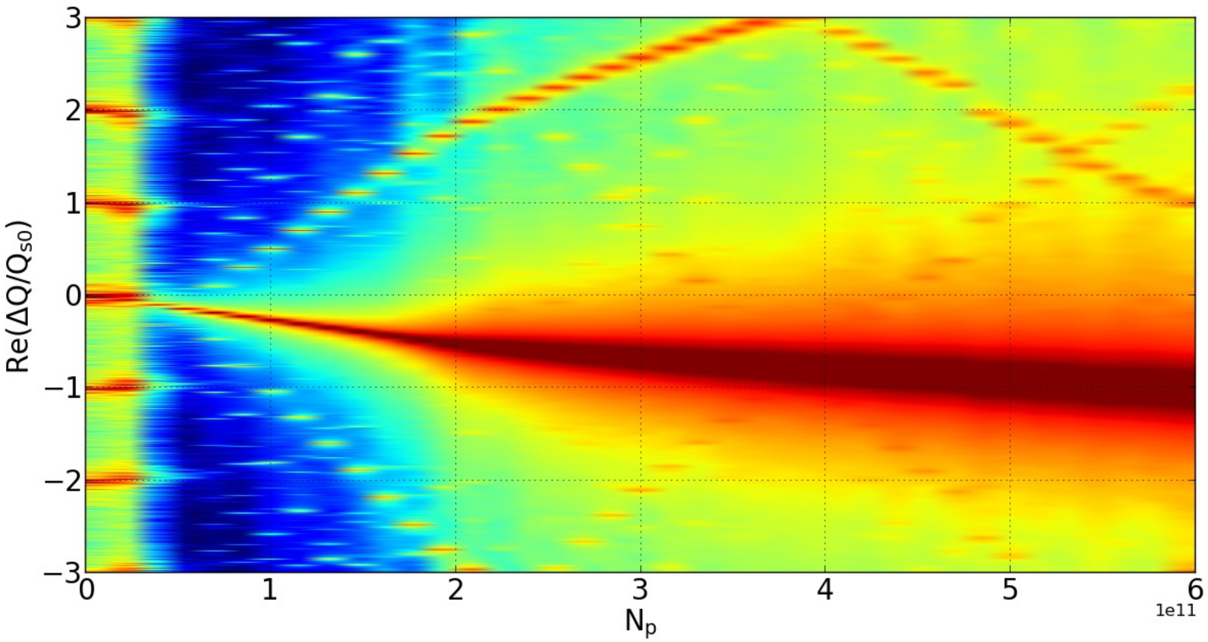


Variable Chromaticity:
Dependence of the TMCI from the Chromaticity



On the left, real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without beamstrahlung, so considering a bunch length of 4.37mm and a value of Chromaticity of +5

On the right, real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without beamstrahlung, so considering a bunch length of 4.37mm and a value of Chromaticity of -5:
the 0-mode is unstable and a feedback system is necessary



TCBI and feedback system

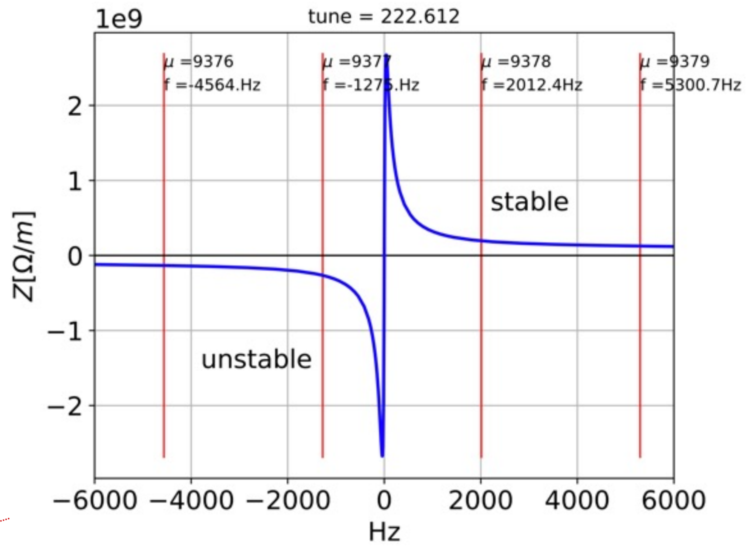
Transverse Coupled Bunch Instability (TCBI)

$$\frac{1}{\tau_{\mu,\perp}} = -\frac{ecI}{4\pi E Q_\beta}\sum_q Re[Z_\perp(\omega_q)]G_\perp\left(\frac{\sigma_z}{c}\omega'_q\right)$$

where $$Re[Z_\perp(\omega_q)] = \mathrm{sgn}(\omega)\frac{C}{2\pi b^3}\sqrt{\frac{2Z_0 c}{\sigma_c|\omega|}}$$

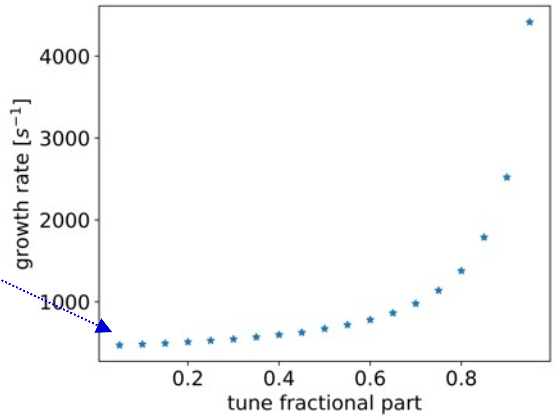
$$\omega_q = (qM + \mu + Q_\beta)\omega_0$$

$$\omega'_q = \omega_q + \xi\frac{\omega_\beta}{\eta}$$



The most dangerous mode is that closest to the origin (with negative frequency)

Rise time of about 6 revolution turns



A robust feedback is required for the instability suppression!

TMCI and feedback system

- In SuperKEKB the transverse feedback was one important source of the ‘-1’ mode instability which limited the machine to reach the nominal intensity. Its damping time is around 100 turns, that is about 1000 1/s.

- What is the effect of feedback in FCC-ee that needs about the same damping time, but this corresponds to only few turns?

A robust feedback is required for the instability suppression!

- Is the TMCI perturbed by the feedback? And what about the longitudinal effect of the wake?

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 041003 (2021)

Imaginary tune split and repulsion single-bunch instability mechanism in the presence of a resistive transverse damper and its mitigation

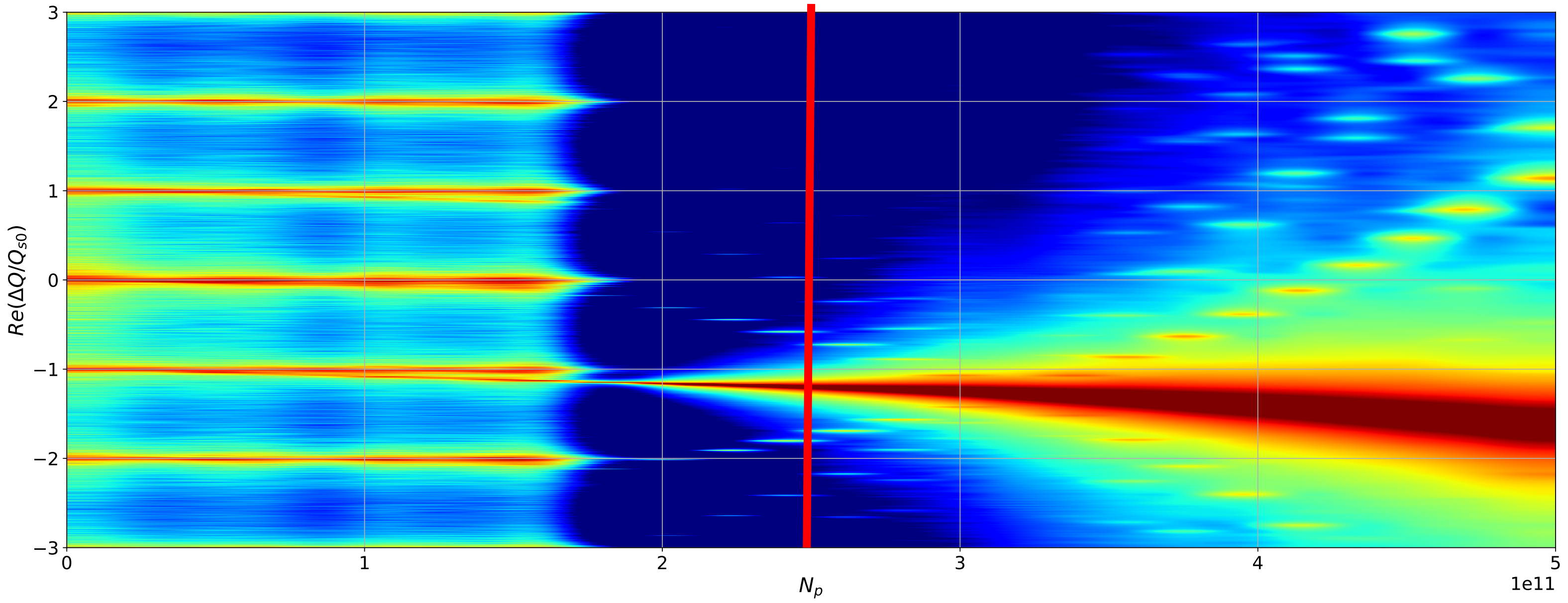
E. Métral

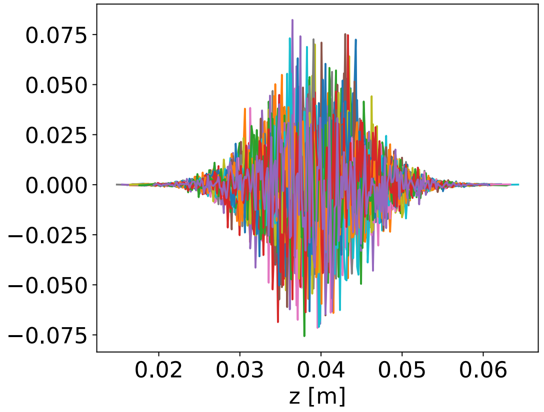
Introduction

[…] However, a resistive transverse damper also destabilizes the single-bunch motion below the transverse mode coupling instability intensity threshold (for zero chromaticity), introducing a new kind of instability, which has been called ITSR instability (for imaginary tune split and repulsion). […]

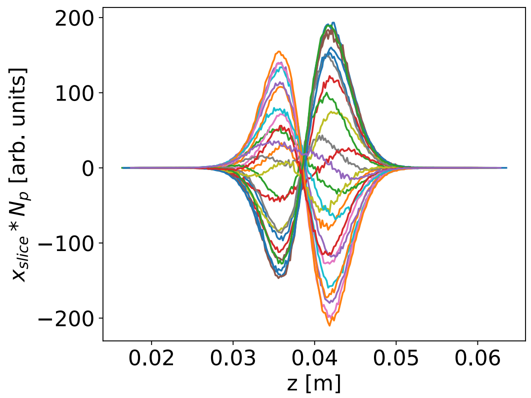
ITSR instability: Imaginary Tune Split and Repulsion

Only Transverse wakefield, resistive feedback, 10 turns damping time





$N_p = 16{\times}10^{10}$

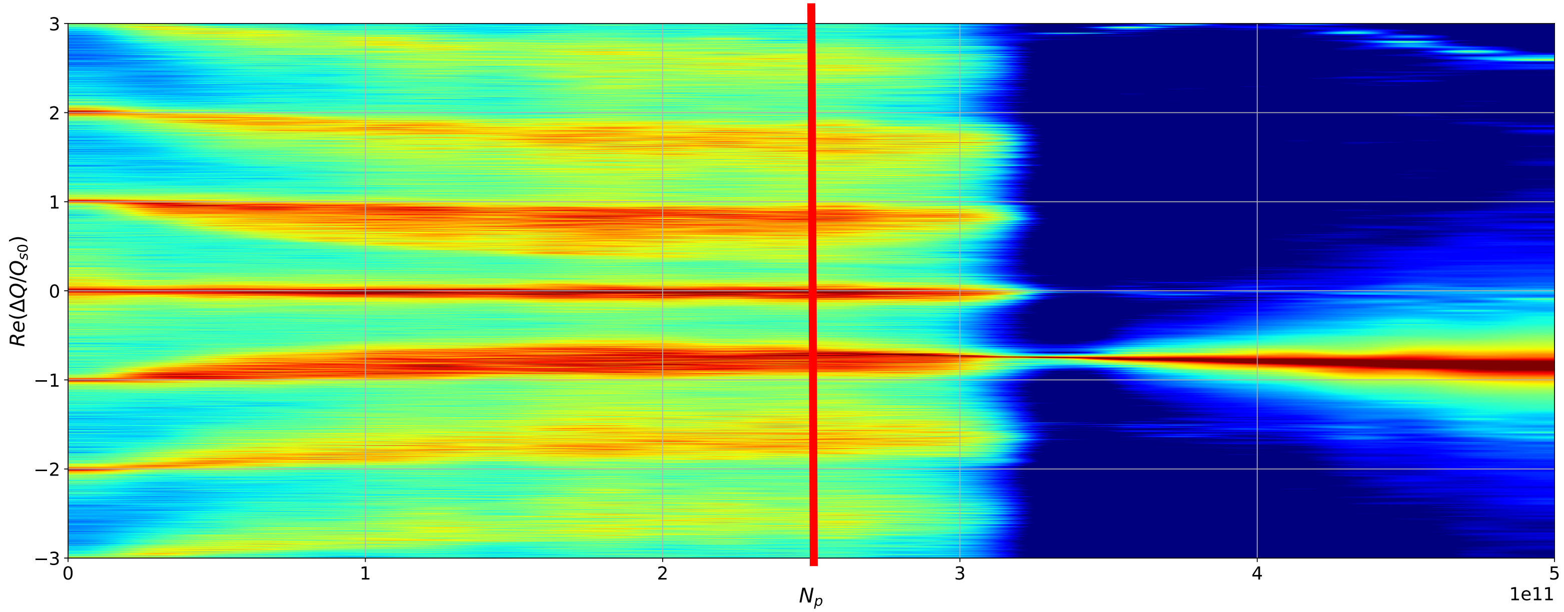


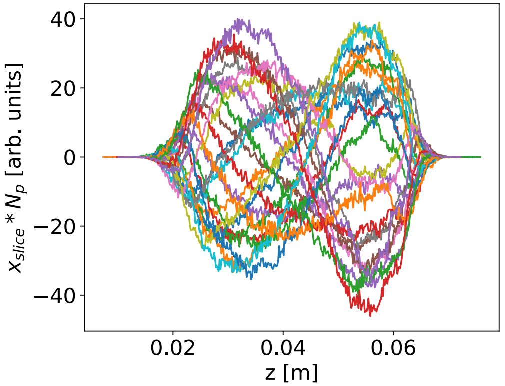
$N_p = 18{\times}10^{10}$

FUTURE CIRCULAR COLLIDER

ITSR instability: Imaginary Tune Split and Repulsion

Long. + Transverse wakefield, resistive feedback, 10 turns damping time



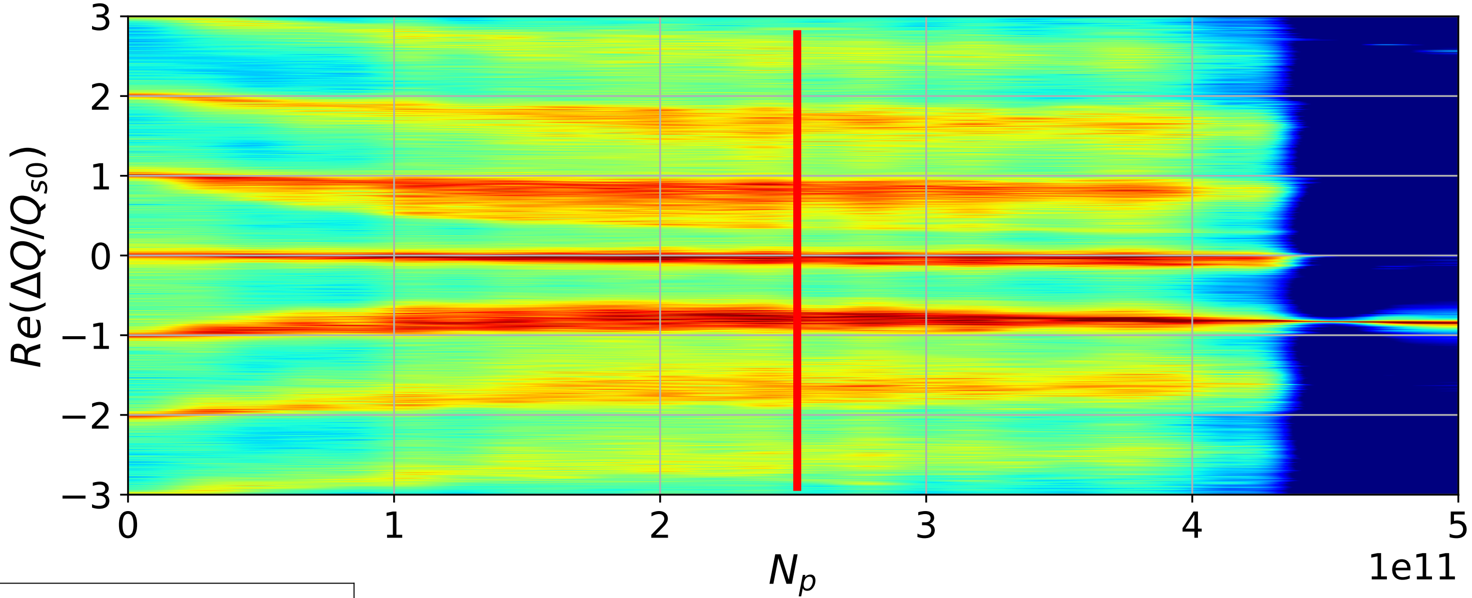


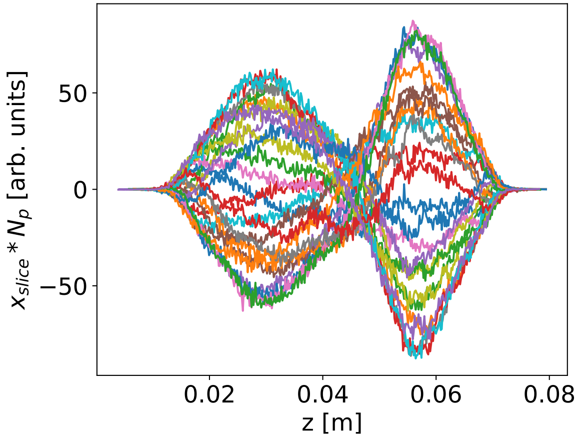
$N_p = 34\times10^{10}$

The spread in the synchrotron tune due to the longitudinal wakefield helps to mitigate the ITSR instability

ITSR instability: Imaginary Tune Split and Repulsion

Long. + Transverse wakefield, resistive feedback, 4 turns damping time



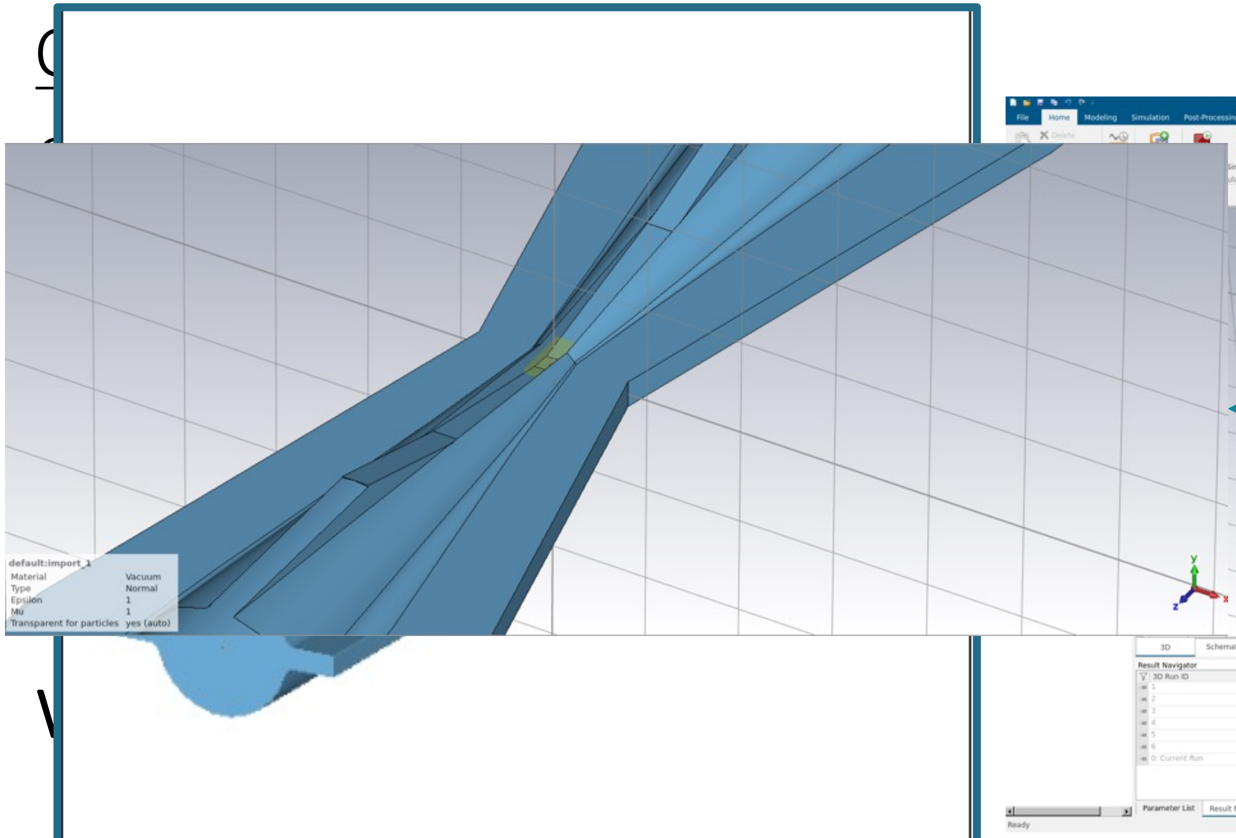


$N_p = 46{\times}10^{10}$

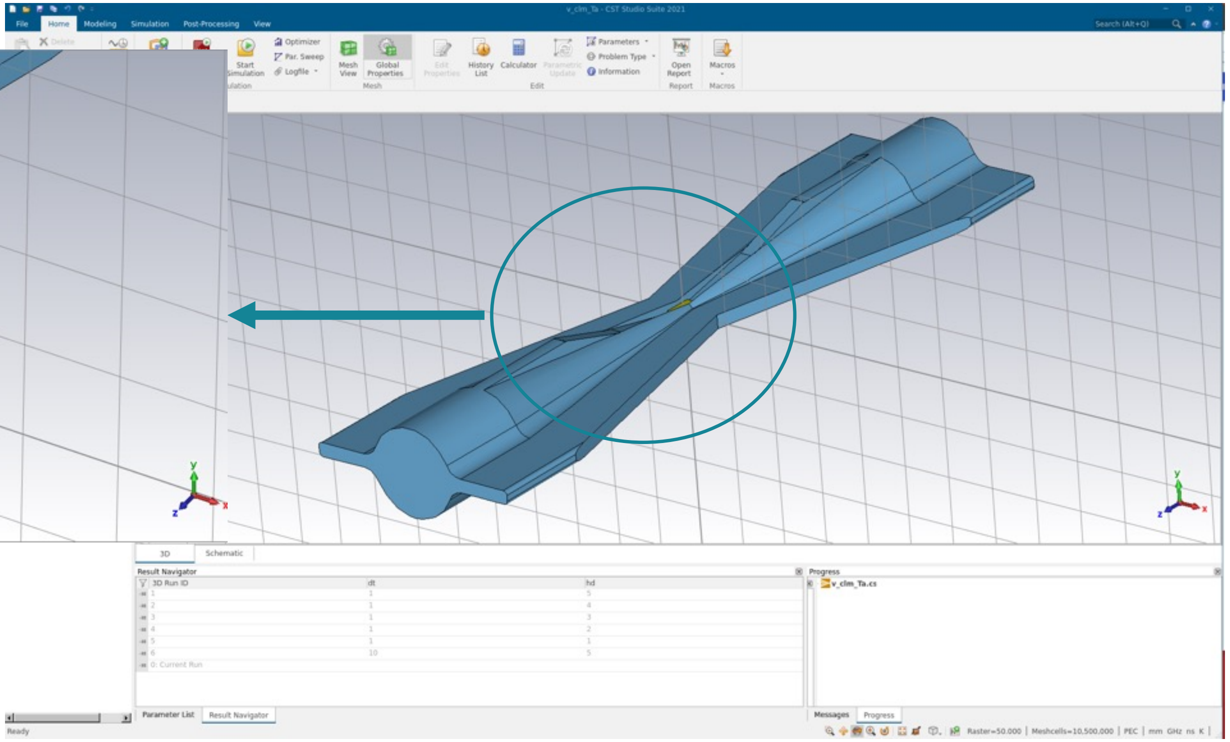
Beamstrahlung reduces the effect of the longitudinal wakefield which, on its turn, has a beneficial effect on the TMCI with a resistive transverse damper. What happens if both effects are present?

FUTURE CIRCULAR COLLIDER

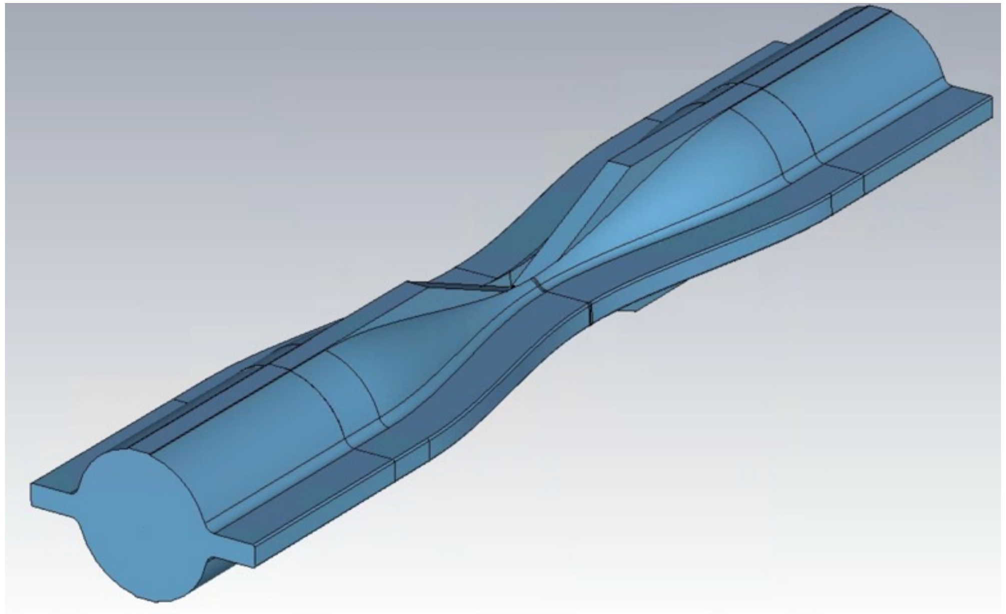
Work in progress: Collimator system



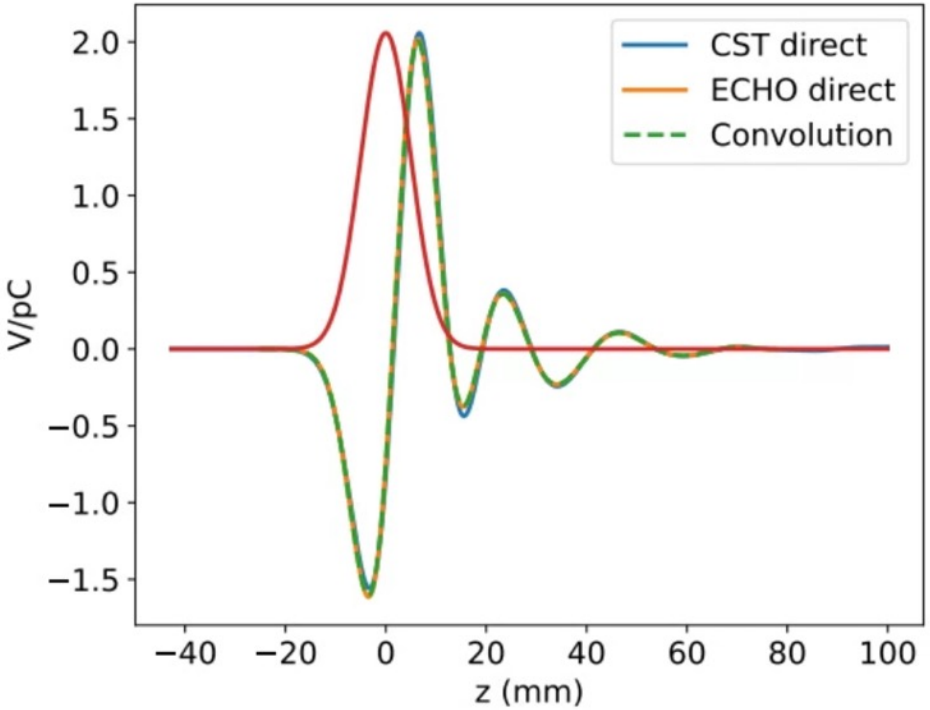
Vertical FCCee collimator



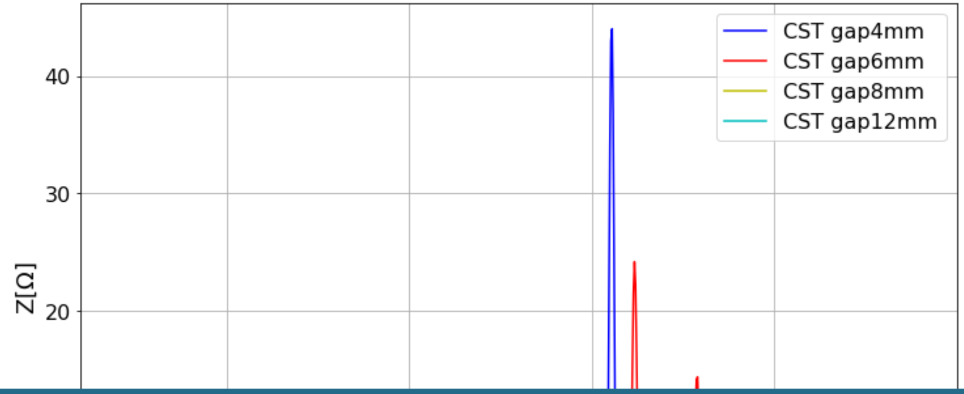
Preliminary work on collimation system

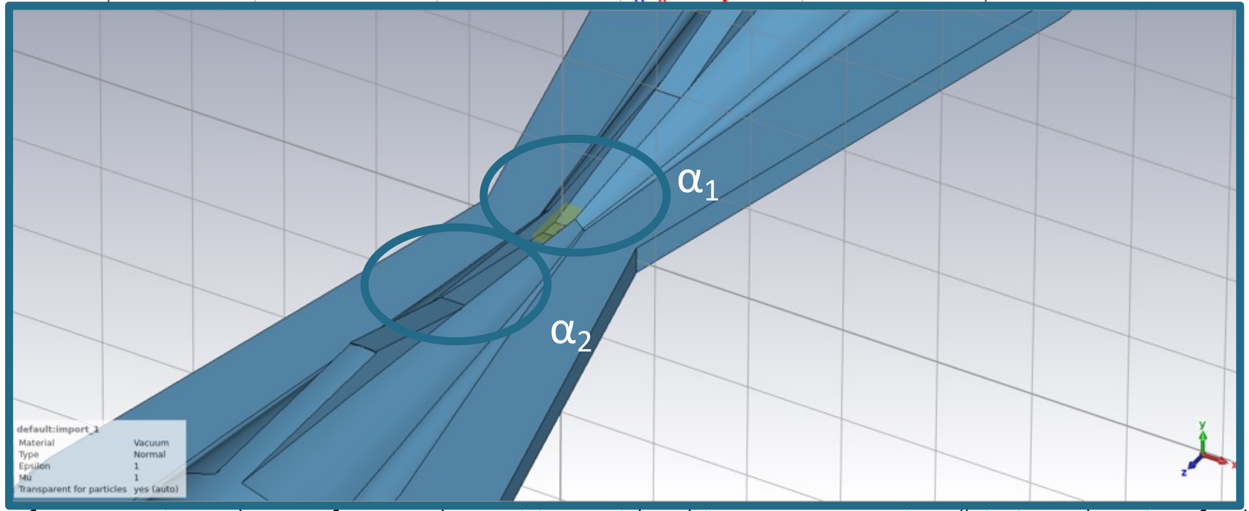


Geometric longitudinal wakefield of a 5 mm Gaussian bunch



Preliminary work





- Used a round taper model to calculate the transverse impedance

The approximate formula that I have used for the round taper is extrapolated from Stupakov1 's paper :

$$Z_{\perp}^{round} = -\frac{iZ_0}{2\pi}\int dz\left(\frac{g'}{g}\right)^2$$

Z_0=377 # Ohm
a, b_1, b_2 are gaps
α_1= 11.74*0.0174533 is the angle of the taper in radiant
α_2= 4.38*0.0174533 is the angle of the taper in radiant

$$Z_{\perp 1}^{round} = \frac{Z_0 * \tan(\alpha_1)}{2\pi}\left(\left(\frac{1}{a}\right)-\left(\frac{1}{b_1}\right)\right)$$

$$Z_{\perp 2}^{round} = \frac{Z_0 * \tan(\alpha_2)}{2\pi}\left(\left(\frac{1}{b_1}\right)-\left(\frac{1}{b_2}\right)\right)$$

$$Z_{\perp}^{round} = Z_{\perp 1}^{round} + Z_{\perp 2}^{round}$$

1: "Low frequency impedance of tapered transitions with arbitrary cross sections" G. Stupakov, Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

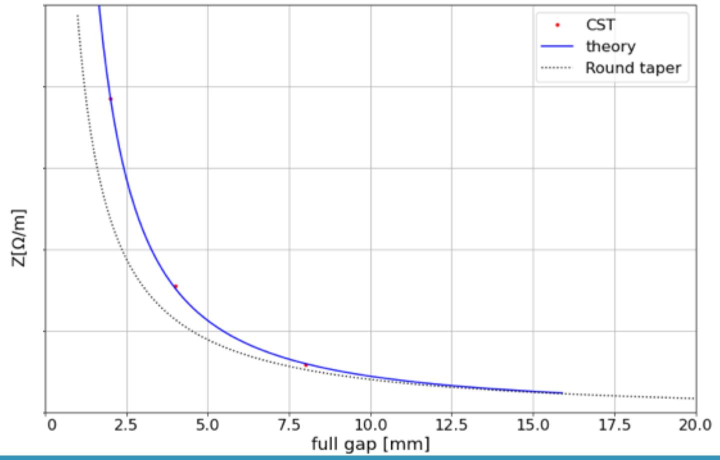
How could we do?

- We have the simulation data for some gaps.
- We extrapolate the transverse impedance at different gaps by using a nonlinear fits in Python:

$$Z = A * g^{-\alpha}$$

Where:
Z - transverse impedance
g - gap
A and alpha - constants to be found during the fit.

- We have the impedance from the theory



Update on collimation model

Summary of the collimator settings for the Z mode. The table doesn't include the SR collimators around the IPs, nor the collimators for a separate off-momentum collimation insertion.
The collimator settings and parameters are very preliminary.

#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	113.05410950062344O
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	1419.3751061378734
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

Observe that the length of these collimators is much longer than the SuperKEKB model (0.3 – 0.4 m).
We are investigating their contribution by considering the RW impedance of parallel plates

Challenges and Future Plan

Continue the work for the evaluation, reduction and optimization of the impedances of the main machine elements (e. g. collimators system), and also for implementing the FCC-ee repository.

Continue to investigate on the beam-beam effect, longitudinal and transverse coupling impedance

Continue to investigate diversified mitigation techniques: feedback system (resistive + reactive), chromaticity, …

Split the machine into segments, each one having its own longitudinal wake, transverse wake weighted by the local beta function, RF system (which is not evenly distributed along the machine), …

Study the effects of possible transverse localized impedances (in particular for the collimation system)

Use a more realistic transverse lattice

Other effects: electron could, (also multi-bunch), ion instabilities …