Impedance model and single beam instabilities
Overview

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FCCIS WP2 workshop 2021ç overview of impedance model and impedance instabilities

Overview	Mauro Migliorati
Impedance database and single-bunch thresholds	Emanuela Carideo
Impedance of bellows	Chiara Antuono
Modelling of the FCC resistive wall impedance	Ali Rajabi (DESY)
Electron-cloud → see talks in the afternoon	

Outline

- FCC-ee main parameters
- Overview of wakefields and impedances evaluated so far
- Longitudinal and transverse single beam instabilities: comments
- Interplay between beam-beam and longitudinal beam coupling impedance

FCC-ee main parameters

Lowest beam energy: highest beam current, highest number of bunches, highest bunch population, and (almost) lowest emittance

Important for collective effects

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-1.0			
# of IPs		4			
Circumference	[km]	91.180			
Bending radius of arc dipole	[km]	9.935			
Energy loss / turn	[GeV]	0.0391	0.370	1.869	10.0
SR power / beam	[MW]	50			
Beam current	[mA]	1400	135	26.7	5.00
Bunches / beam		8800	1320	280	42
Bunch population	[10^{11}]	2.76	1.94	1.81	2.26
Horizontal emittance ε_x	[nm]	0.71	2.17	0.64	1.49
Vertical emittance ε_y	[pm]	1.42	4.34	1.29	2.98
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.5		7.33	
Arc sextupole families		75		146	
$\beta^*_{x/y}$	[mm]	150 / 0.8	200 / 1.0	300 / 1.0	1000 / 1.6
Transverse tunes/IP $Q_{x/y}$		55.543 / 55.600		100.543 / 99.600	
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.138	0.069 / 0.137	0.103 / 0.202	0.157 / 0.238
Bunch length (SR/BS) σ_z	[mm]	4.32 / 15.2	2.96 / 5.90	2.50 / 4.90	1.67 / 2.54
RF voltage 400/800 MHz	[GV]	0.120 / 0	1.35 / 0	2.48 / 0	4.0 / 7.67
Synchrotron tune Q_s		0.0370	0.0237	0.0438	0.0890
Long. damping time	[turns]	1170	216	64.5	18.5
RF acceptance	[%]	1.6	4.3	2.3	3.7
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.5
Beam-beam ξ_x/ξ_y [a]		0.0040 / 0.159	0.0135 / 0.110	0.0185 / 0.141	0.096 / 0.138
Luminosity / IP	[10^{34}/cm^{2}s]	181	17.4	7.8	1.25
Lifetime (q + BS)	[sec]	–		422	2770
Lifetime (lum)	[sec]	1136	1197	552	743

[a] incl. hourglass.

FCC-ee updated main parameters at lowest energy: comparison with CDR

In Layout 31.10 → 4 IPs

Parameter list	Layout 31.10	CDR
Circumference (km)	91.180	95.146
Beam energy (GeV)	45.6	45.6
Beam current (A)	1.28	1.4
Bunch population [10^{11}]	2.76	1.69
Bunch length [mm](SR/BS)	4.32/15.2	3.5/12.1
Energy spread(SR/BS) [10^{-3}]	0.39/1.38	0.38/1.54
Synchrotron tune	0.0370	0.0248
Bunches/beam	8800	16400
Mom compaction [10^{-6}]	28.5	15.3
Energy loss/turn (MeV)	39.1	35.7
RF Voltage (MV)	120	98

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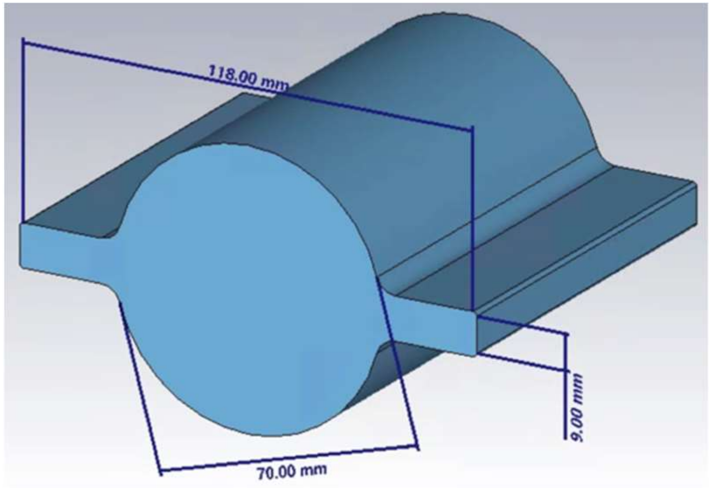
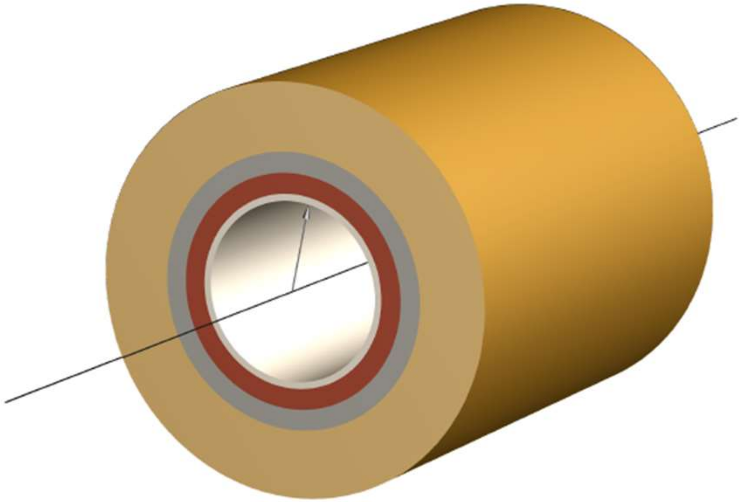
Resistive wall

Real beam pipe cross section

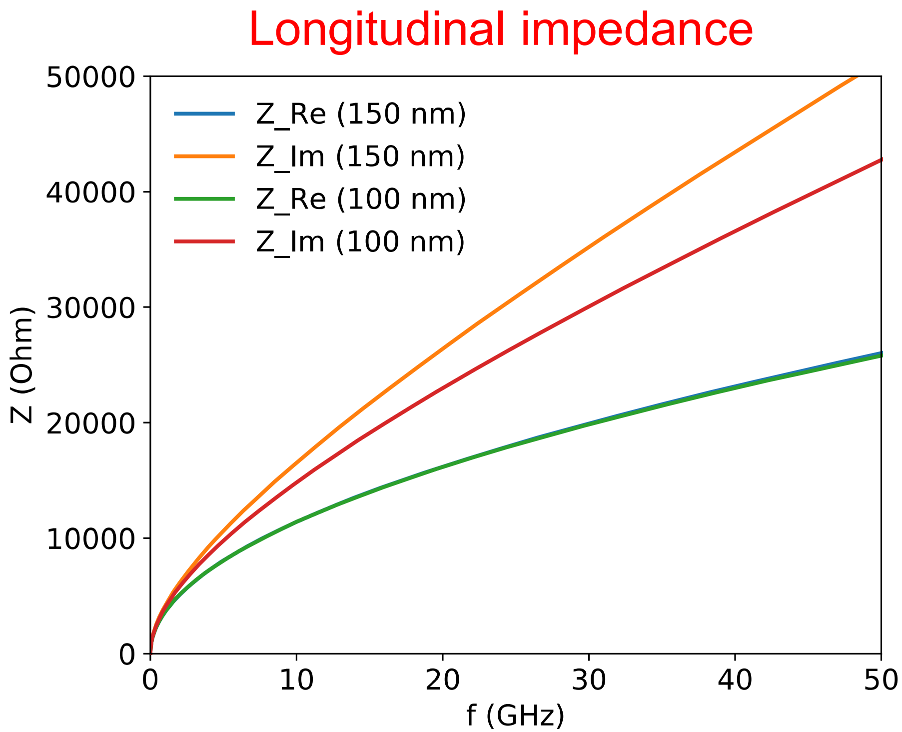


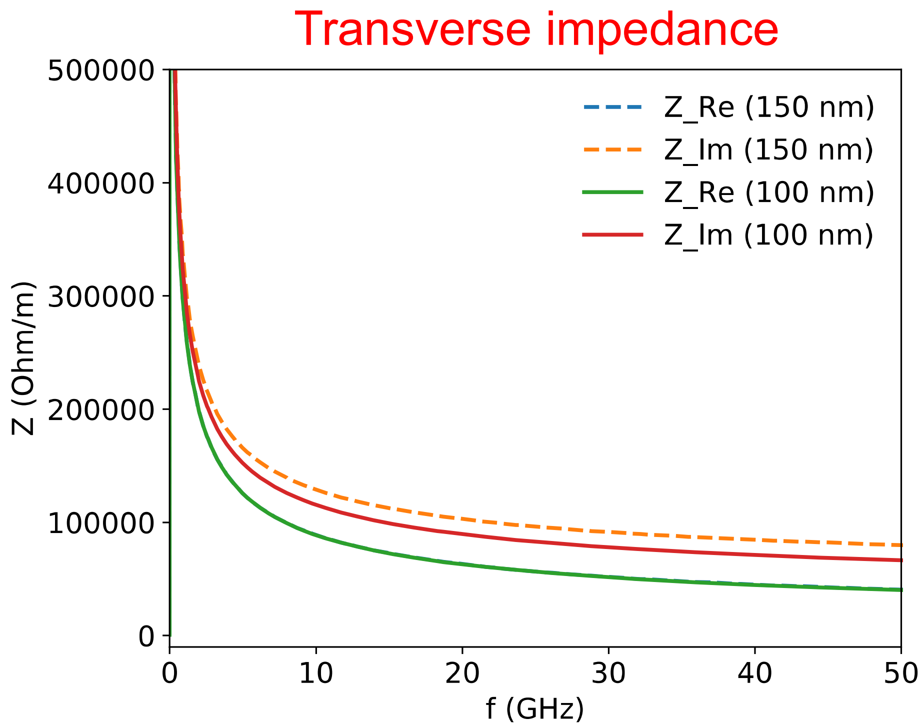
IW2D used model



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	$\Delta = 150\ nm$	$\rho = 10^{-6} \Omega m$

Resistive wall

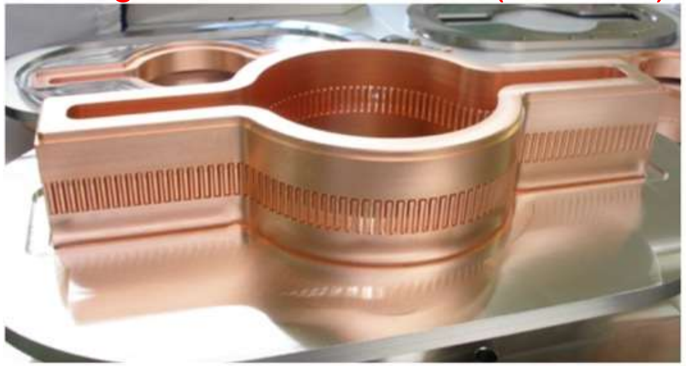


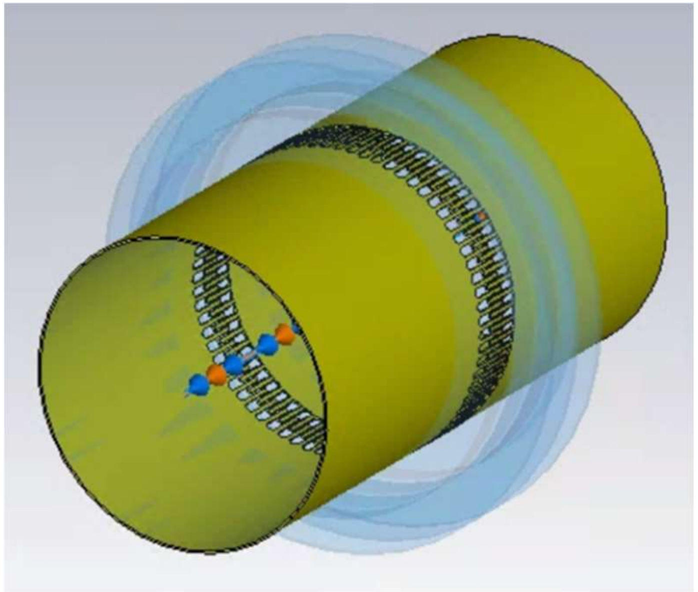


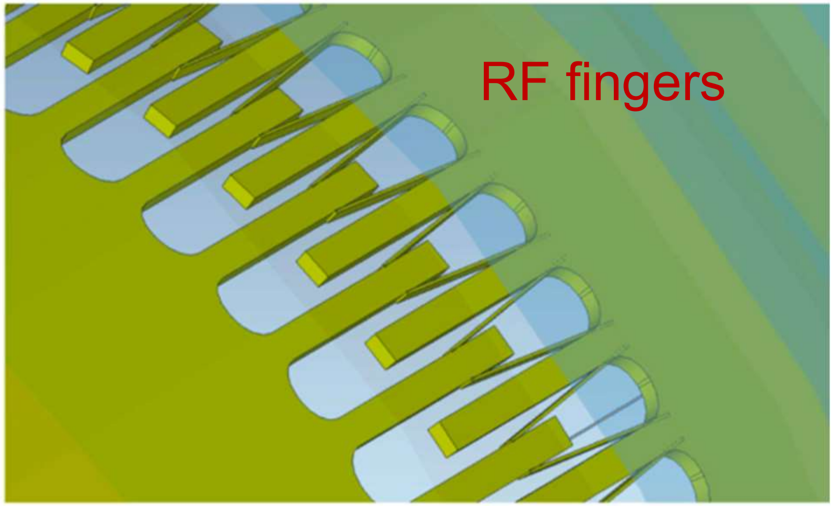
IW2D results: comparison between 100 nm and 150 nm coatings
(new reference value from vacuum group)

Bellows – initial model

Y. Suetsugu, Japan-Italy Collaboration Meeting "Crab Factories” 2008 (INFN-LNF)







A comment on the number of bellows:

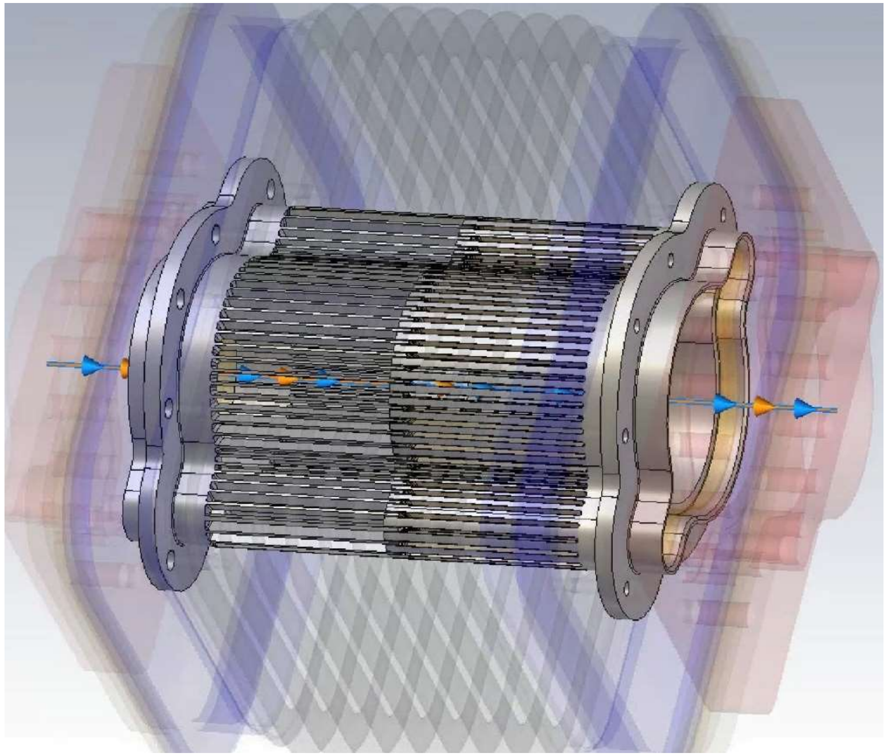
- 2900 dipole arcs 24 m long. We consider bellows every 8 m → 2900*3=8700
- 2900 quads/sextupoles arcs

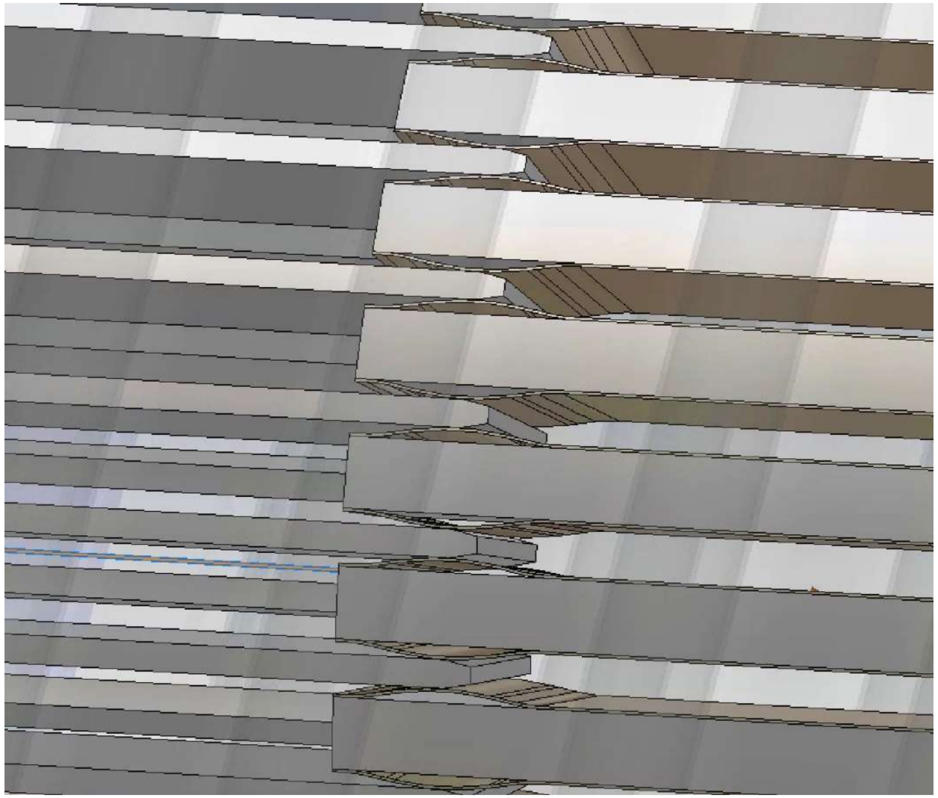
total of 11600 bellows plus:

- RF, injection system, collimators, …

As a pessimistic estimation we have considered 20000 bellows

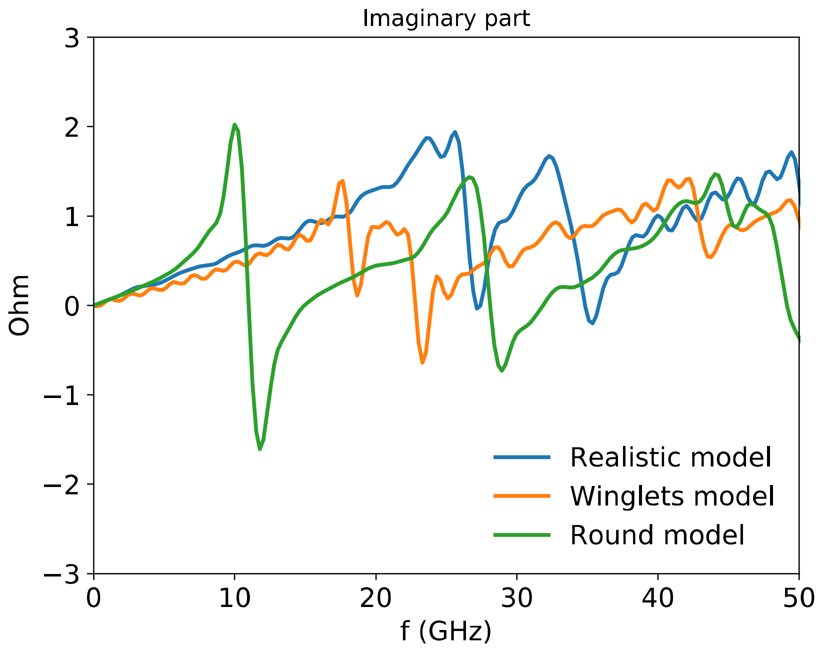
Bellows – realistic model

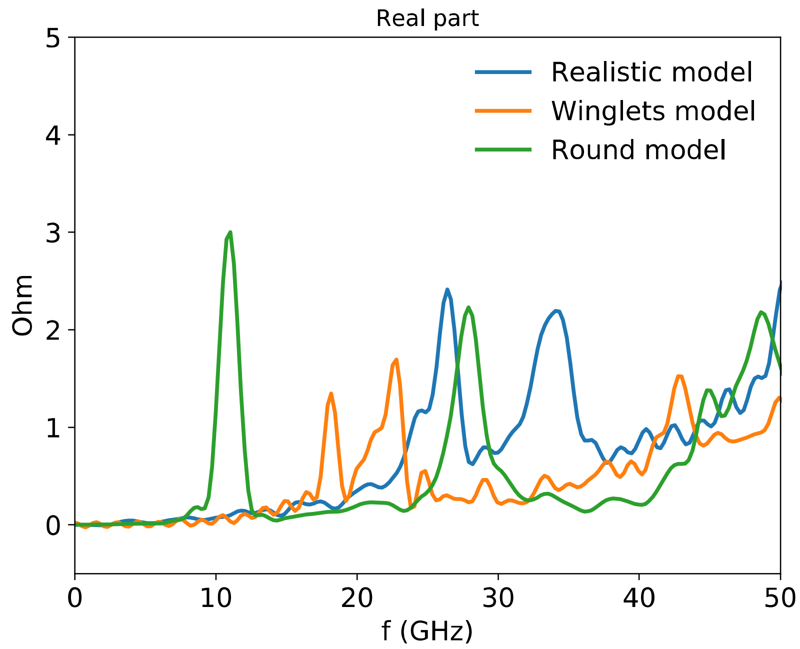




Bellows – realistic model

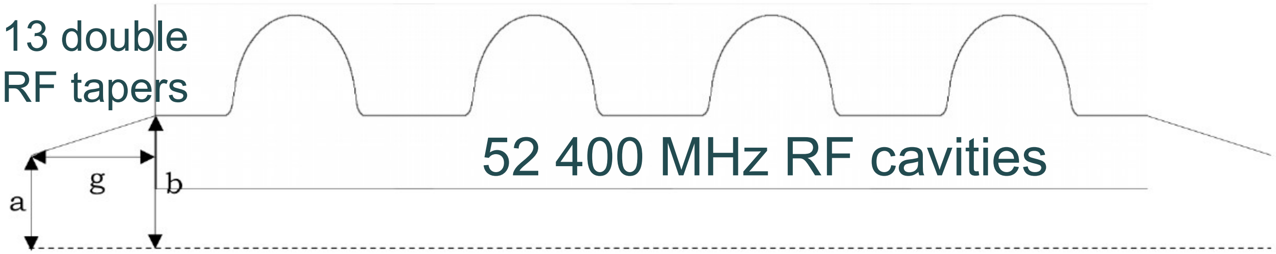
Longitudinal impedance



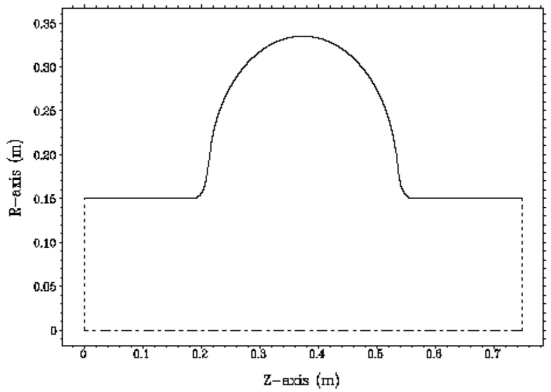


RF system

13 double RF tapers

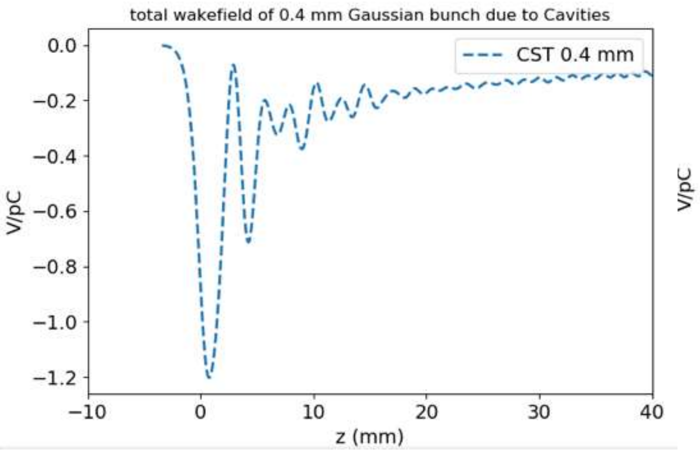


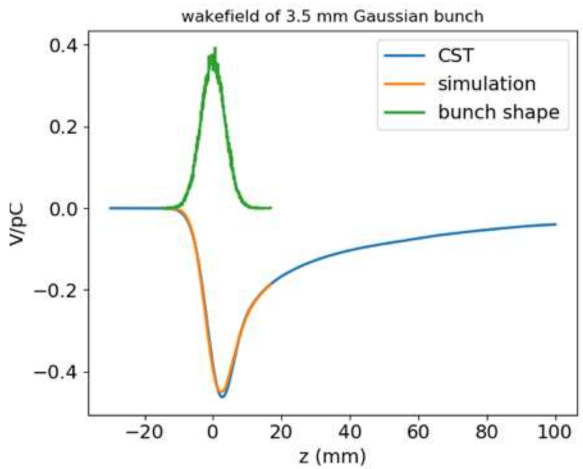
52 400 MHz RF cavities

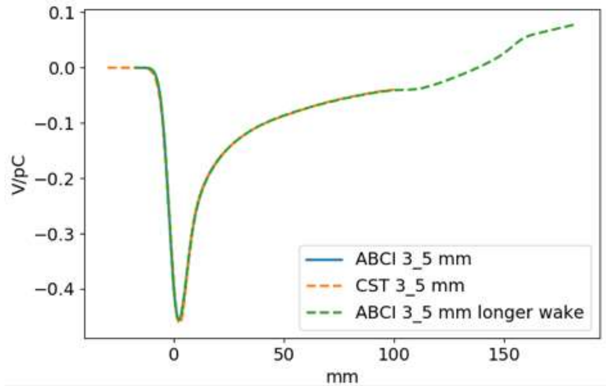


Tapers: transition from radius a = 50 mm outside the cryomodule to radius b = 150 mm inside the cryomodule (or vice-versa).

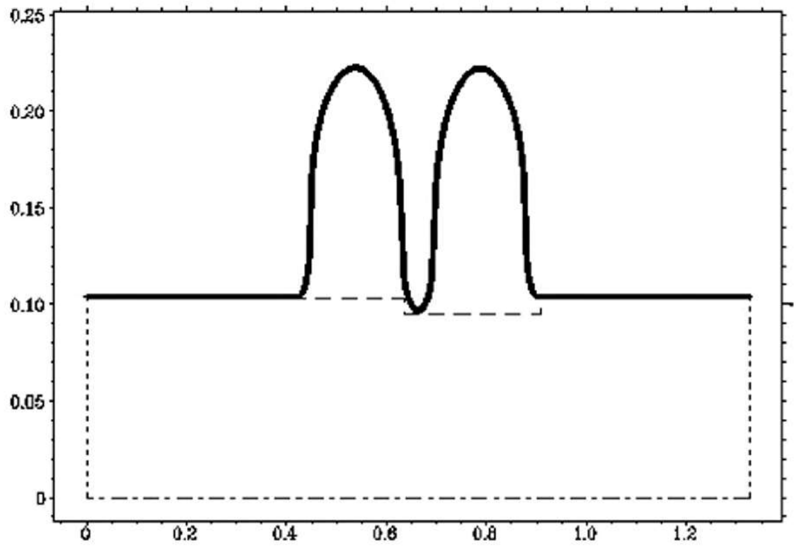
We assumed g = 0.5 m

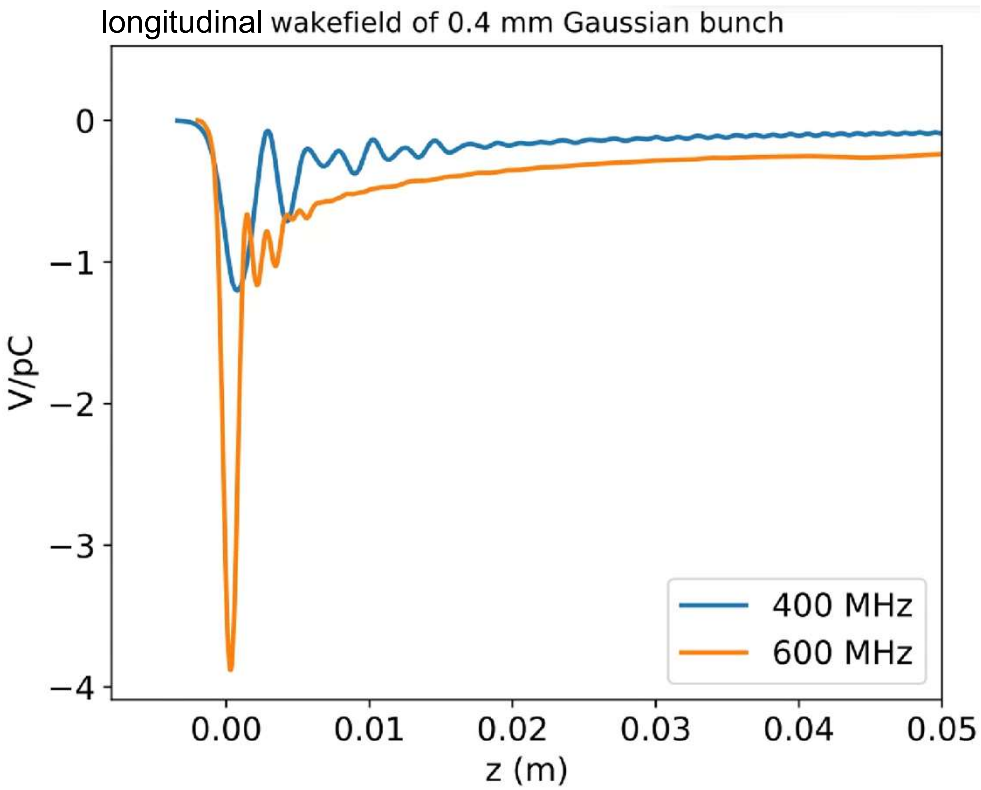




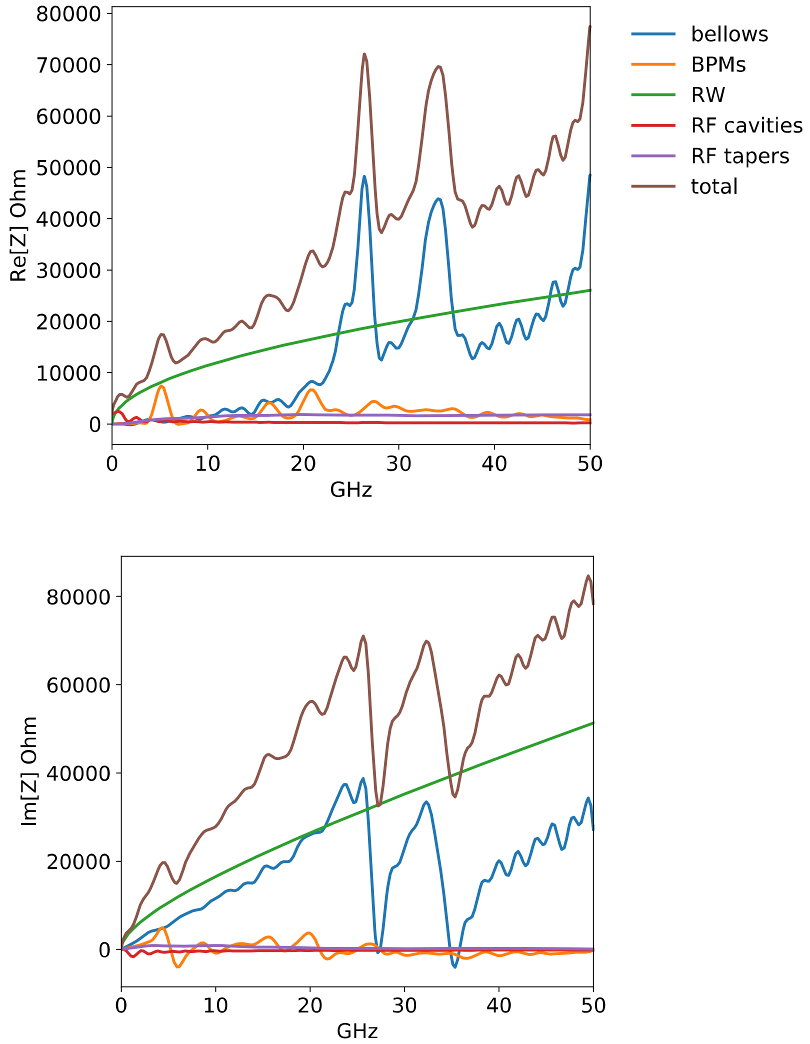


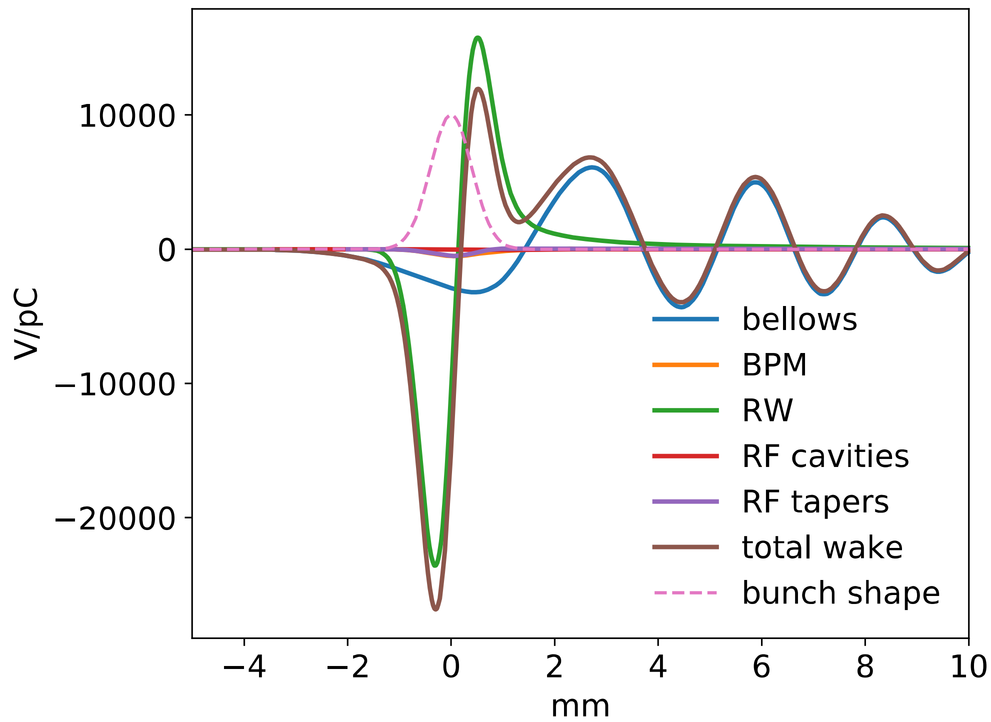
RF system – 600 MHz cavity option



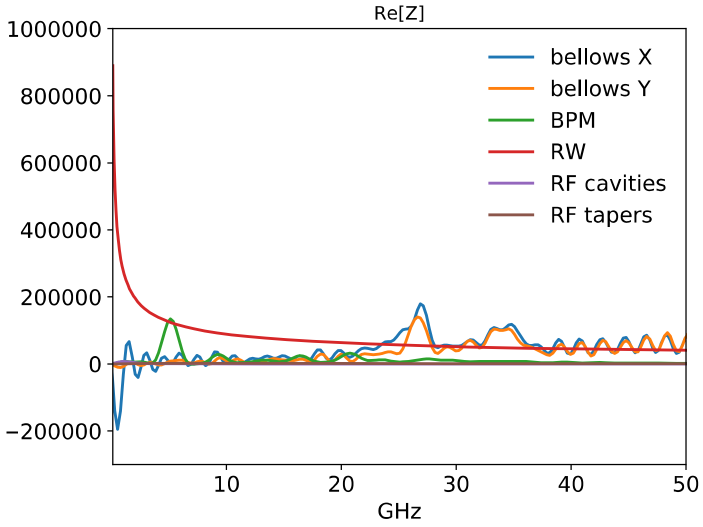


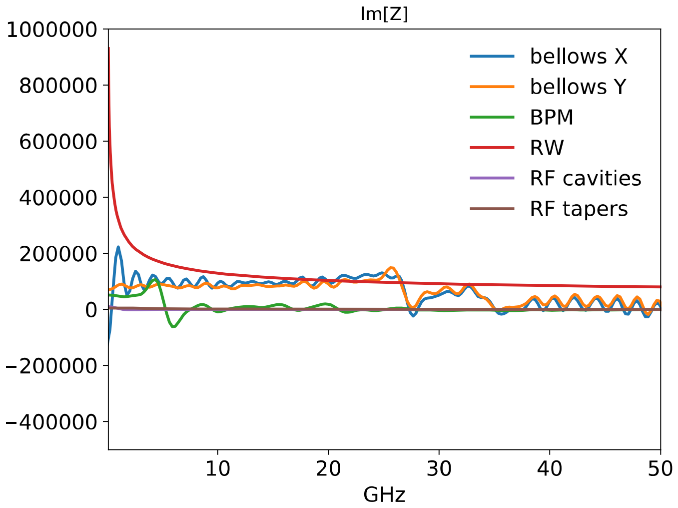
Total impedance and wake – longitudinal plane

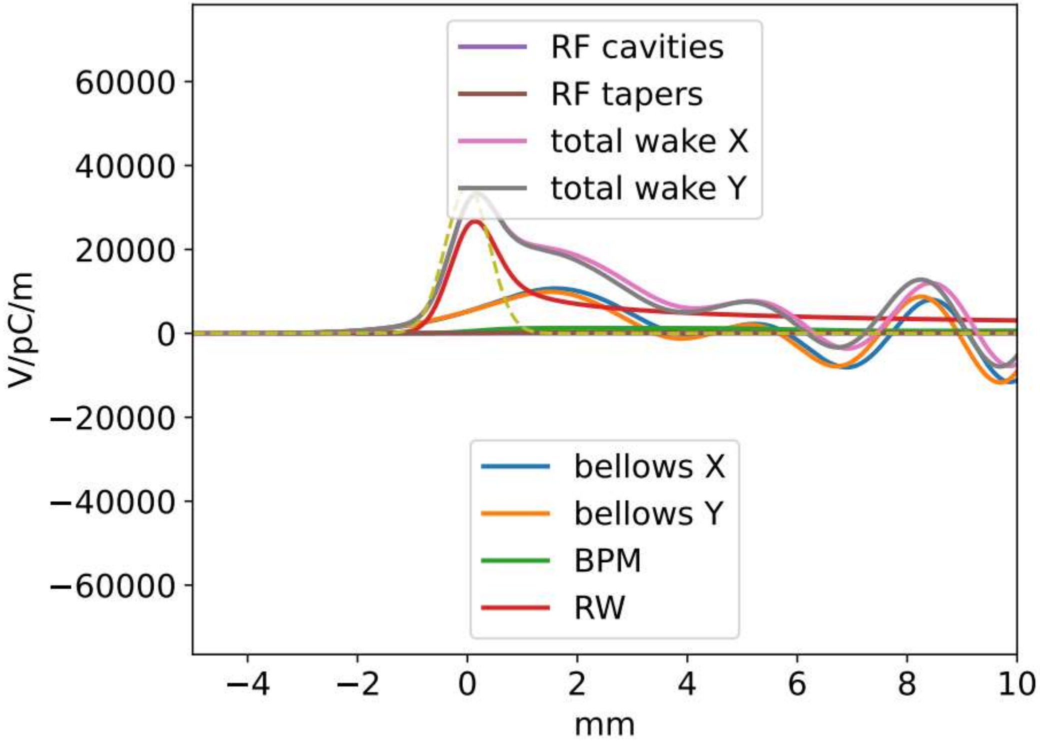




Total impedance and wake – transverse plane







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Some comments on the impedance budget and collective effects

- FCC-ee is still an ongoing project, and as we evaluate new devices, the total machine impedance increases more and more
- We are still missing several important devices, such as the collimation system, vacuum flanges, …
- On the other hand, the impedance evaluated so far already demonstrates how this machine can become critical due to collective effects (see Emanuela's talk)
- The instabilities shown in the following talks will change based on the new impedance contributions that will gradually be added, but they suggest that we need to look for possible mitigation solutions.

Single beam instabilities

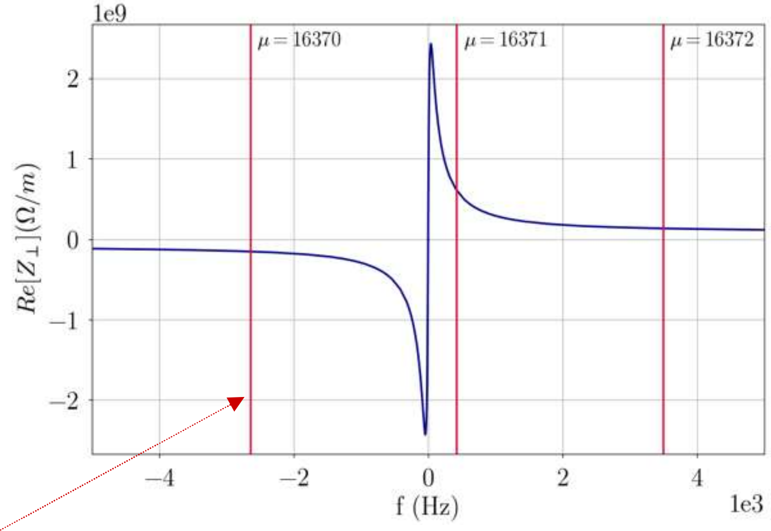
Transverse Coupled Bunch Instability (TCBI)

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

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

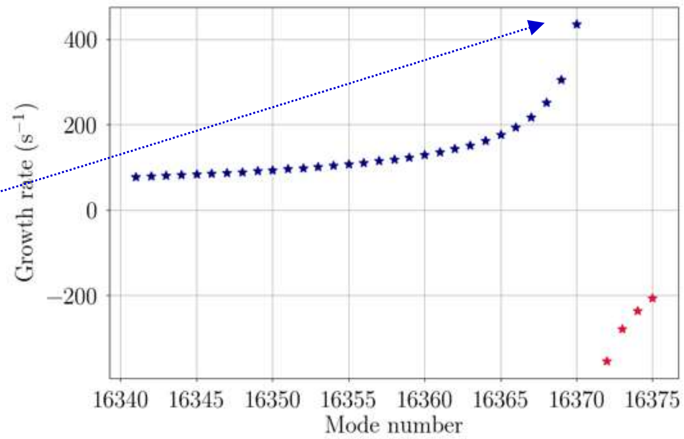
$$\omega_q = \left(qM + \mu + Q_\beta\right)\omega_0$$

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



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

Its growth time is about 7 revolution turns



A robust feedback is required for the instability suppression!

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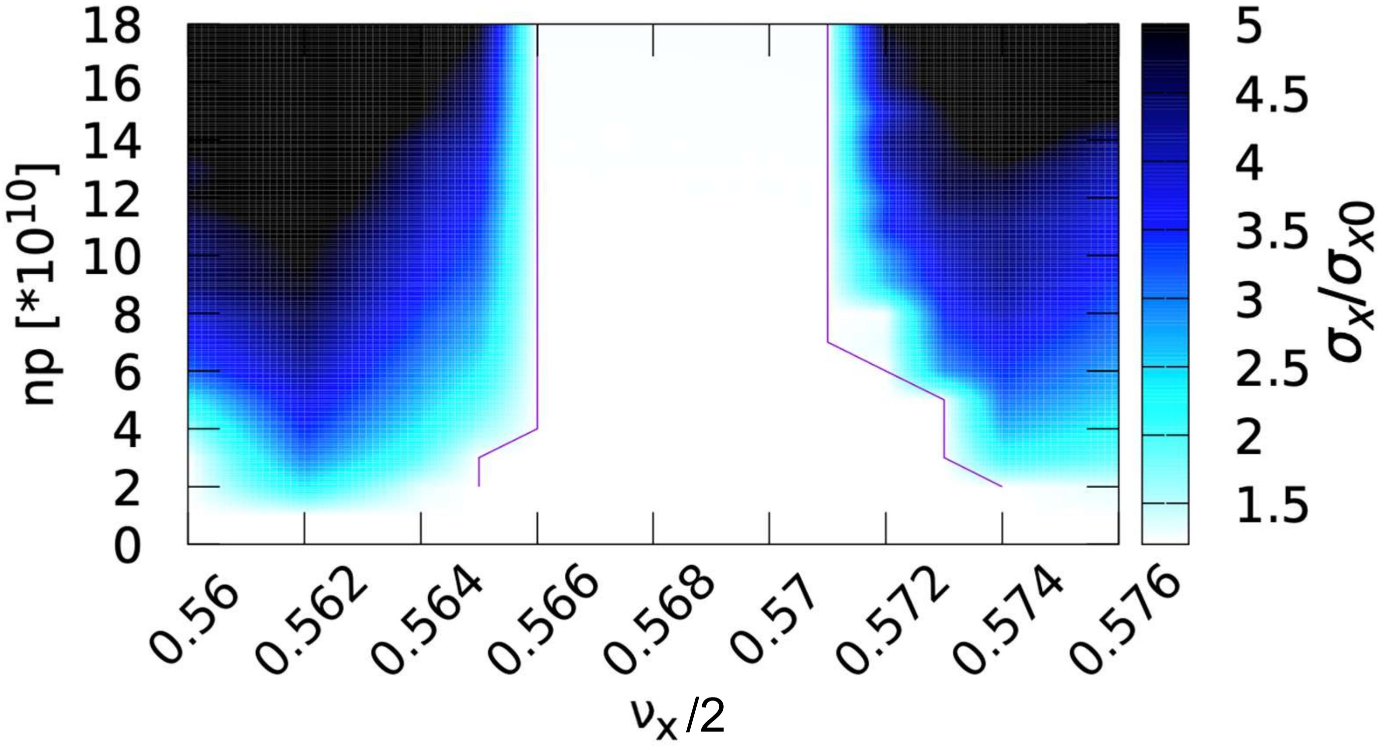
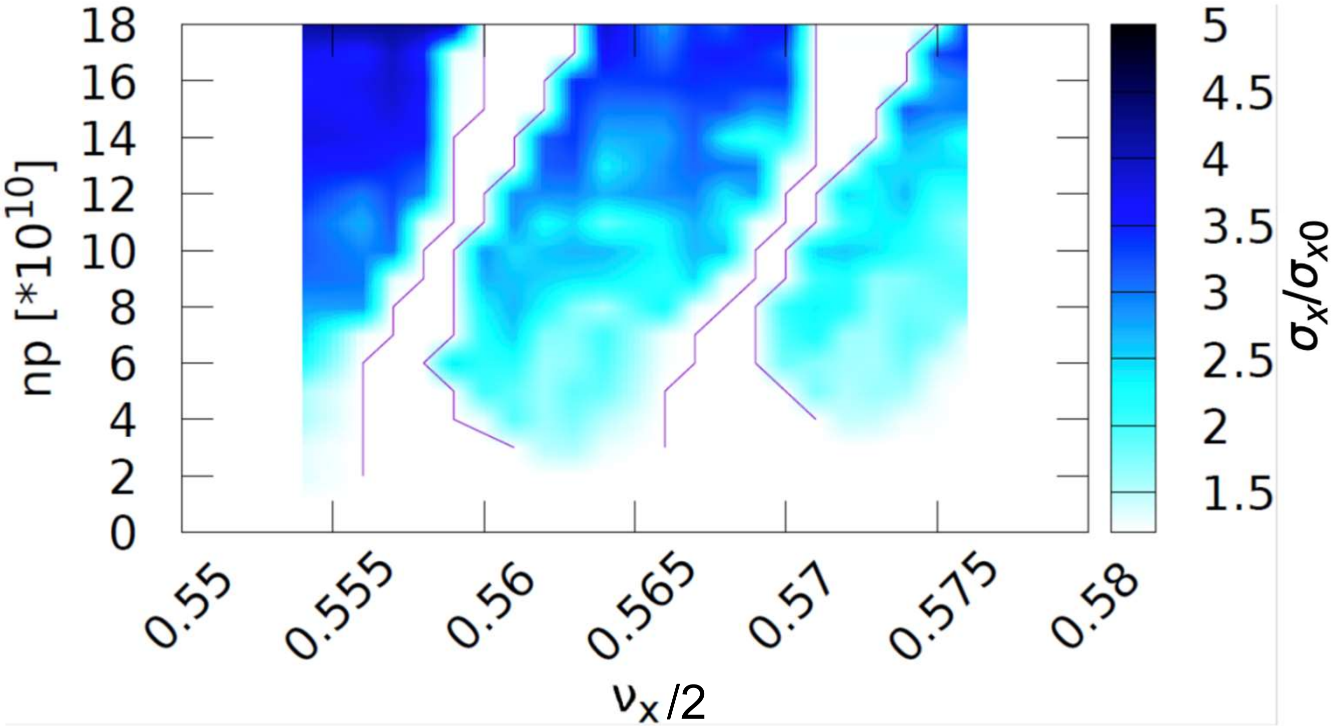
Interplay between beam-beam and longitudinal impedance (thanks to Y. Zhang from IHEP – China)

The X-Z instability is a novel coherent beam-beam instability appearing with a large crossing angle and resulting in a blow-up of the horizontal beam size



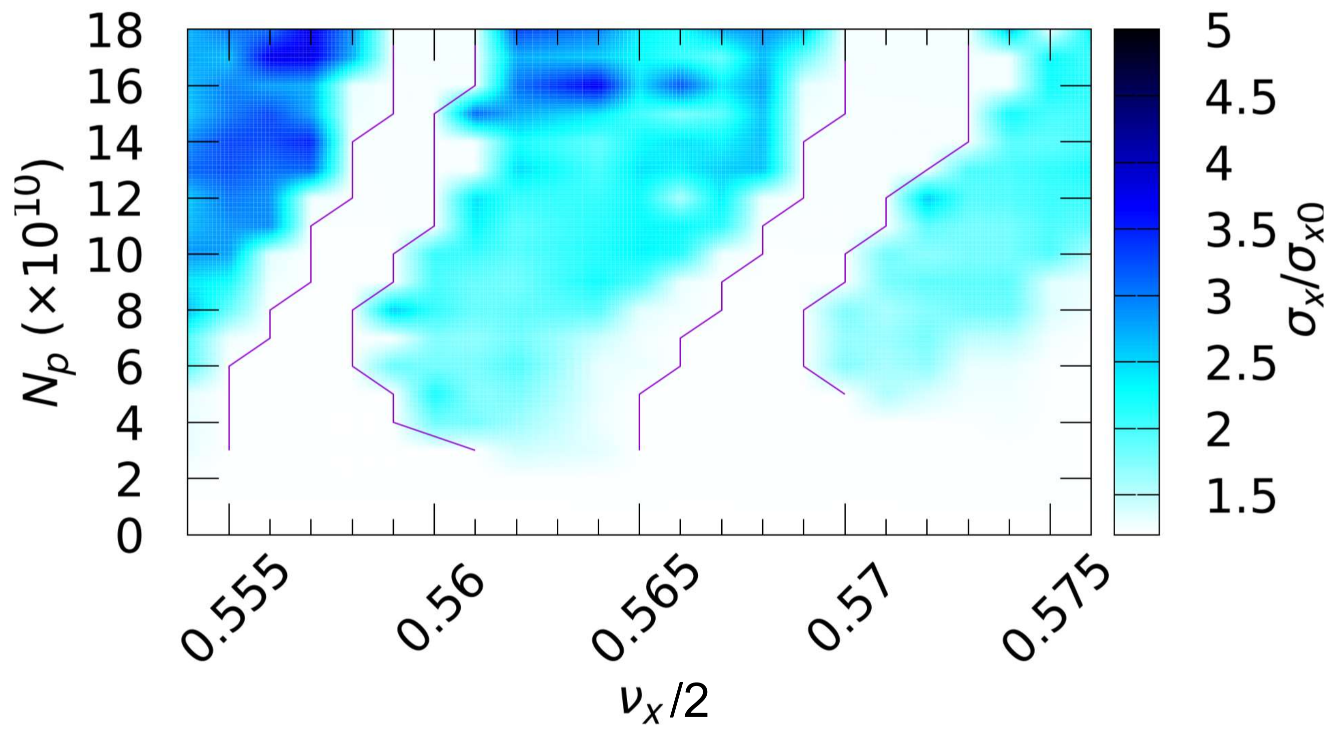
Without impedance – CDR parameters

Interplay between beam-beam and longitudinal impedance



With impedance – CDR parameters

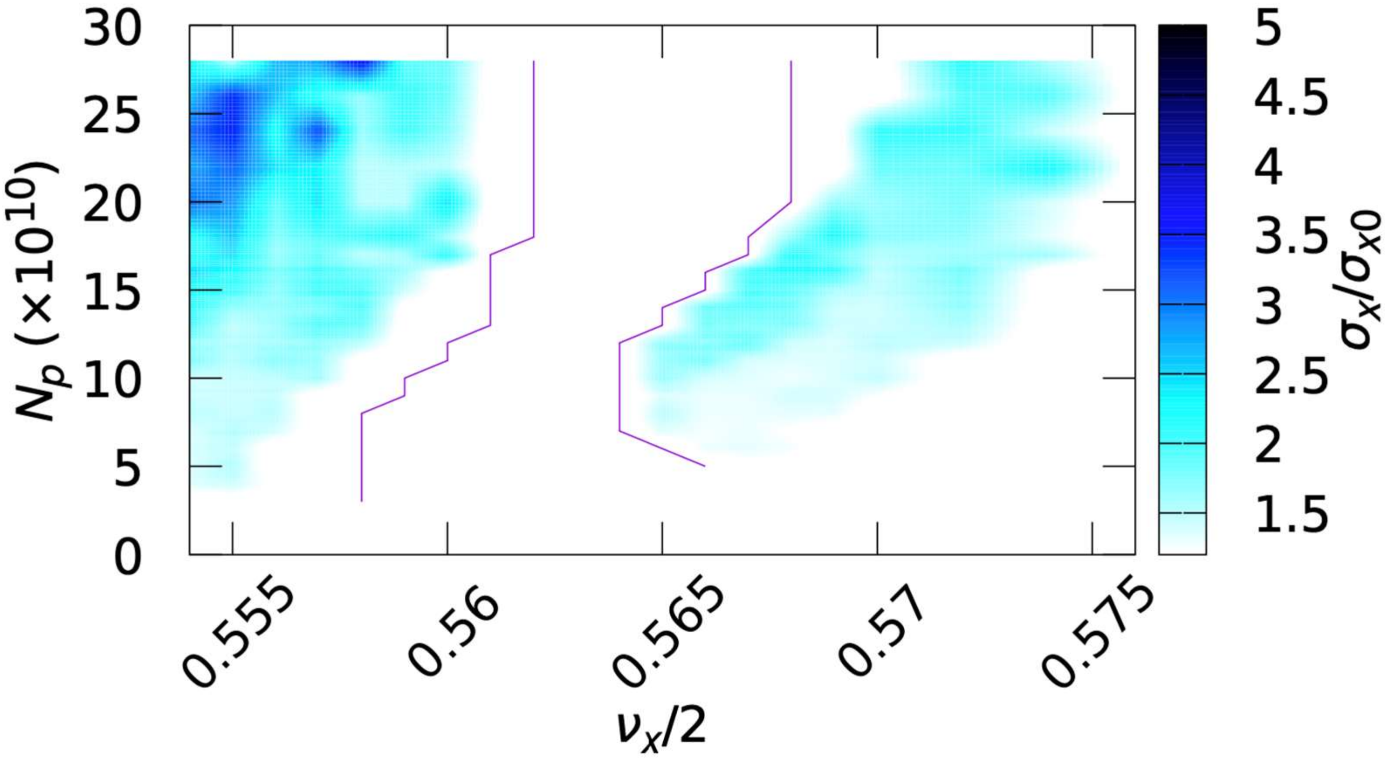
Interplay between beam-beam and longitudinal impedance



With impedance – CDR parameters – Qx'=5

Interplay between beam-beam and longitudinal impedance

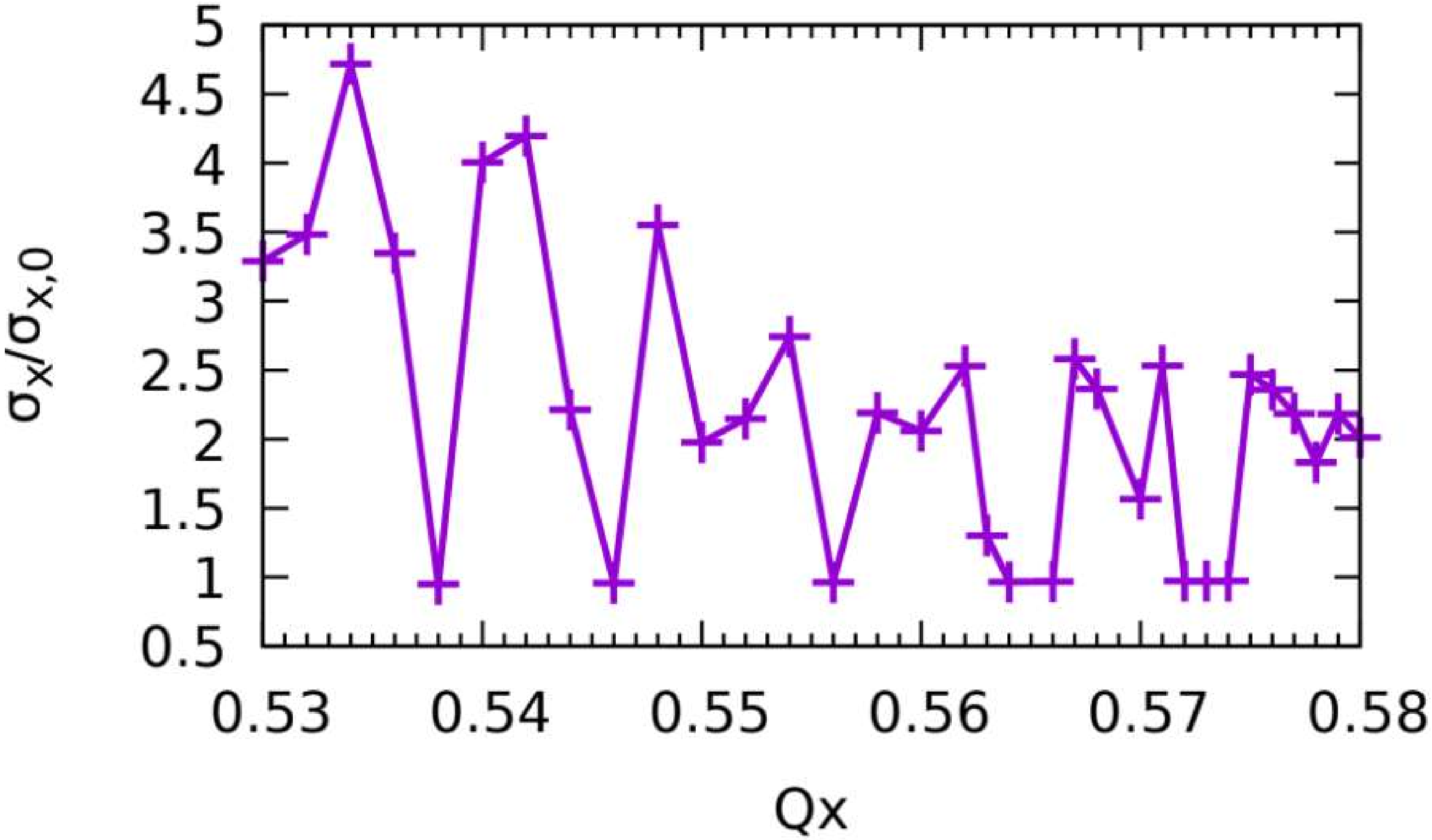
Mitigation methods for CDR parameters: higher harmonic cavity, higher momentum compaction factor



Higher momentum compaction factor

Interplay between beam-beam and longitudinal impedance

Preliminary study with new parameters: relative transverse size vs tune at nominal intensity with updated parameters and impedance



Conclusions & discussions

- Important missing sources:
  - Collimators
  - Kickers
  - Vacuum Flanges
  - SR absorbers (first estimation gave negligible contribution)

- A fellow should start to work for the impedance budget starting from January 2022

Conclusions & discussions

- So far, we have used a single localized kick for both longitudinal and transverse wake. Also the longitudinal and transverse maps are localized in a single point of the machine
- For the transverse plane, it is possible to split the machine into segments (it’s necessary to change the script, not the code), but this has not been done so far (at least for FCC-ee)
- For the longitudinal plane, as far as I understand, this is not possible and one should change the source

Conclusions & discussions

- It is interesting to 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), eventually a higher harmonic cavity system, …
- This could also allow to study the effects of possible transverse localized impedances
- So far the transverse map has been considered linear. It would be interesting to import MADX lattice and use directly this one for the simulations of transverse dynamics

Conclusions & discussions

- So far only the longitudinal wake has been taken into account in the beam-beam effect thanks to the collaboration with Yuan Zhang from IHEP – China
- However, from what we have seen in the single beam study (see Emanuela's talk), there is an interplay between the longitudinal and transverse wake which could be important also for the beam-beam effect
- By considering what we have seen so far, we need to investigate, in parallel to the instability thresholds, possible mitigation methods

Other topics

- Electron could, including the multi-bunch effects
- Ion instabilities
- Impedance evaluation, repository, and collective effects in the Booster and in the whole injection system
- Longitudinal and transverse feedback system for coupled bunch instabilities (in particular, very important for the transverse plane due to the resistive wall, also in the Booster)
- …