



DIPARTIMENTO DI SCIENZE DI BASE  
E APPLICATE PER L'INGEGNERIA



## Collective effects in FCC-ee

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## 2023 activity: a new parameter list (for mid-term review)

Note:

lower single bunch intensity ( $1.5 \times 10^{11}$  with respect to  $2.6 \times 10^{11}$ )

longer bunch (5.6 mm with respect to 4.37 mm)

lower synchrotron tune (0.029 with respect to 0.037)

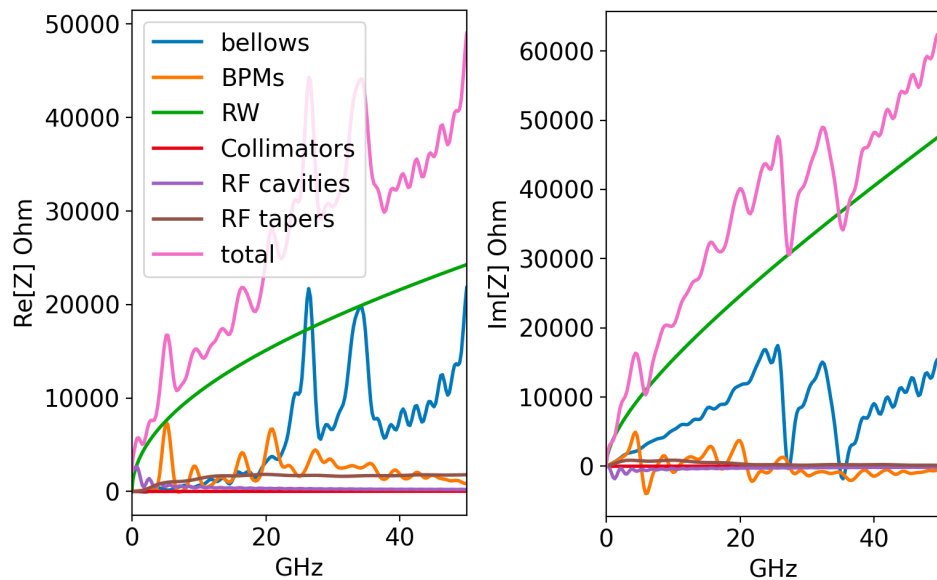
Table 1: FCC-ee collider parameters for Z as of Apr. 20, 2023.

Beam energy	[GeV]	45.6	
Version		Apr. 20	Feb. 07
Layout		PA31-3.0	
# of IPs		4	
Circumference	[km]	90.658816	
Bending radius of arc dipole	[km]	9.936	
Energy loss / turn	[GeV]	0.0394	
SR power / beam	[MW]	50	
Beam current	[mA]	1270	
Colliding bunches / beam		15880	9200
Colliding bunch population	$[10^{11}]$	1.51	2.60
Horizontal emittance at collision $\varepsilon_x$	[nm]	0.71	
Vertical emittance at collision $\varepsilon_y$	[pm]	1.4	
Lattice vertical emittance $\varepsilon_{y, \text{lattice}}$	[pm]	0.75	< 0.3
Arc cell		Long 90/90	
Momentum compaction $\alpha_p$	$[10^{-6}]$	28.6	
Arc sextupole families		75	
$\beta_{x/y}^*$	[mm]	110 / 0.7	100 / 0.8
Transverse tunes $Q_{x/y}$		214.158 / 214.200	214.260 / 214.380
Chromaticities $Q'_{x/y}$		0 / +5	0 / 0
Energy spread (SR/BS) $\sigma_\delta$	[%]	0.039 / 0.089	0.039 / 0.143
Bunch length (SR/BS) $\sigma_z$	[mm]	5.60 / 12.7	4.37 / 15.9
RF voltage 400/800 MHz	[GV]	0.079 / 0	0.120 / 0
Harmonic number for 400 MHz		121200	
RF frequency (400 MHz)	[MHz]	400.786684	
Synchrotron tune $Q_s$		0.0288	0.0370
Long. damping time	[turns]	1158	
RF acceptance	[%]	1.05	1.6
Energy acceptance (DA)	[%]	$\pm 1.0$	
Beam crossing angle at IP	[mrad]	$\pm 15$	
Crab waist ratio	[%]	70	97
Beam-beam $\xi_x/\xi_y^a$		0.0023 / 0.096	0.0023 / 0.139
Lifetime (q + BS + lattice)	[sec]	15000	20
Lifetime (lum) <sup>b</sup>	[sec]	1340	1010
Luminosity / IP	$[10^{34}/\text{cm}^2\text{s}]$	140	186

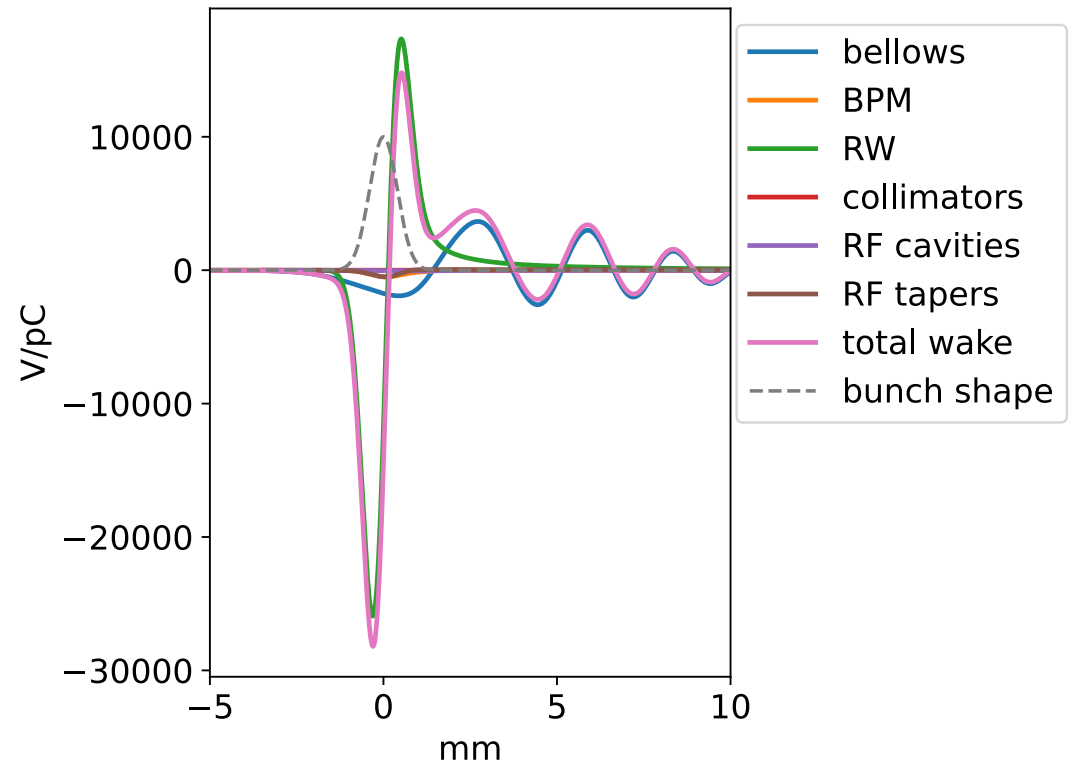
<sup>a</sup>incl. hourglass.

<sup>b</sup>only the energy acceptance is taken into account for the cross section

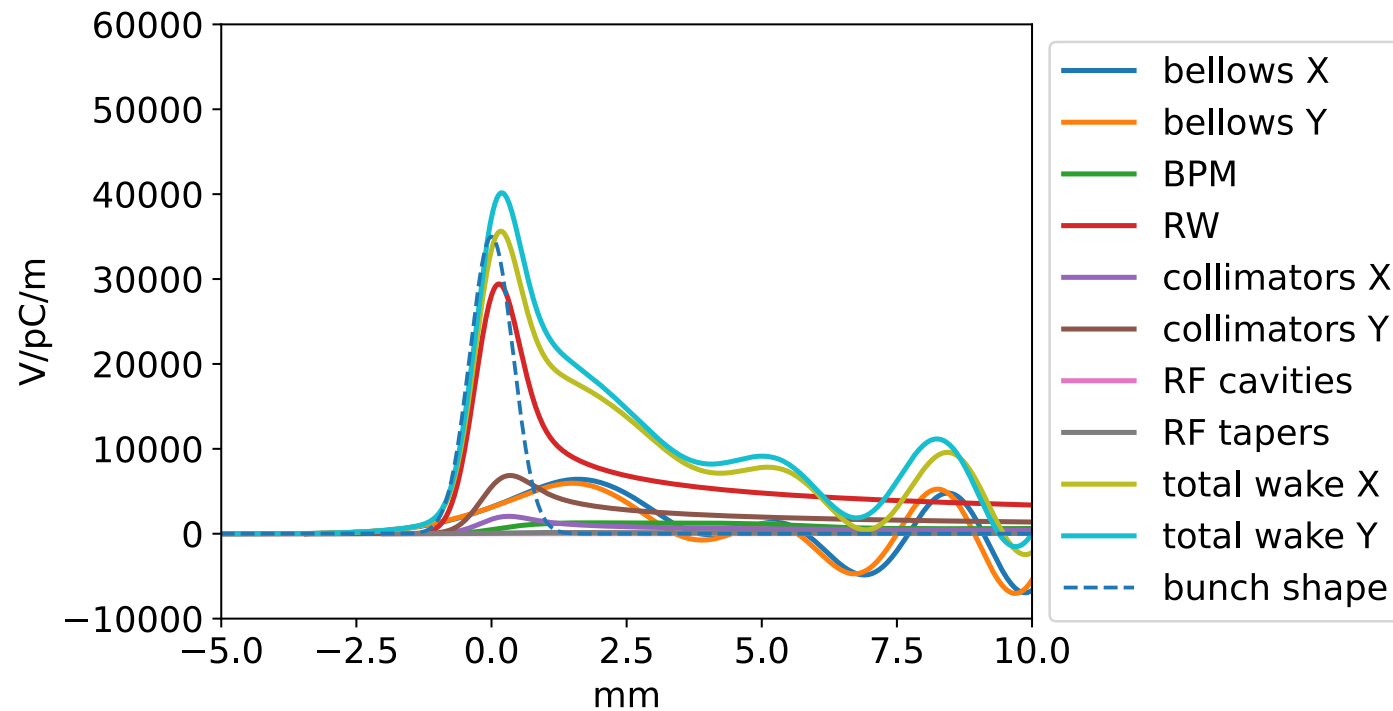
## Longitudinal impedance and wake potential of a 0.4 mm Gaussian bunch used as Green function in beam dynamics simulations



NB: the bunch cutoff frequency for  $\sigma_z = 14$  mm is about 3.4 GHz



## Transverse dipolar wake potential of a 0.4 mm Gaussian bunch used as Green function in beam dynamics simulations

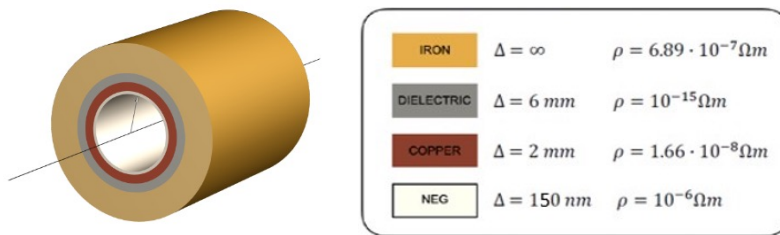


In beam dynamics simulations we have also included the quadrupolar term (small contribution so far).

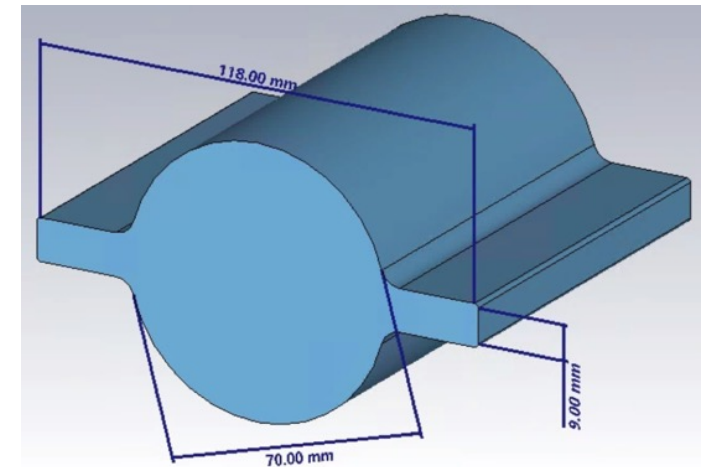
## Main impedance sources

### 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.



**Contribution of the winglets:** a 2D electromagnetic solver VACI (A. Rajabi) gives the RW impedance and wake for the geometry with the winglets. Very small differences have been obtained with respect to the circular beam pipe.



## Main impedance sources

beam pipe radius reduction (35 mm → 30 mm)

$$Z_{\parallel}(\omega) = C \frac{Z_0 \omega}{4\pi c b} \left\{ [\operatorname{sgn}(\omega) - i] \delta_2 - 2i\Delta \left( 1 - \frac{\sigma_1}{\sigma_2} \right) \right\}$$

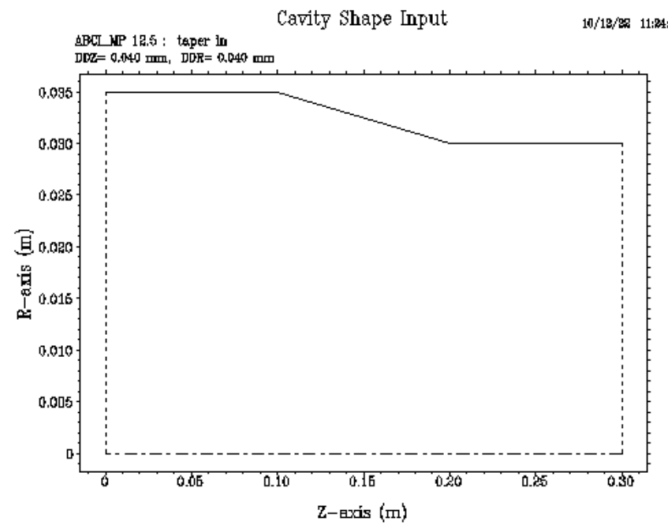
$$Z_{\perp}(\omega) = C \frac{Z_0}{2\pi b^3} \left\{ [\operatorname{sgn}(\omega) - i] \delta_2 - 2i\Delta \left( 1 - \frac{\sigma_1}{\sigma_2} \right) \right\}$$

Since the transverse dipolar wake is proportional to  $1/b^3$ , passing from 35 to 30 mm means an increase in impedance and wake amplitude of  $\frac{35^3}{30^3} = 1.6 \rightarrow 60\%$

Reduction of beam pipe radius only in short straight sections (quads and sexts):  
10 km of pipe with 30 mm of radius:

the total RW passes from '1' to '1.06': an increase in the transverse impedance due to RW of 6%, but there are tapers ...

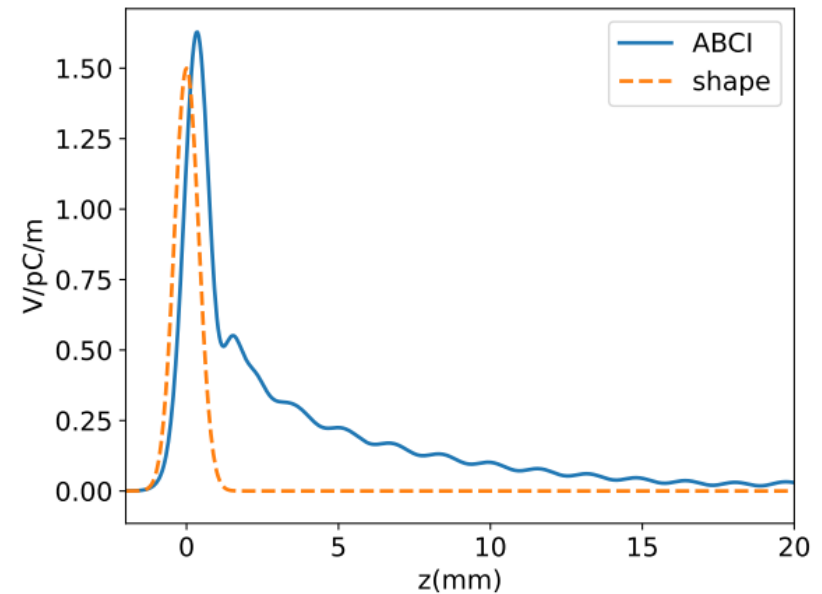
## Tapers



If we multiply this by 2 (double taper) and by 1500 (number of sections), we have a peak at about 5000 V/pC/m.

This is about 12.5% of the total transverse dipolar wake that we have evaluated so far. **Is it possible to reduce this geometric impedance?**

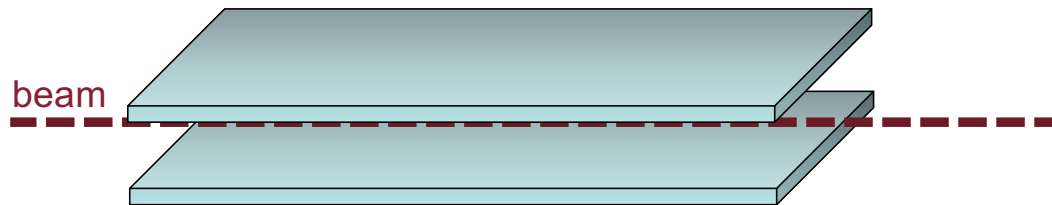
Transverse dipolar vertical wake of a 0.4 mm bunch length for a single taper (in) once that the 'potential difference' term due to the different radii (which disappears for a double taper in-out) is subtracted



## Collimation system

Table of the collimator settings for the Z machine and for the 4 IPs layout. The synchrotron collimators and masks upstream the IPs are not included in this table.

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.b1	primary	0.4	11.0	0.005504	MoGR	H	0.0	0.0	0.0	352.578471	113.054110
tcp.v.b1	primary	0.4	65.0	0.002332	MoGR	V	90.0	0.0	0.0	147.026106	906.282898
tcs.h1.b1	secondary	0.3	13.0	0.004162	Mo	H	0.0	0.0	0.0	144.372060	936.118623
tcs.v1.b1	secondary	0.3	75.5	0.00203	Mo	V	90.0	0.0	0.0	353.434125	509.320452
tcs.h2.b1	secondary	0.3	13.0	0.005956	Mo	H	0.0	0.0	0.0	295.623450	1419.375106
tcs.v2.b1	secondary	0.3	75.5	0.002118	Mo	V	90.0	0.0	0.0	494.235759	554.055888
tcp.hp.b1	primary	0.4	29.0	0.005755	MoGR	H	0.0	0.0	0.0	55.469637	995.306256
tcs.hp1.b1	secondary	0.3	32.0	0.01649	Mo	H	0.0	0.0	0.0	373.994993	377.277726
tcs.hp2.b1	secondary	0.3	32.0	0.011597	Mo	H	0.0	0.0	0.0	184.970621	953.229862



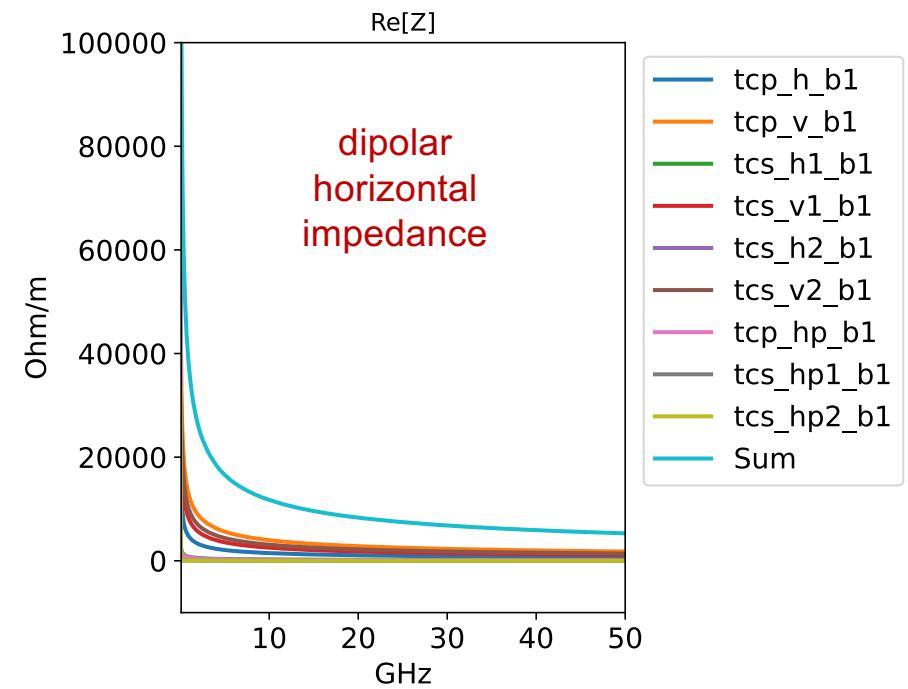
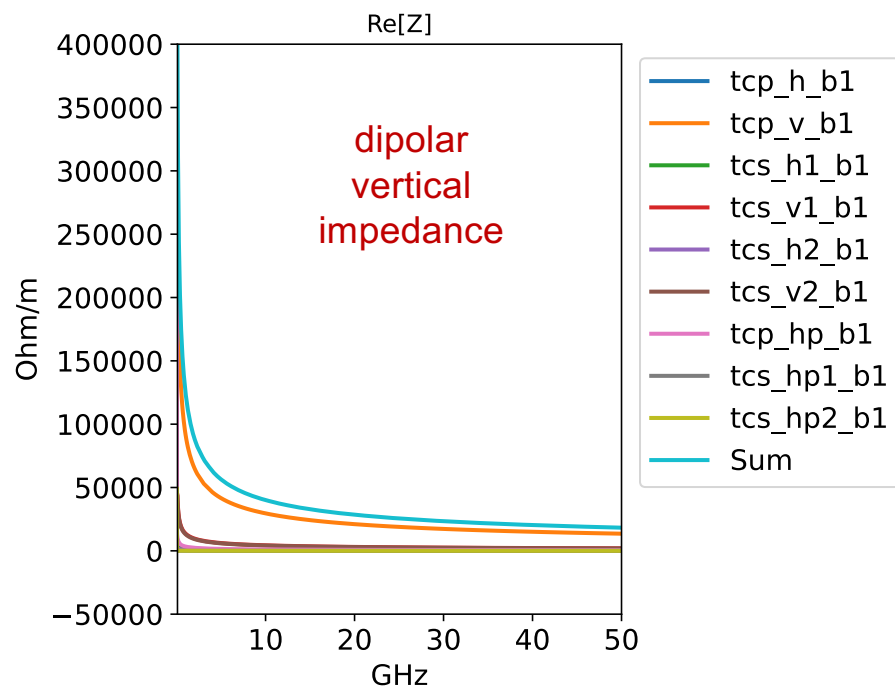
For the resistive wall contribution we suppose parallel plates with infinite thickness and use IW2D for the impedance and wakefield evaluation.

$$\sigma_{MoGR} = 10^6 S/m \quad \sigma_{Mo} = 18.7 \times 10^6 S/m$$

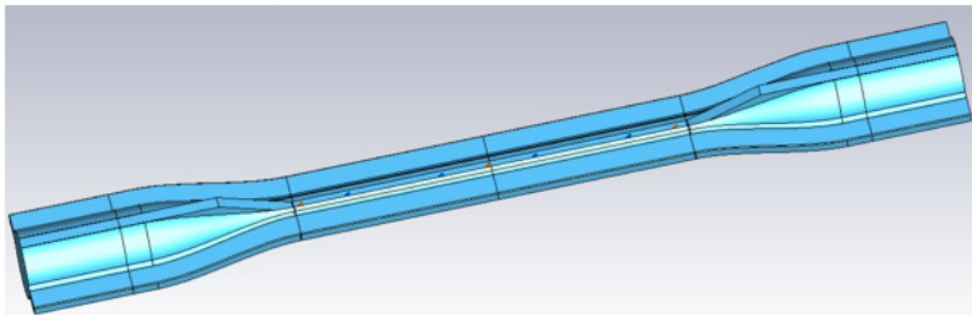
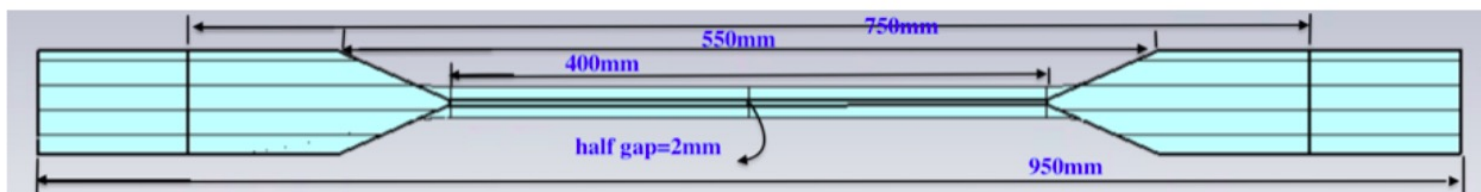


## Collimation system

$$Z(\omega) \frac{\beta_{x,y}}{\langle \beta_{x,y} \rangle} \quad \langle \beta_{x,y} \rangle = \frac{1}{C} \oint \beta_{x,y} ds = 144.1, 241.5 \text{ m}$$

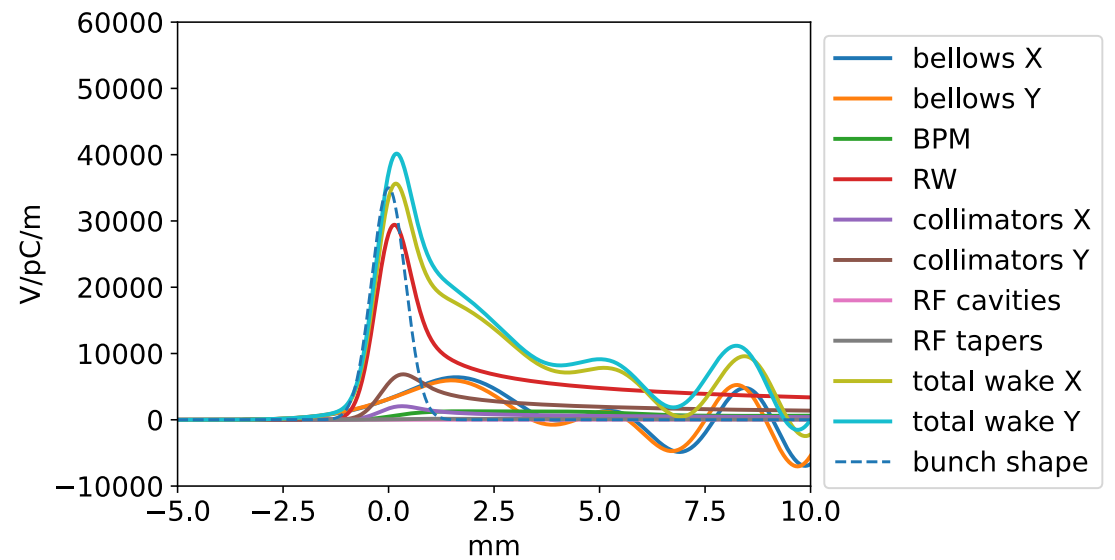
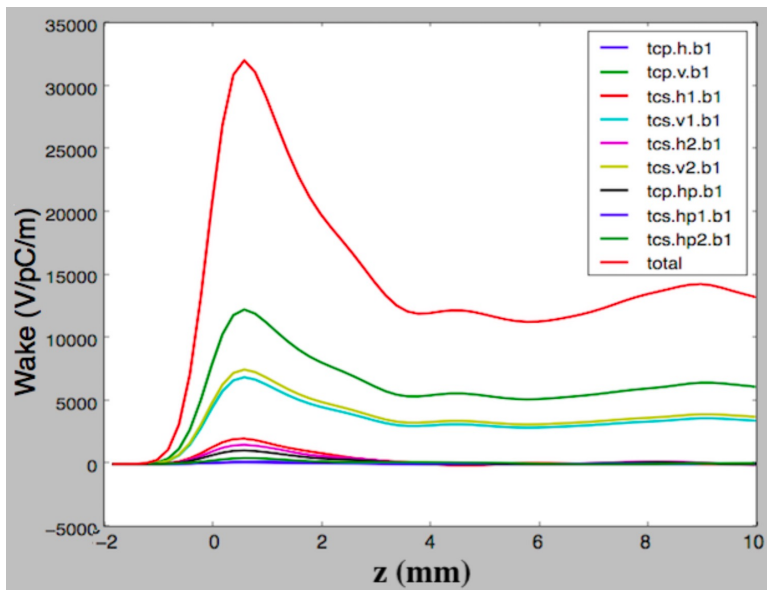


## Work in progress: geometrical wakefield due to collimators



name	type	length [m]	nsigma	half-gap [m]	material
tcp.h.b1	primary	0.4	11.0	0.005504	MoGR
tcp.v.b1	primary	0.4	65.0	0.002332	MoGR
tcs.h1.b1	secondary	0.3	13.0	0.004162	Mo
tcs.v1.b1	secondary	0.3	75.5	0.00203	Mo
tcs.h2.b1	secondary	0.3	13.0	0.005956	Mo
tcs.v2.b1	secondary	0.3	75.5	0.002116	Mo
tcp.hp.b1	primary	0.4	29.0	0.005755	MoGR
tcs.hp1.b1	secondary	0.3	32.0	0.01649	Mo
tcs.hp2.b1	secondary	0.3	32.0	0.011597	Mo

## Work in progress: geometrical wakefield due to collimators

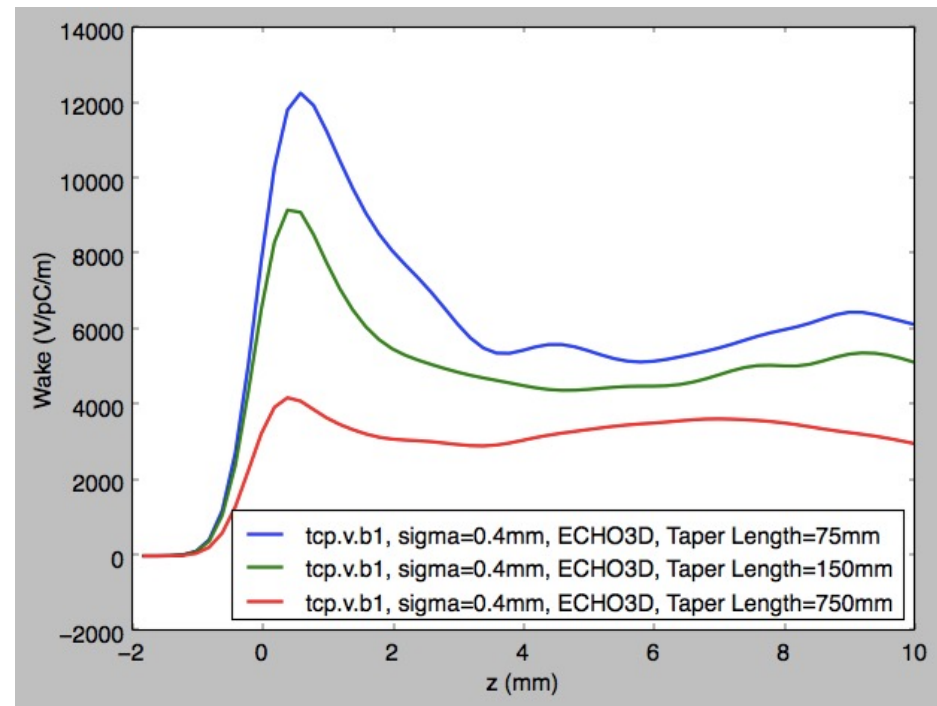
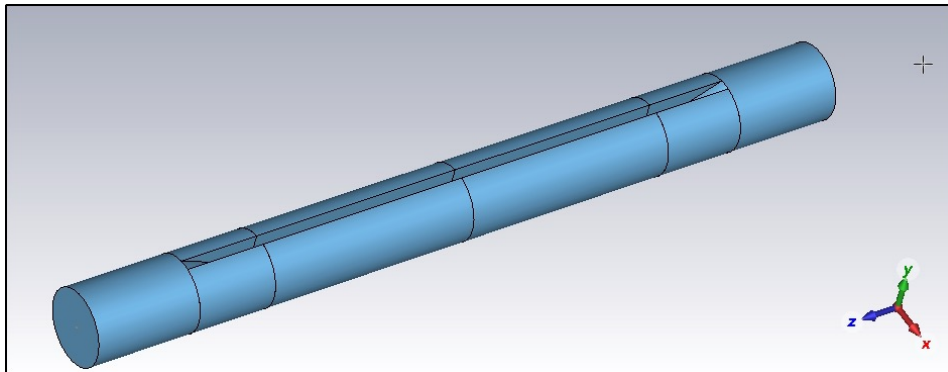


## Work in progress: geometrical wakefield due to collimators

How to mitigate this geometrical contribution?

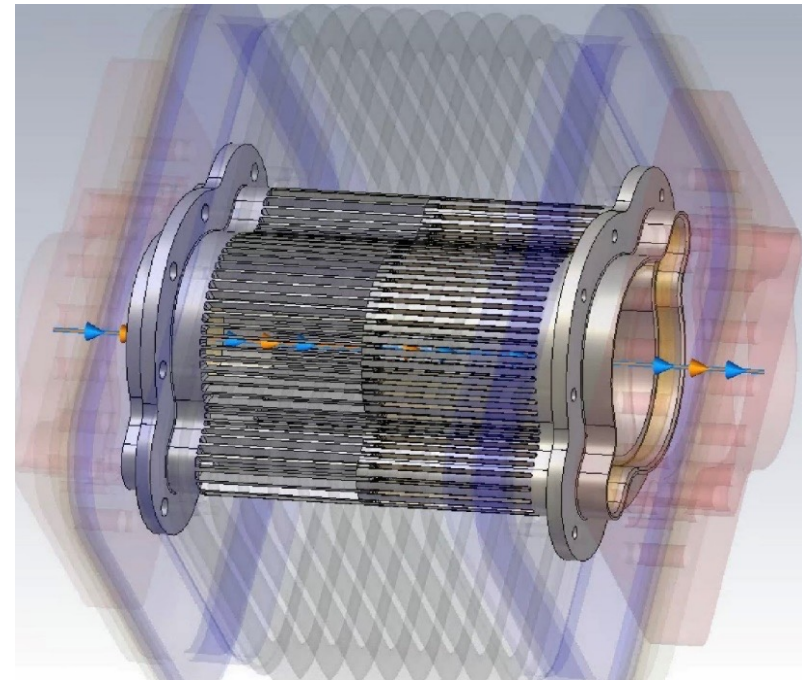
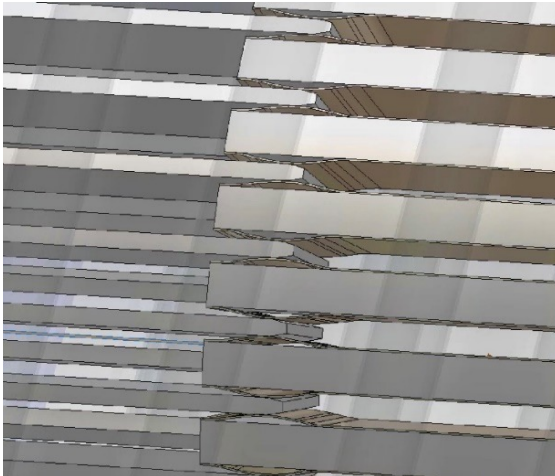
We tried to increase of the taper length, but the results were not satisfactory as expected.

We are investigating other geometries.



## Main impedance sources

**Bellows** We're still using the SuperKEKB model with RF fingers with a total of 8700 bellows: 2900 dipole arcs 24 m long with bellows every 12 m plus 2900 quads/sexts arcs. But other geometries are under investigation in the vacuum group.



## Single bunch collective effects in the longitudinal plane: comparison between old and new parameters

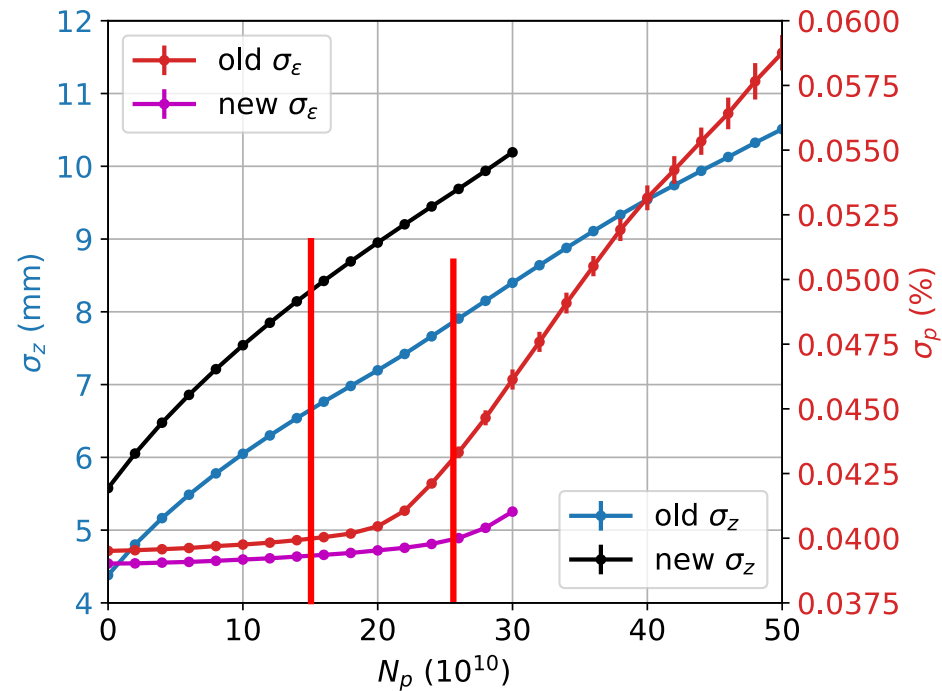
With beamstrahlung we have  
found that at  $1.5 \times 10^{11}$  ppb:

$$\sigma_z = 13.6 \text{ mm (w/o ZL)}$$

$$\sigma_z = 14.0 \text{ mm (w/ ZL)}$$

$$\sigma_p = 9.45 \times 10^{-4} \text{ (w/o ZL),}$$

$$\sigma_p = 9 \times 10^{-4} \text{ (w/ ZL)}$$

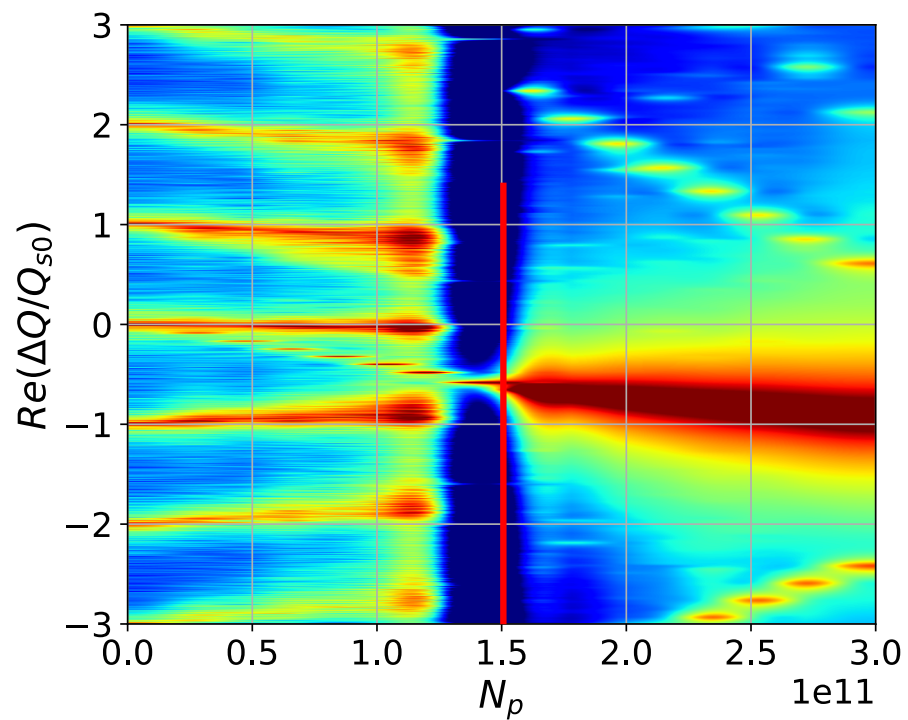


## Transverse coupled bunch instability and feedback system

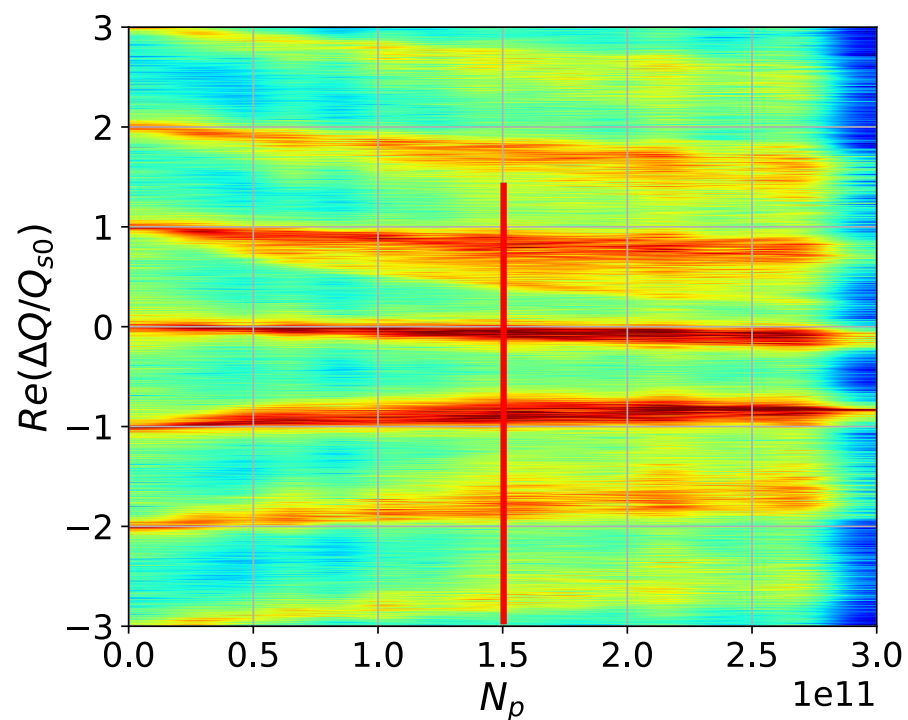
- A bunch-by-bunch feedback system is necessary, in particular in the transverse plane, to suppress the TCBI due to the real part of the RW impedance at low frequency.
- The damping time depends on the fractional part of the tune, however, it should be of the order of 1-2 ms, similar to the damping time of SuperKEKB, for example (about 1 ms).
- 2 ms in FCC-ee corresponds to 6-7 turns. We must pay attention to the design of such a feedback system.
- A proposal is to use a combination of a bunch-by-bunch and a frequency domain feedback system.
- The bunch-by-bunch feedback system is also useful to suppress the single bunch TMCI,

## Single bunch collective effects in the transverse plane: new parameters

no feedback



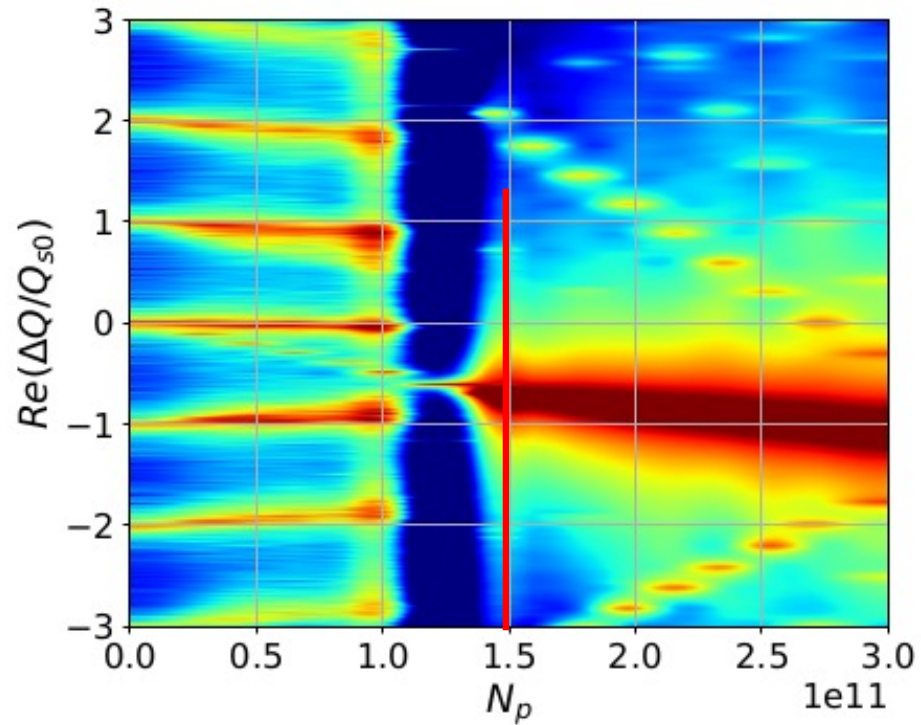
with feedback



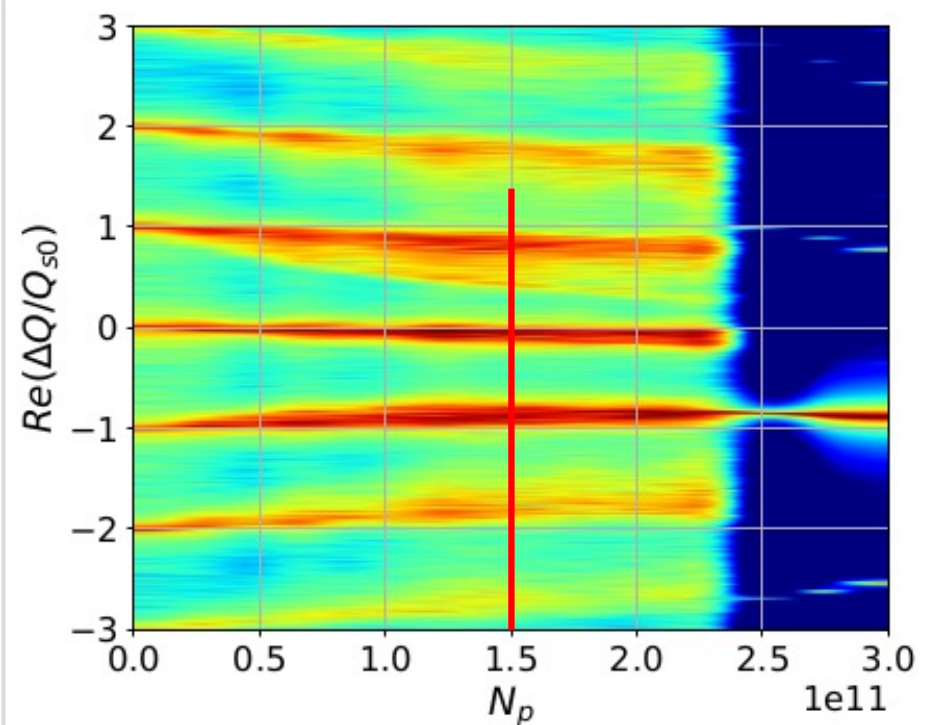


## Single bunch collective effects in the transverse plane: new parameters and reduced beam pipe (from 35 mm to 30 mm of radius)

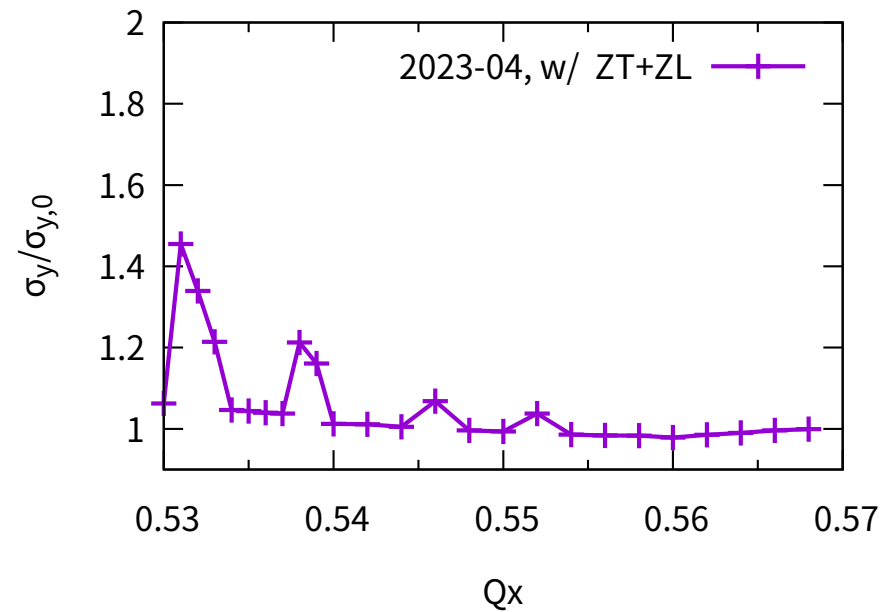
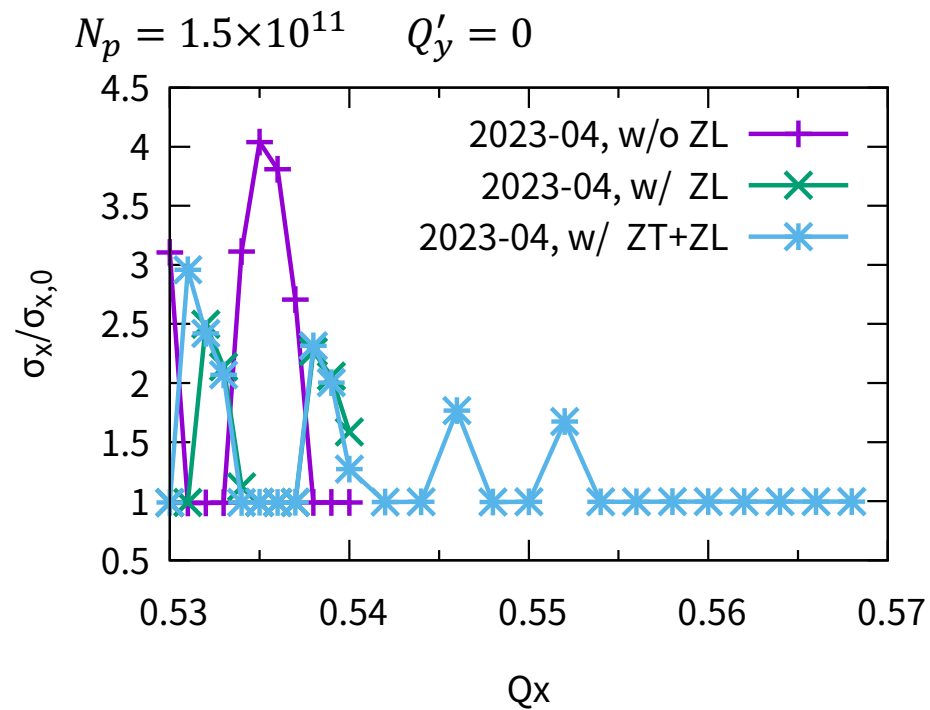
no feedback



with feedback



## Work in progress: interplay between beam-beam and coupling impedance



## 2024 activity

- FCC-ee is an ongoing project, and, as we analyse new devices, we find a continuous increase in the total machine impedance. On the other hand, the impedance evaluated so far already shows that collective effects play an important role in the stability of the machine, and particular efforts must be directed to impedance optimization.
- Open questions so far: collimator's geometry, collective effects with beam-beam with 30 mm vacuum chamber. However, also the optics can change (new working point from Pantaleo?).
- Beam instability thresholds and stability regions can change according to the new impedance sources that will be gradually added and to new parameter lists.
- The studies so far show a strong interplay between longitudinal wakefield, transverse wakefield, feedback system and beam-beam: each effect cannot be studied independently from the others.
- It is fundamental to have different available tools for counteracting collective effects.

FTE 2024 in Roma1: M. Migliorati 0.5

### Requests 2024:

- Travels: 6 k€ (FCC week in USA, CERN, KEK)
- Software: 12 k€ (CST Microwave Studio)