Collective effects

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Acknowledgements: collimation, vacuum and RF groups

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Outline

- FCC-ee main parameters (for mid-term review)
- Review of wakefields and impedance model
- Transverse coupled bunch instabilities and feedback system
- Interplay between beam-beam and coupling impedance

FCC-ee main parameters (for mid-term review)

Note:

lower single bunch intensity (1.5e11 with respect to 2.6e11)

longer bunch (5.6 mm with respect to 4.37 mm)

lower synchrotron tune (0.029 with respect to 0.037)

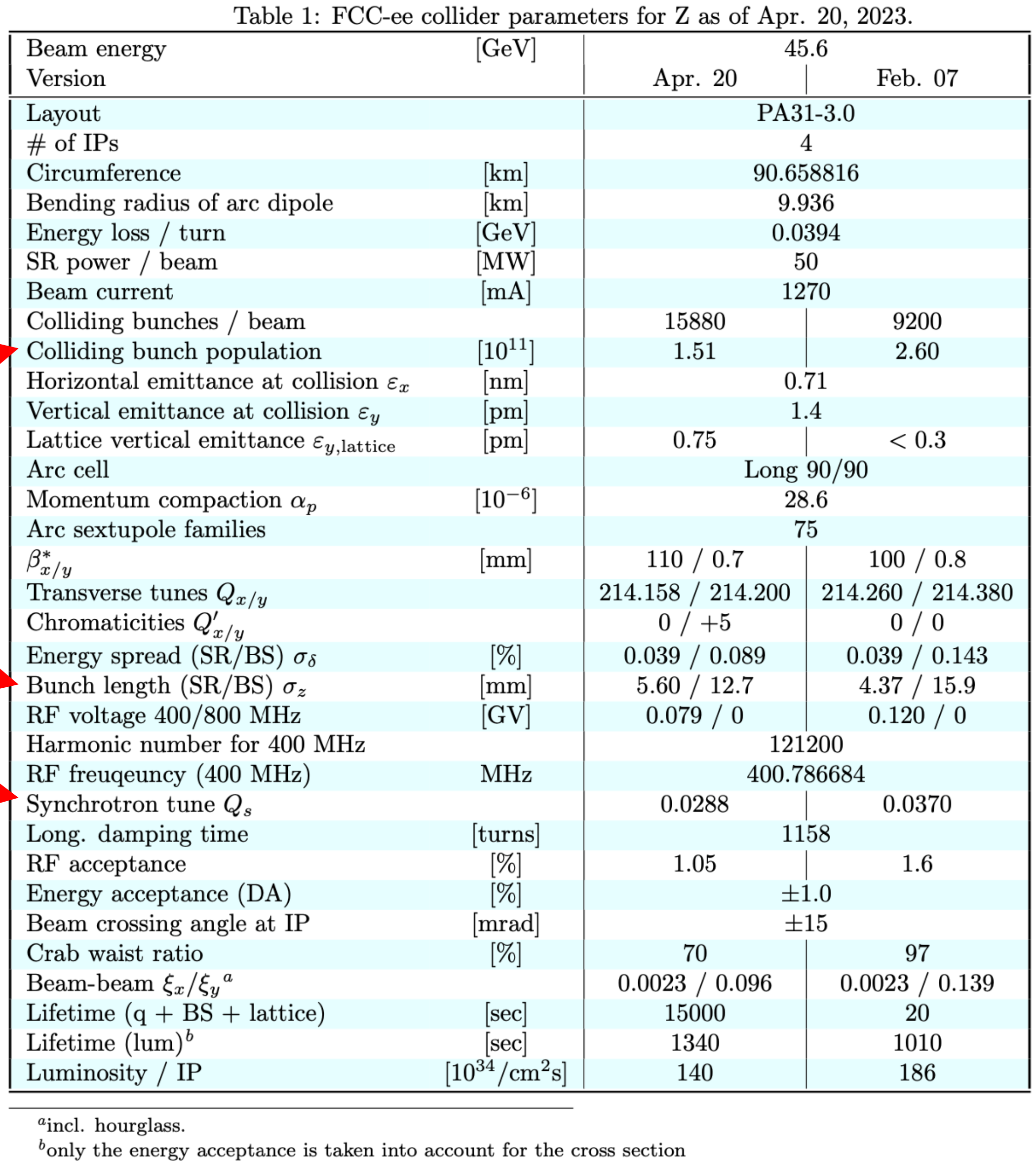

Table 1: FCC-ee collider parameters for Z as of Apr. 20, 2023.

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 ε_x	[nm]	0.71	
Vertical emittance at collision ε_y	[pm]	1.4	
Lattice vertical emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	< 0.3
Arc cell		Long 90/90	
Momentum compaction α_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) σ_δ	[%]	0.039 / 0.089	0.039 / 0.143
Bunch length (SR/BS) σ_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 freuqeuncy (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)	[%]	±1.0	
Beam crossing angle at IP	[mrad]	±15	
Crab waist ratio	[%]	70	97
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.0023 / 0.139
Lifetime (q + BS + lattice)	[sec]	15000	20
Lifetime (lum)[b]	[sec]	1340	1010
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	140	186

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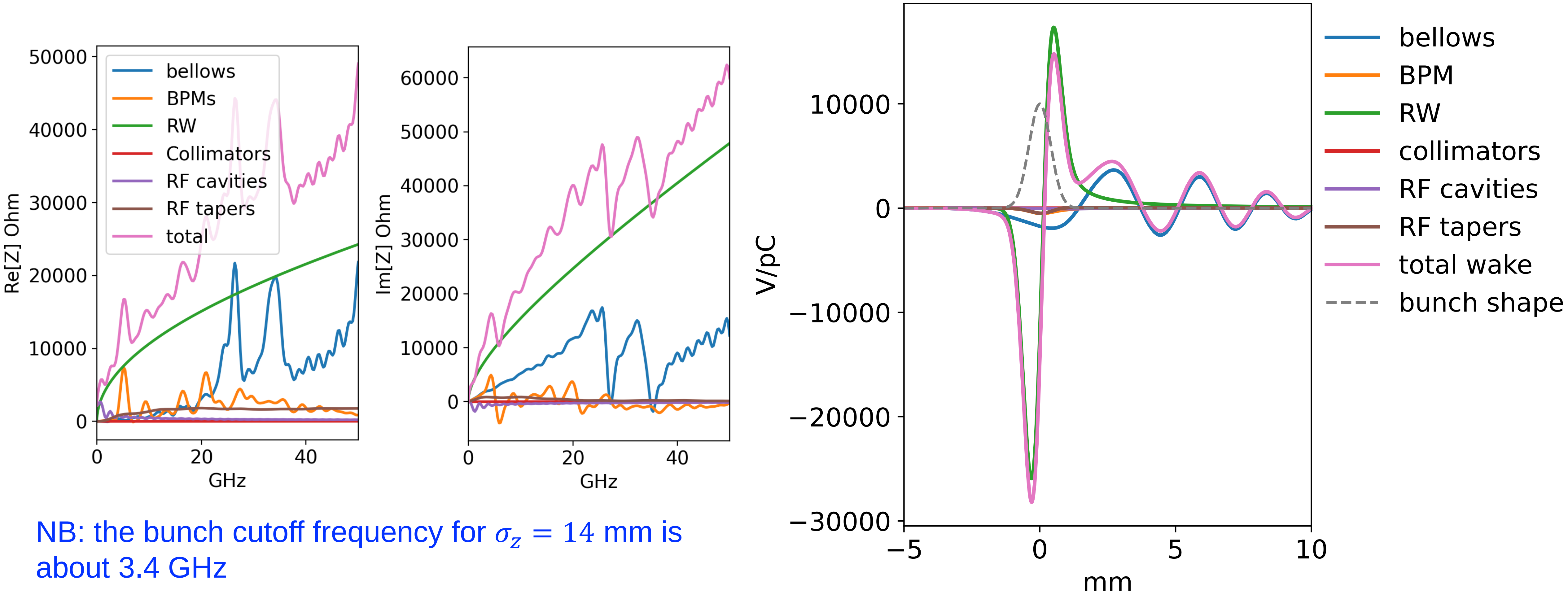
[a] incl. hourglass.

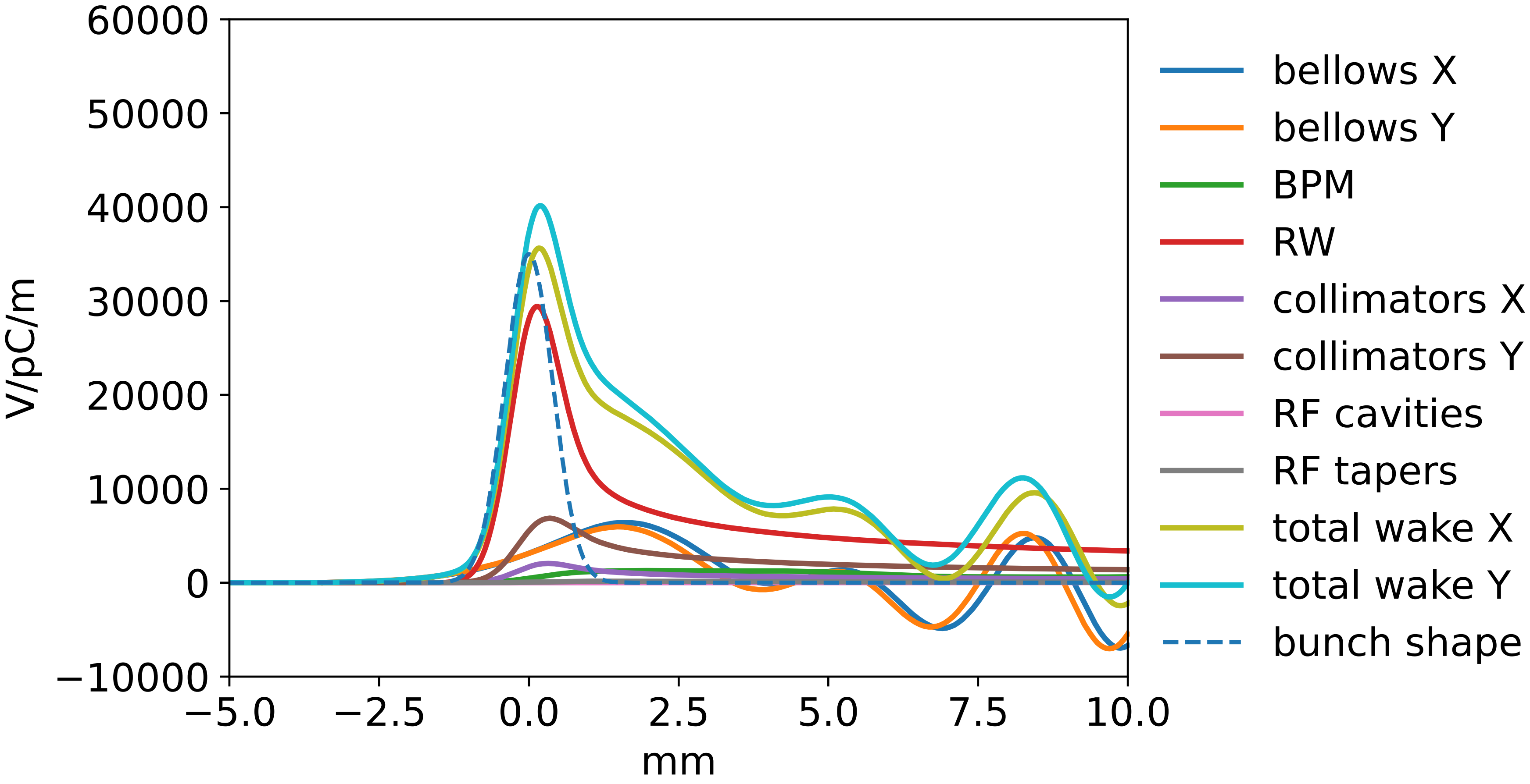
[b] only the energy acceptance is taken into account for the cross section

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

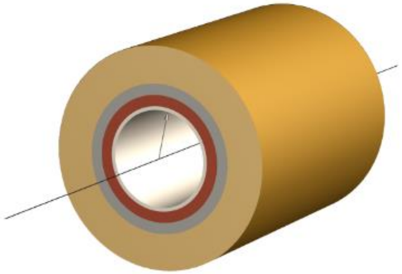


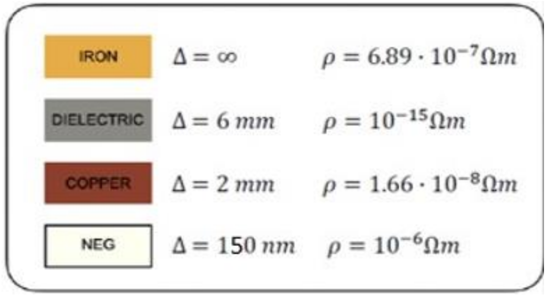
In beam dynamics simulations we have also included the quadrupolar term (small contribution so far).

Main impedance sources

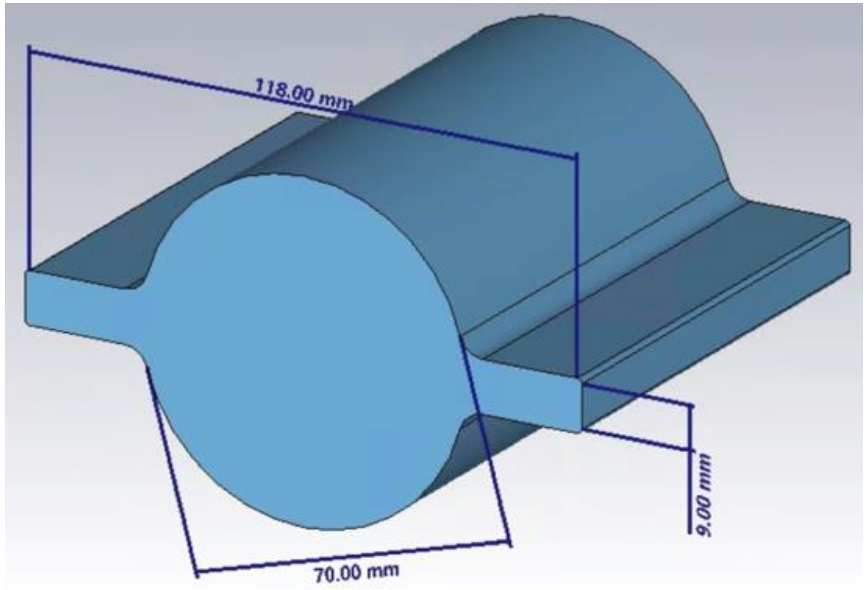
Resistive wall

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.





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



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)

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

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

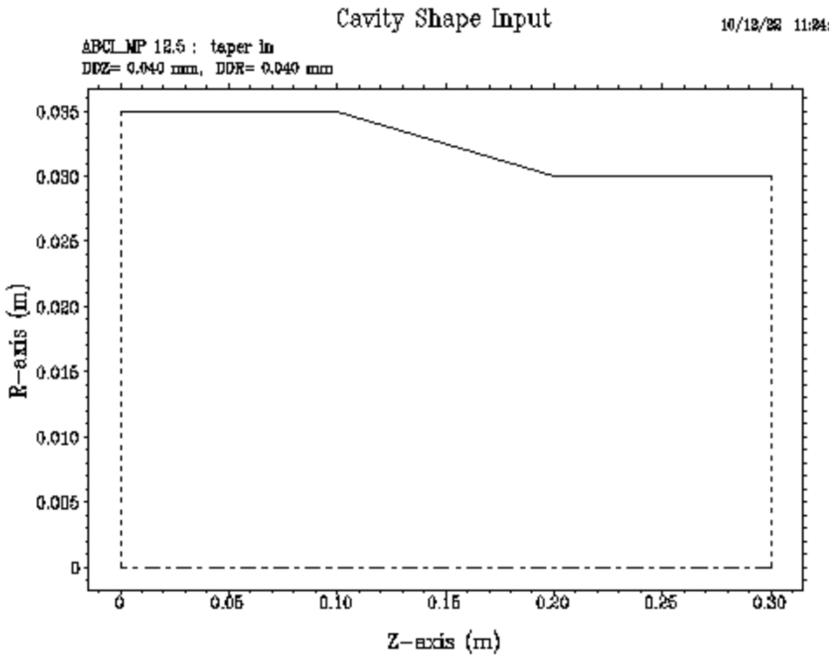
Since the transverse dipolar wake is proportional to $1/b^3$, passing from 35 to 30 mm means an increase in impedance and wake amplitude of $\frac{35^3}{30^3} = 1.6 \rightarrow 60\%$

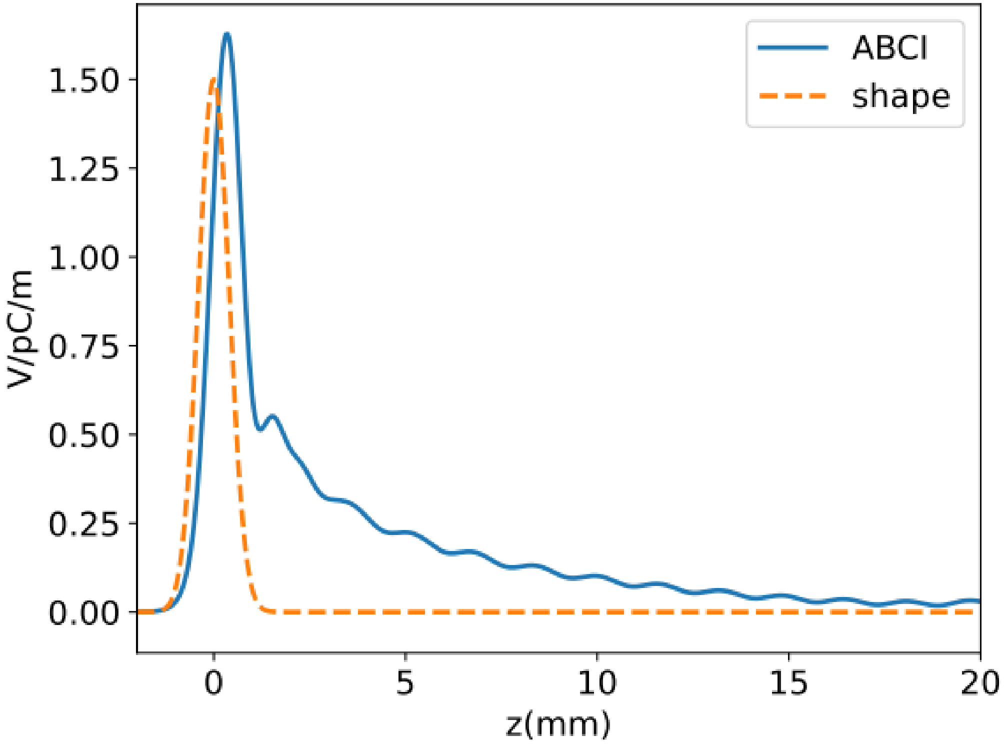
Reduction of beam pipe radius only in short straight sections (quads and sexts): 10 km of pipe with 30 mm of radius:

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

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



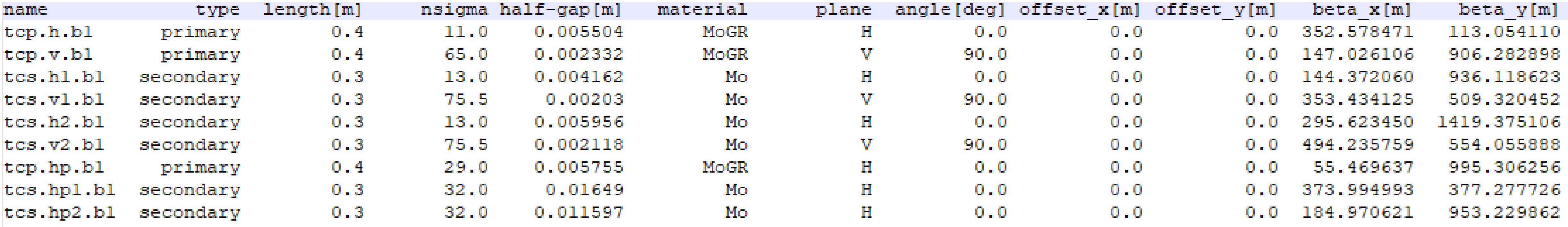


If we multiply this by 2 (double taper) and by 1500 (number of sections), we have a peak at about 5000 V/pC/m.

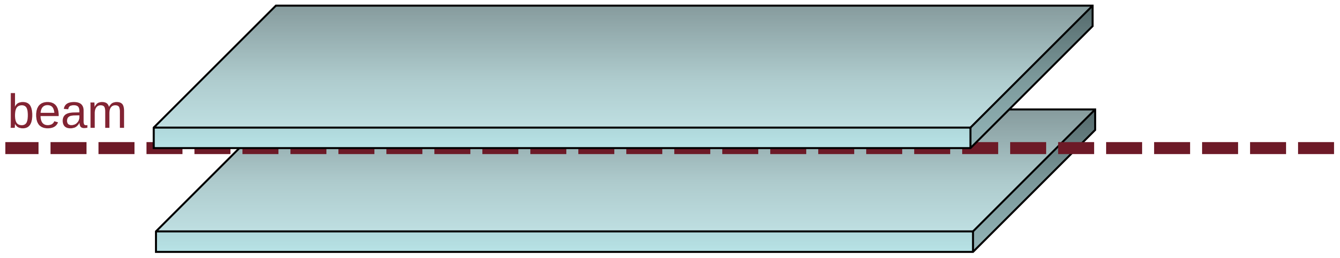
This is about 12.5% of the total transverse dipolar wake that we have evaluated so far. Is it possible to reduce this geometric impedance?

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.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

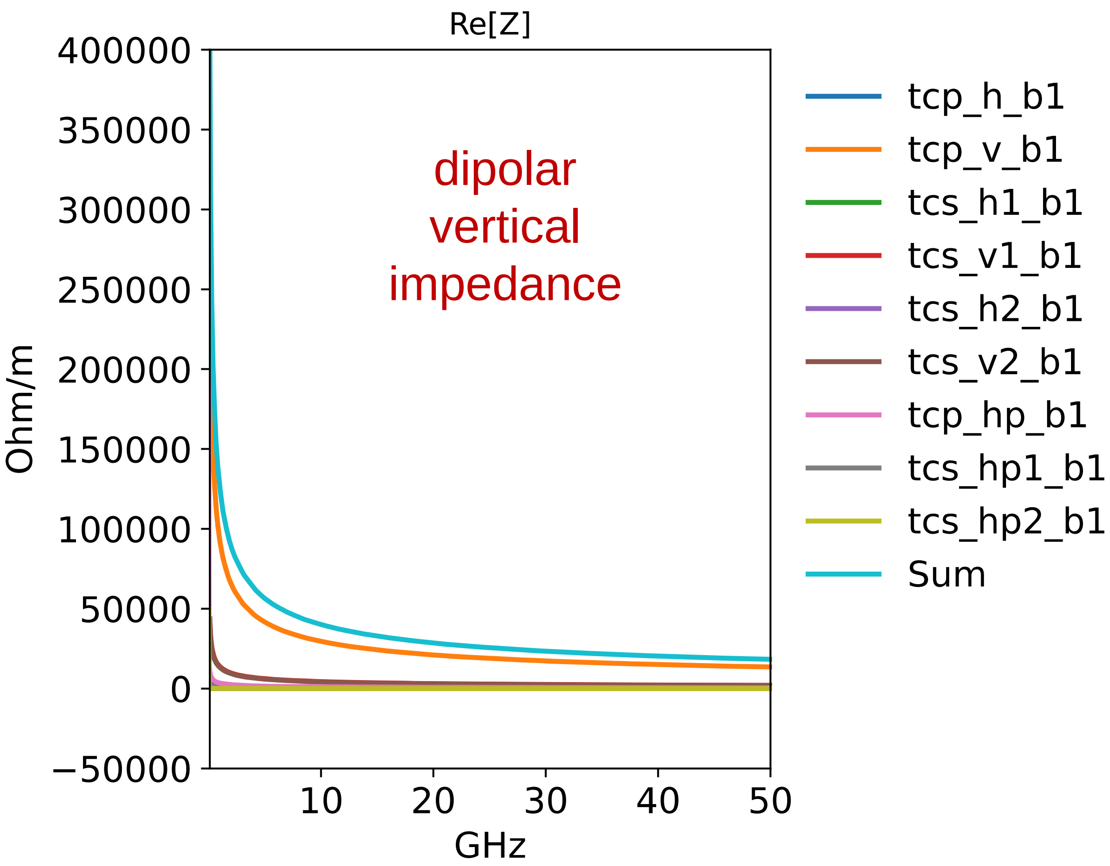


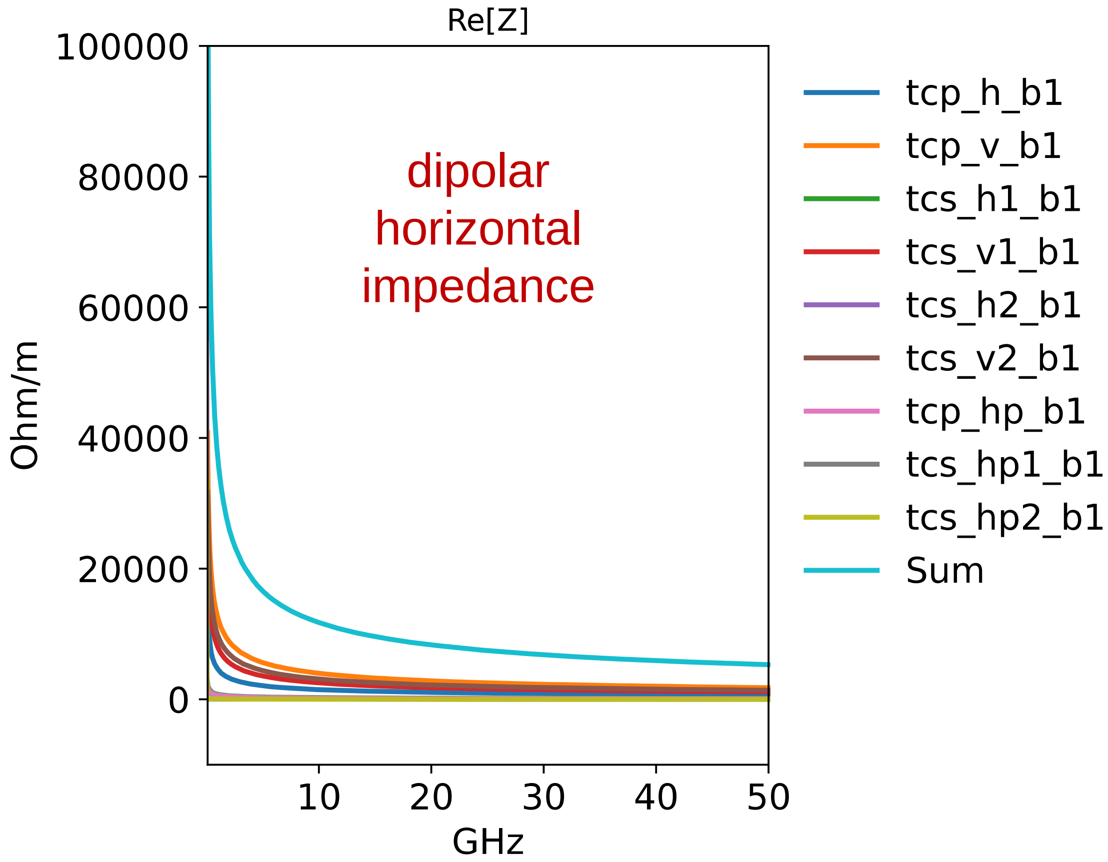
For the resistive wall contribution we suppose parallel plates with infinite thickness and use IW2D for the impedance and wakefield evaluation.

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

Collimation system

$$Z(\omega)\frac{\beta_{x,y}}{<\beta_{x,y}>} \qquad <\beta_{x,y}> = \frac{1}{C}\oint \beta_{x,y}\,ds = 144.1, 241.5\ m$$

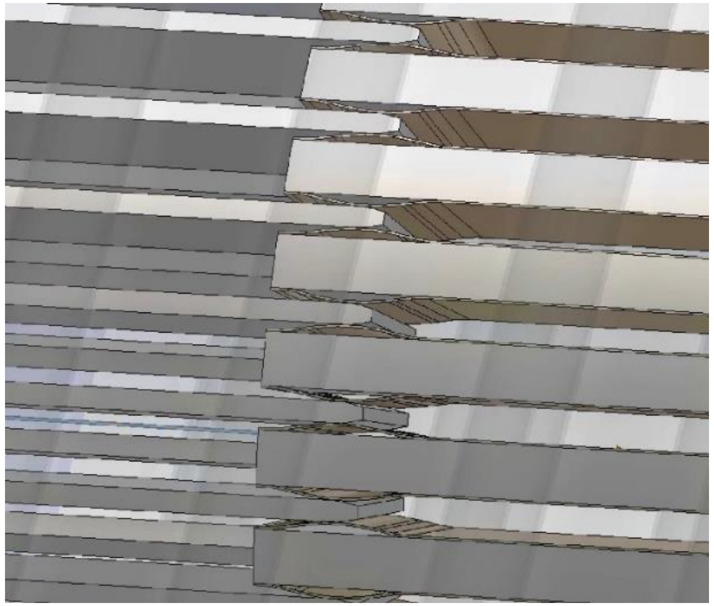

dipolar vertical impedance

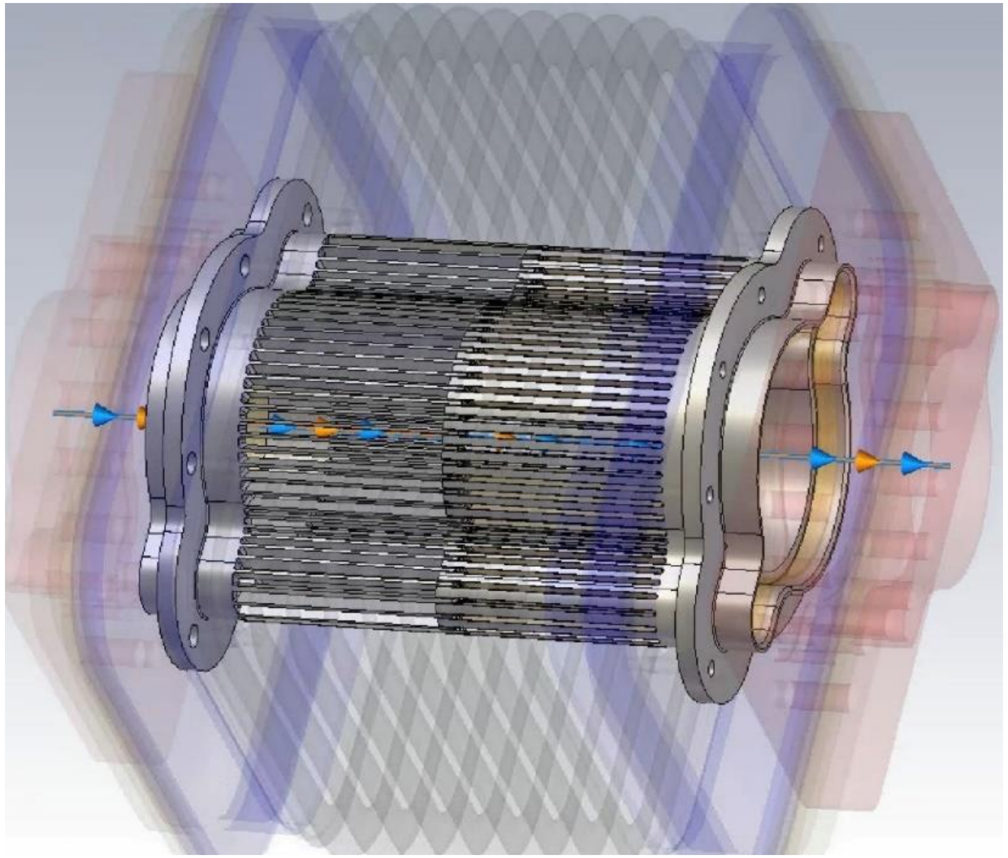

dipolar horizontal impedance

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.



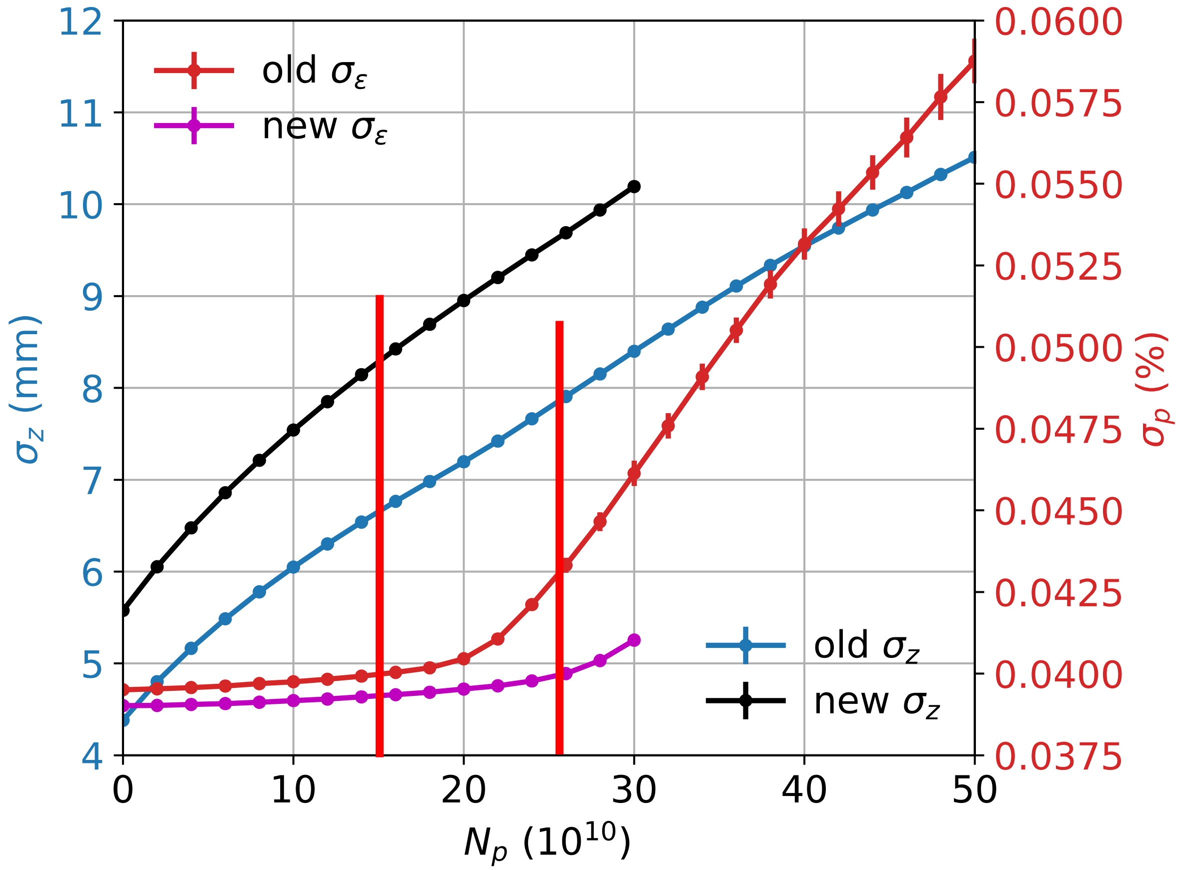


Single bunch collective effects in the longitudinal plane: comparison between old and new parameters

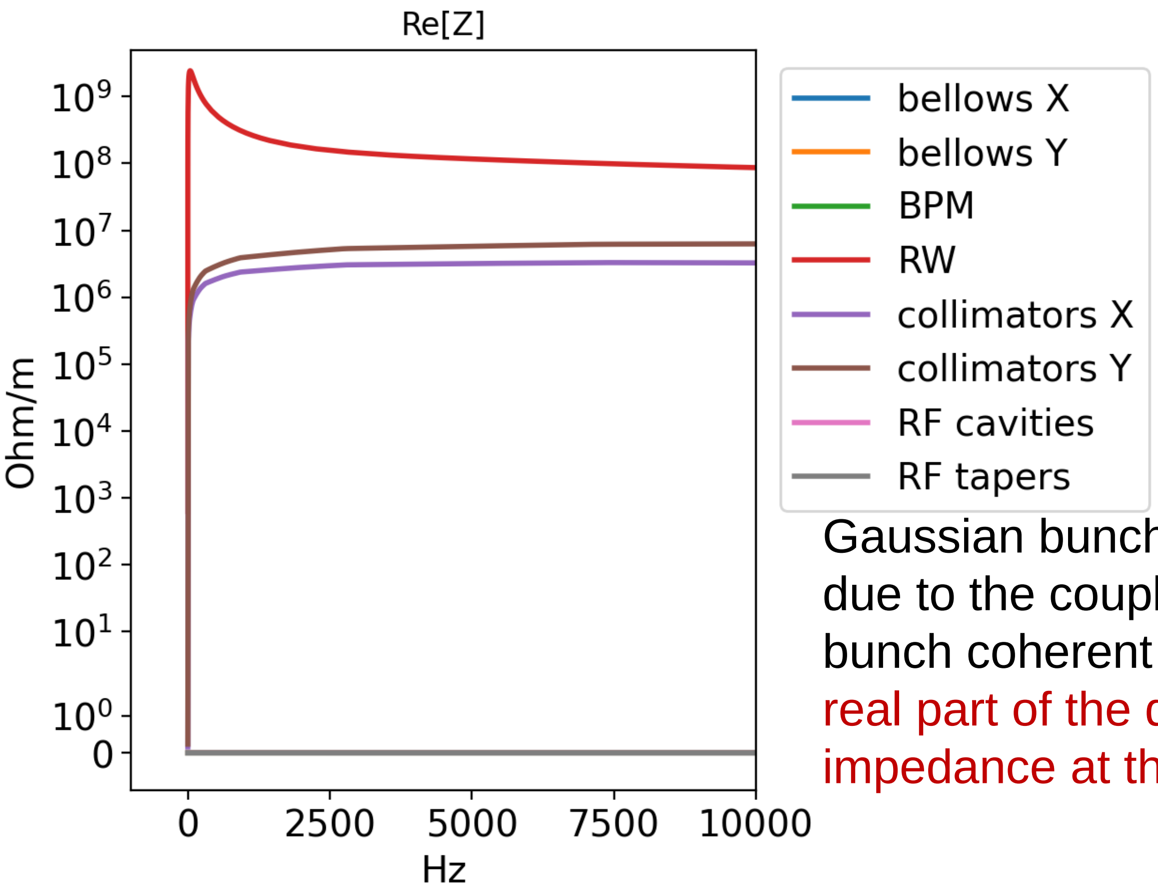
With beamstrahlung we have found that at 1.5e11 ppb:

σ_z = 13.6 mm (w/o ZL)
σ_z = 14.0 mm (w/ ZL)

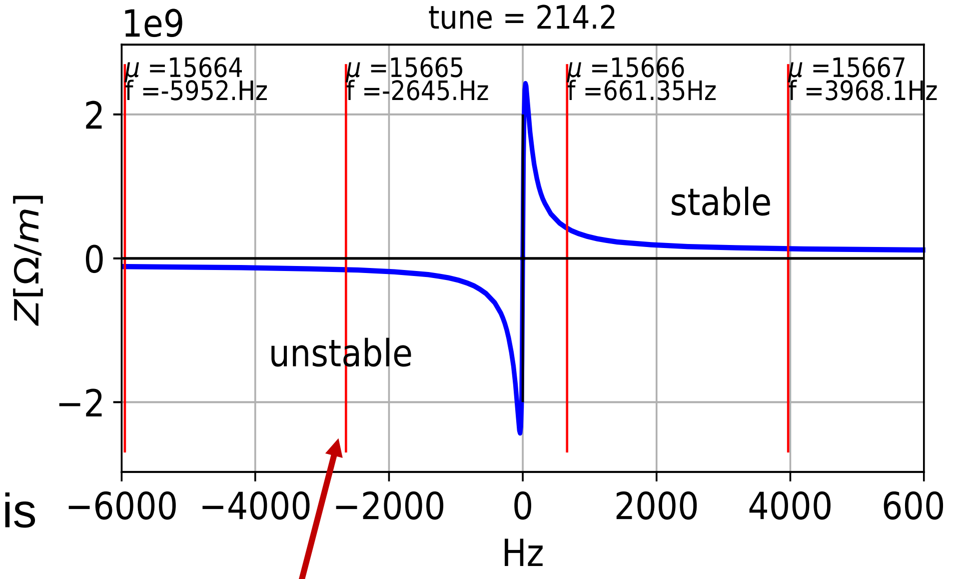
σ_p = 9.45e-4 (w/o ZL),
σ_p = 9e-4 (w/ ZL)



Transverse coupled bunch instability and feedback system



The TCBI is evaluated by considering the lowest azimuthal intra-bunch mode (rigid dipolar oscillations) and Gaussian bunches. The instability is due to the coupling of the multi-bunch coherent frequencies with the real part of the dipolar coupling impedance at the lowest frequencies.

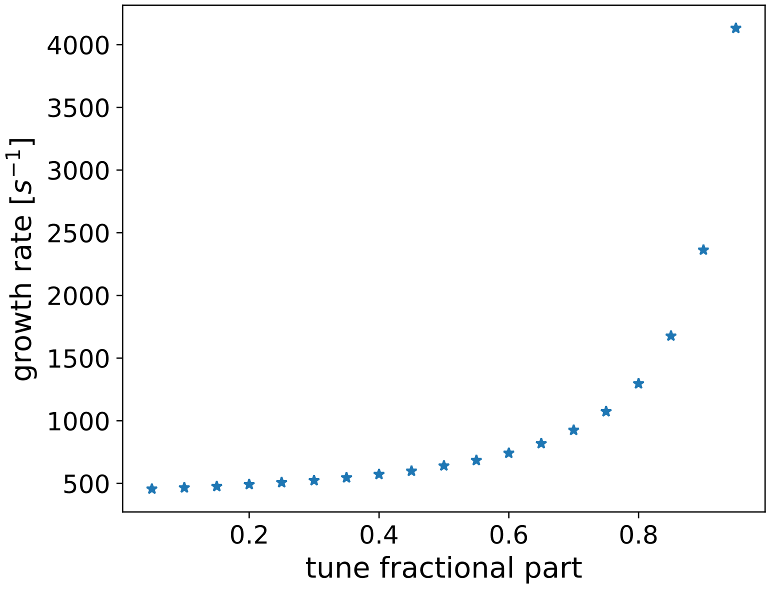


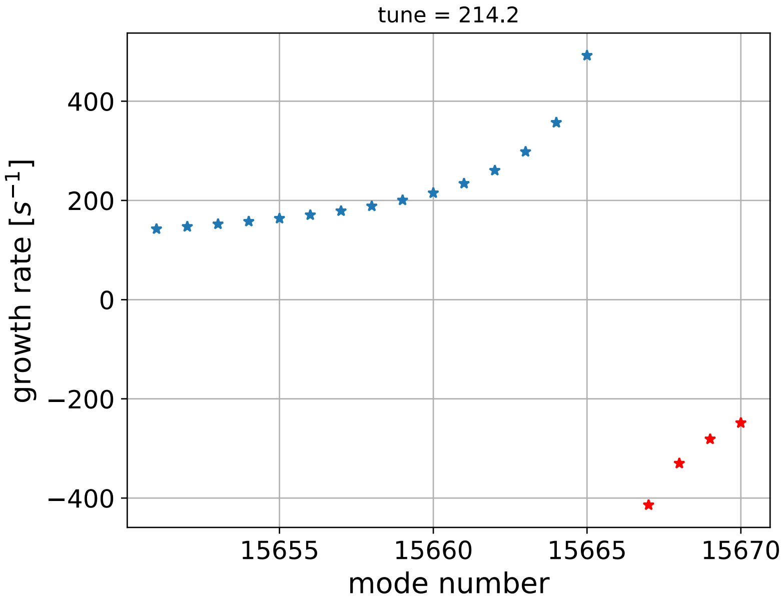
The most dangerous mode is that closest to the origin (with negative frequency)

From the real part of the transverse impedance at low frequency we see that only the RW contribution due to the beam pipe is important. Collimators do not seem to contribute much at such low frequencies

Transverse coupled bunch instability and feedback system

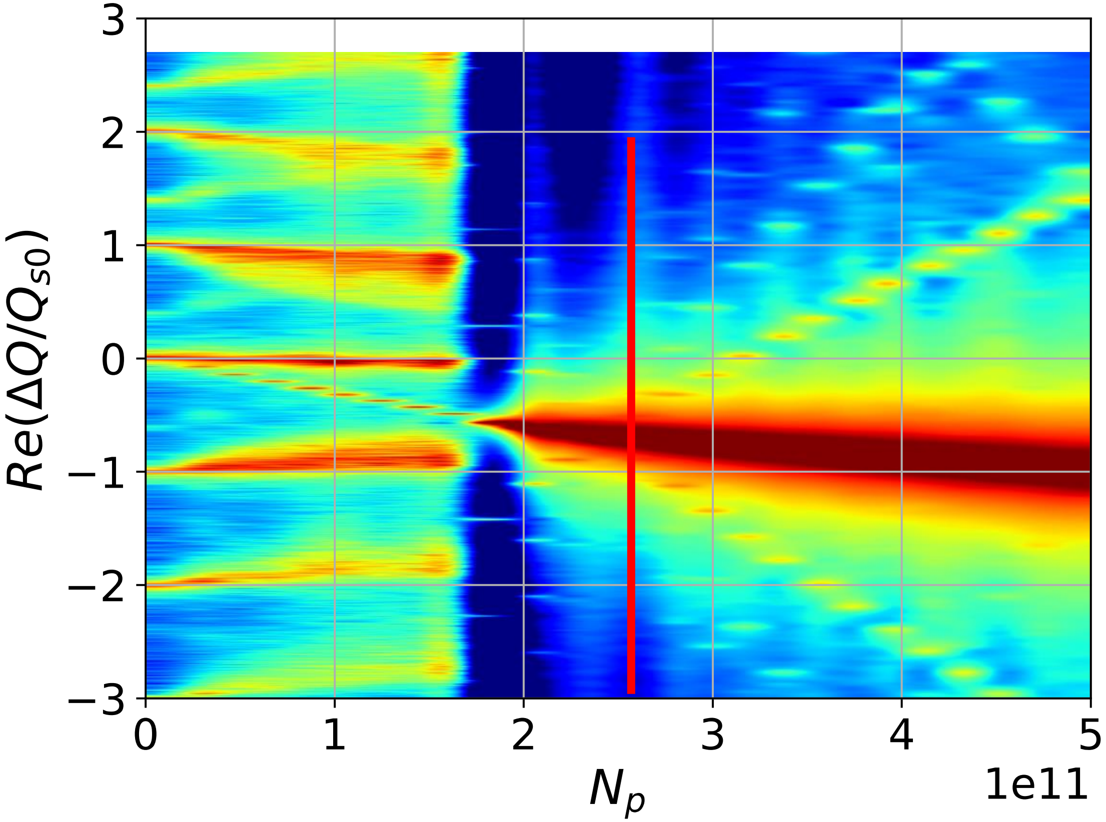
- To suppress the TCBI, a bunch-by-bunch feedback system is necessary.
- The damping time in the transverse plane should be of the order of 2 ms, similar to the damping time of SuperKEKB, for example (about 1 ms).
- However, 2 ms in FCC-ee corresponds to 6-7 turns. We must pay attention to the design of such a feedback system.
- The bunch-by-bunch feedback system is also useful to suppress the single bunch TMCI, even if it can excite the '-1 mode' instability.
- The good news is that its threshold has an intensity higher than that corresponding to the TMCI without the feedback.



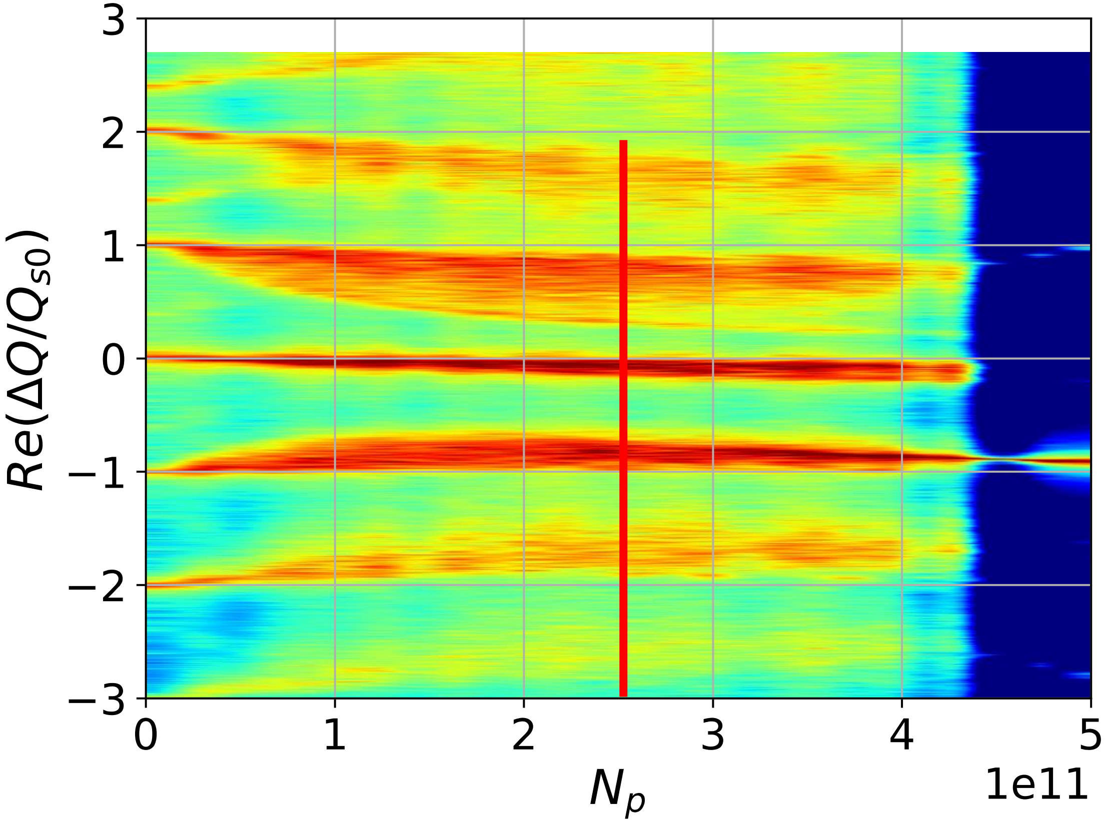


Single bunch collective effects in the transverse plane: old parameters

no feedback

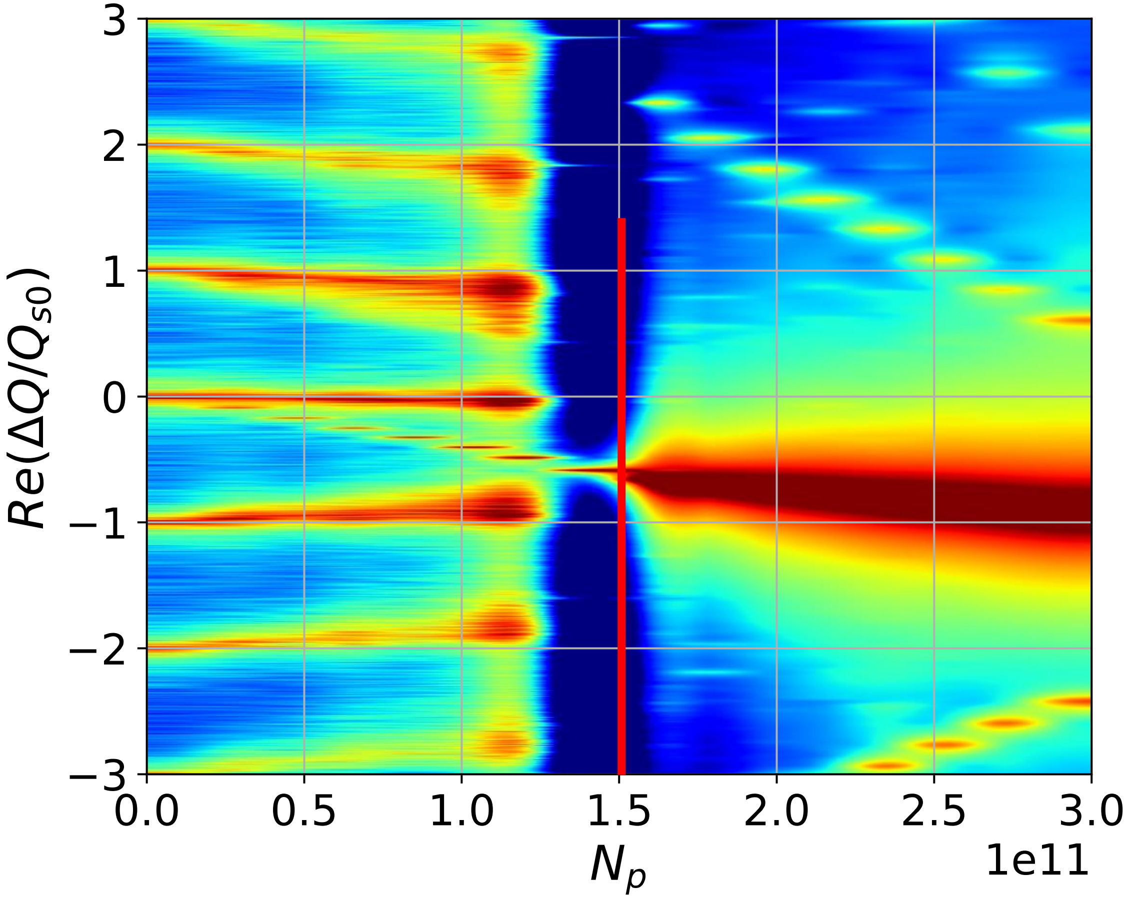


with feedback

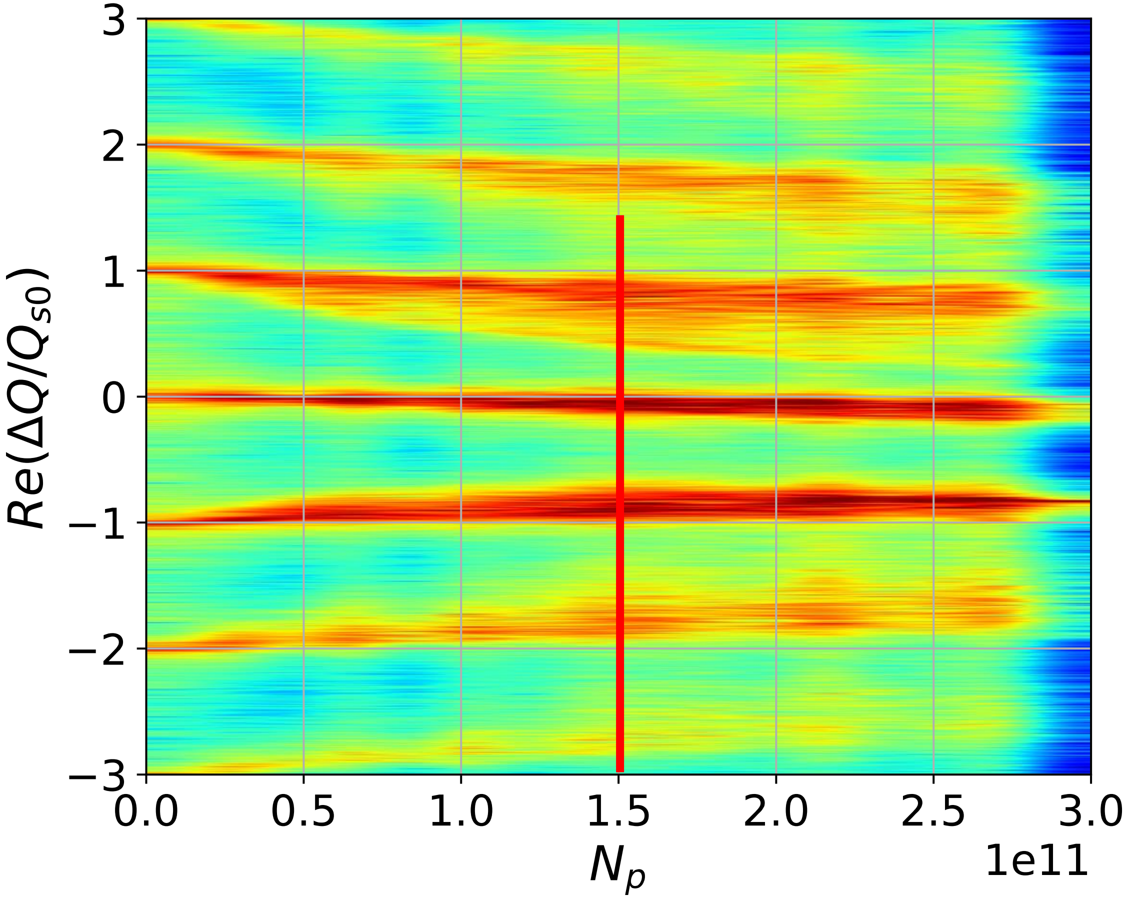


Single bunch collective effects in the transverse plane: new parameters

no feedback

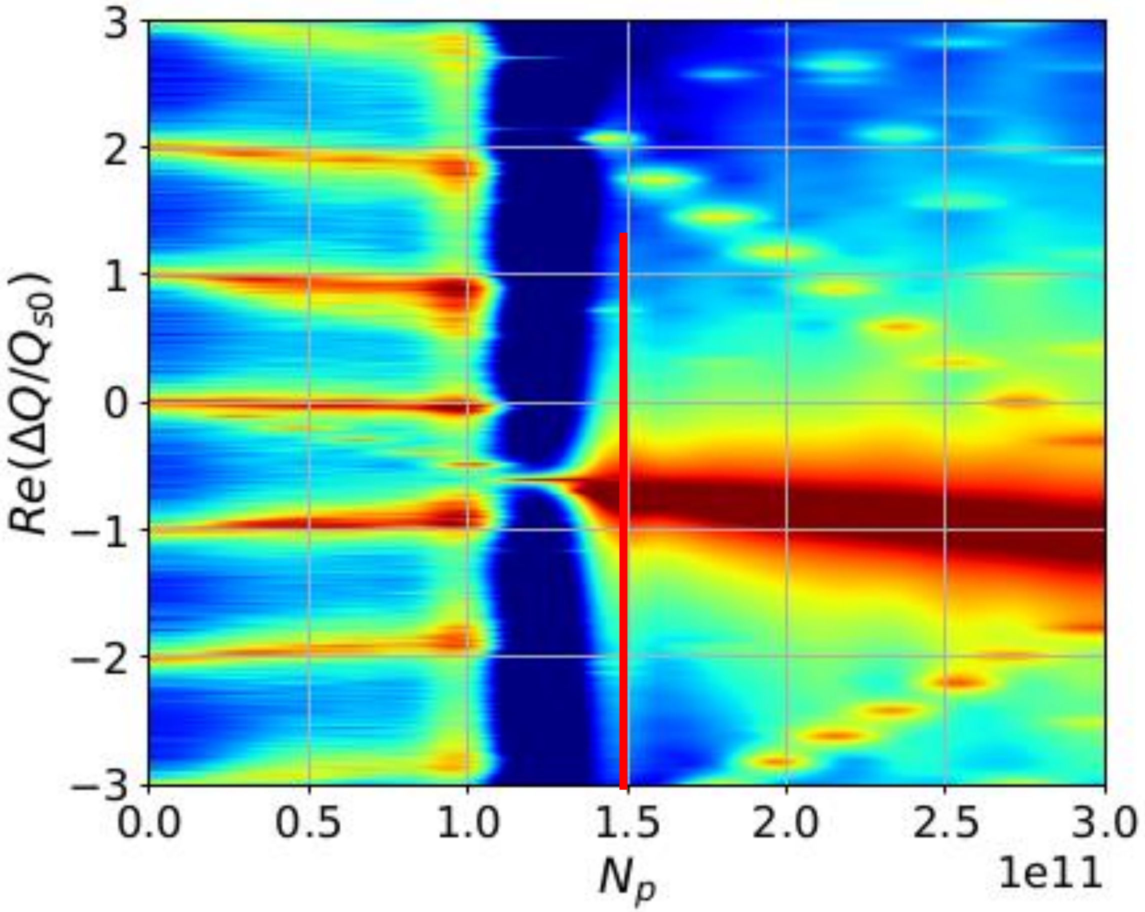


with feedback

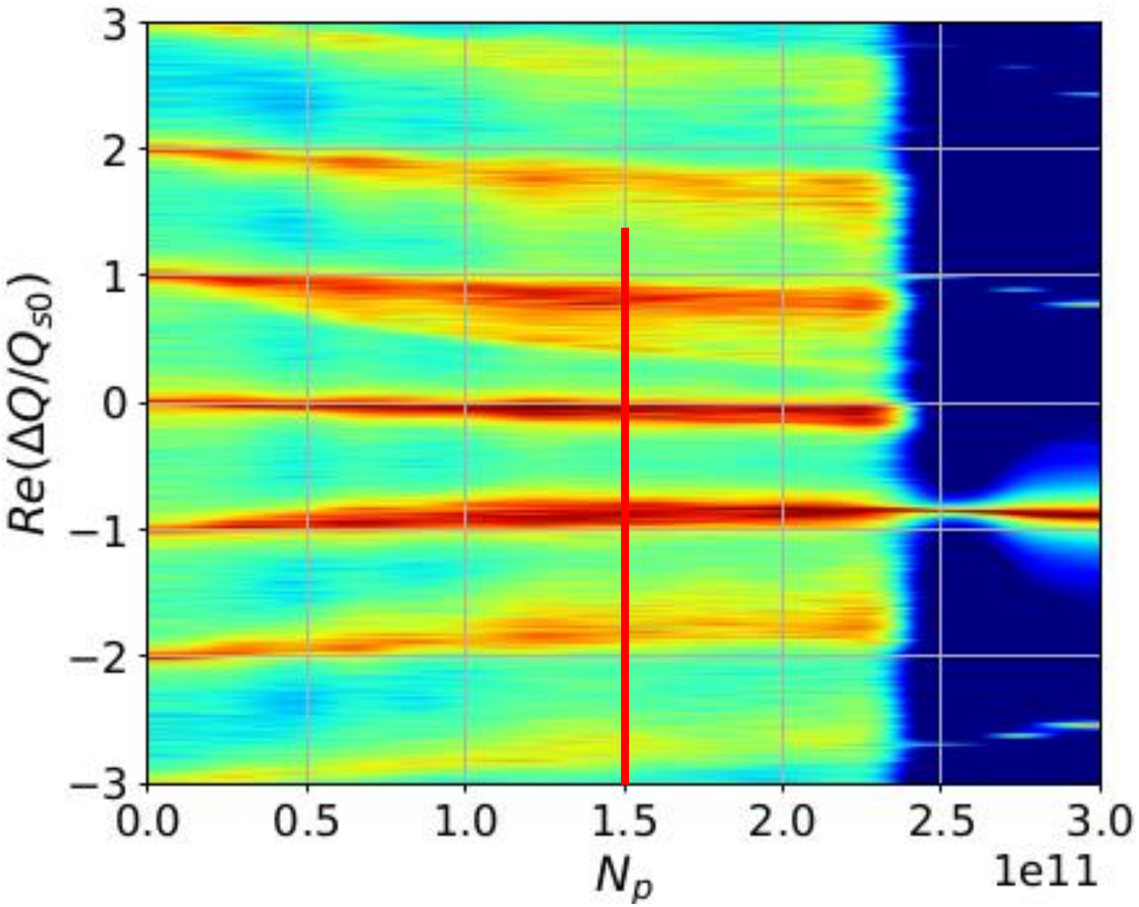


Single bunch collective effects in the transverse plane: new parameters and reduced beam pipe (from 35 mm to 30 mm of radius)

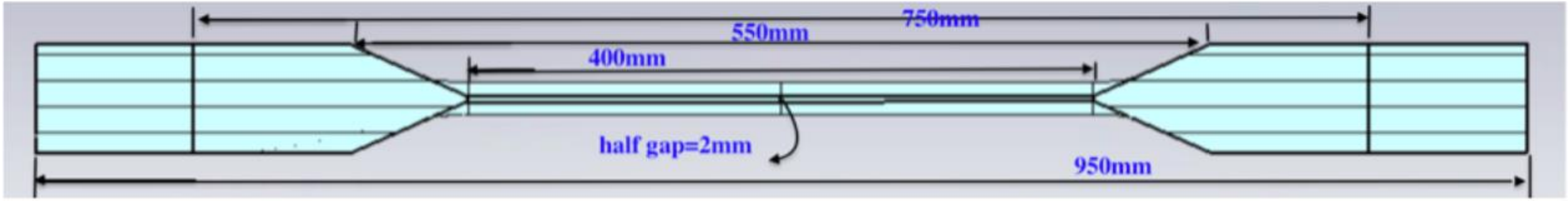
no feedback

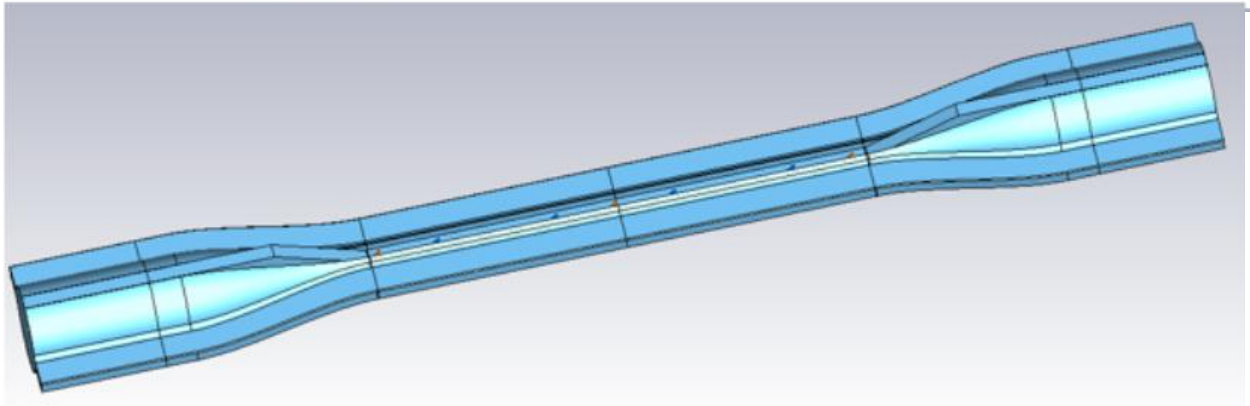


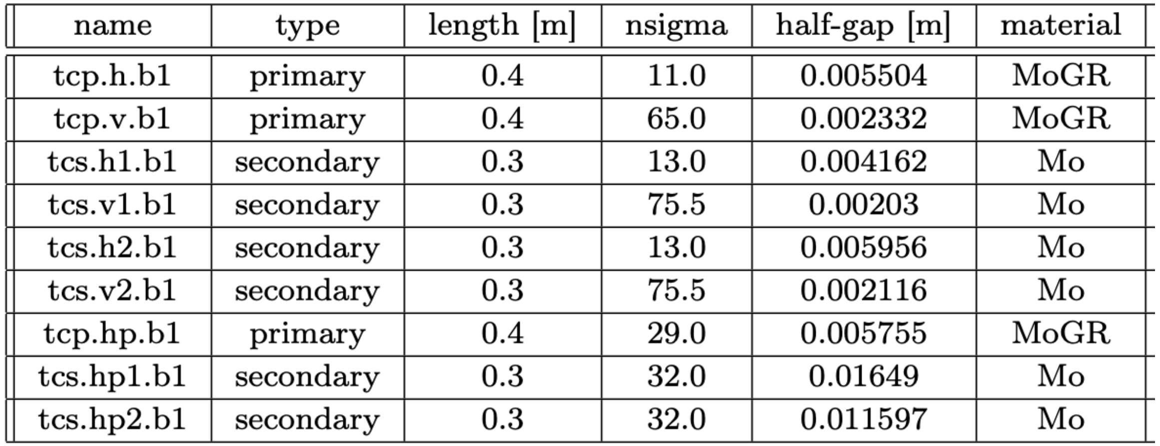
with feedback



Work in progress: geometrical wakefield due to collimators







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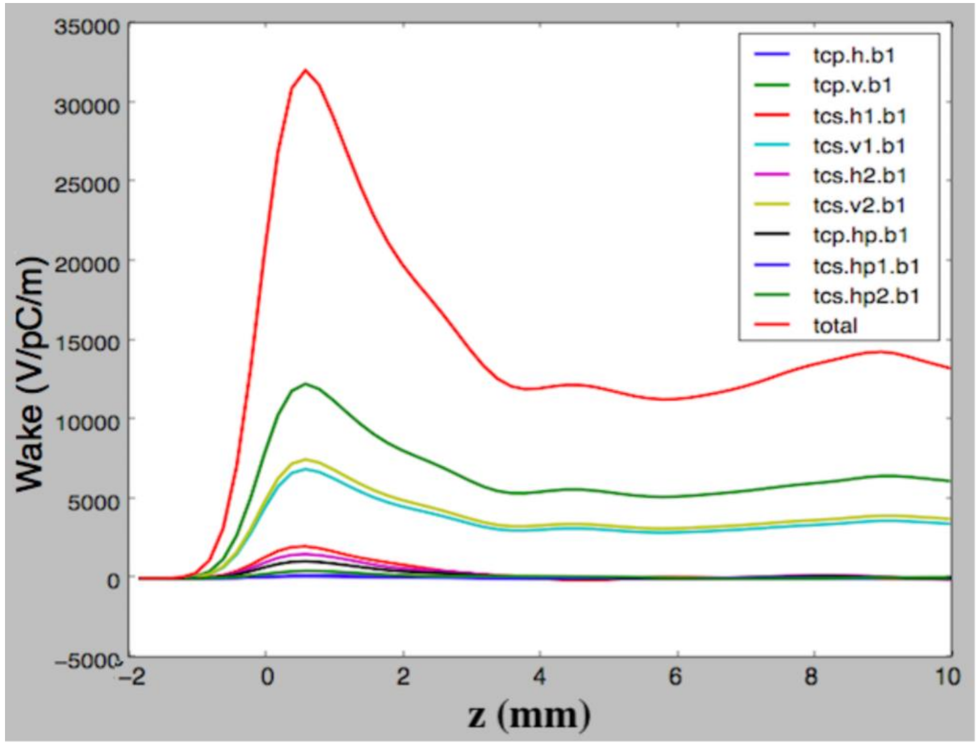
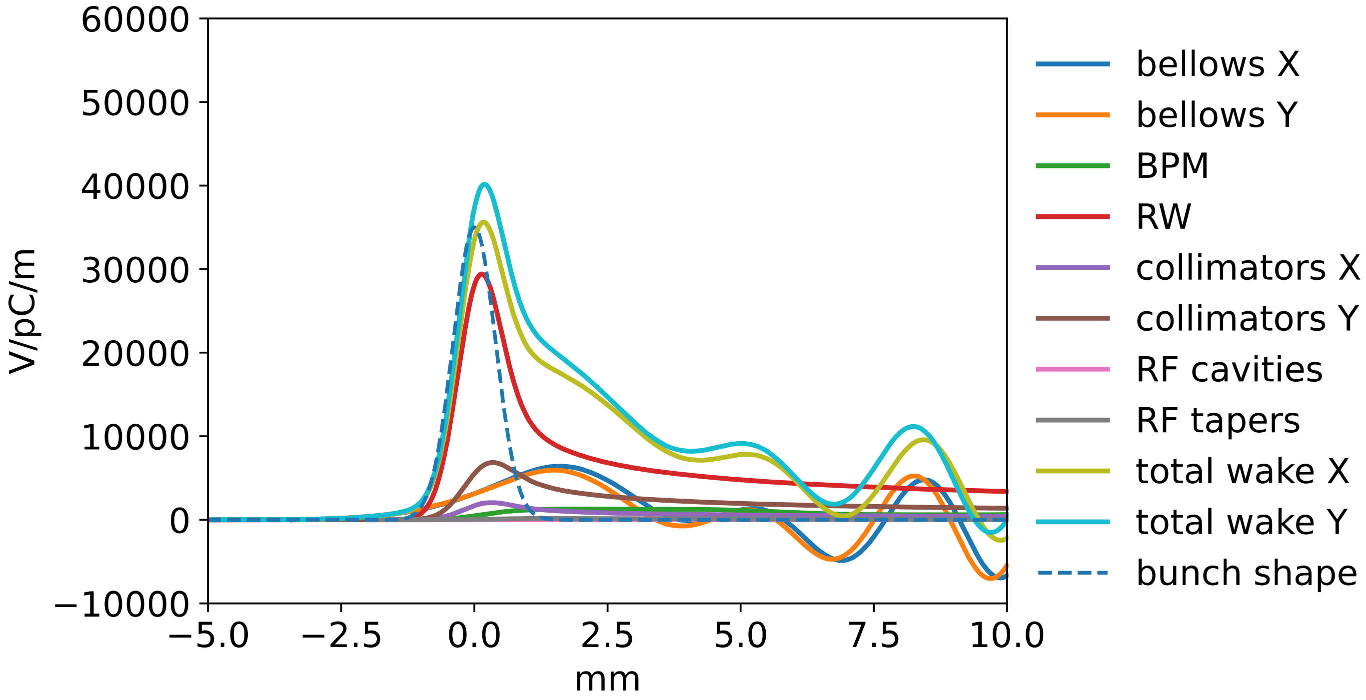
tcp.v.b1	primary	0.4	65.0	0.002332	MoGR
tcs.h1.b1	secondary	0.3	13.0	0.004162	Mo
tcs.v1.b1	secondary	0.3	75.5	0.00203	Mo
tcs.h2.b1	secondary	0.3	13.0	0.005956	Mo
tcs.v2.b1	secondary	0.3	75.5	0.002116	Mo
tcp.hp.b1	primary	0.4	29.0	0.005755	MoGR
tcs.hp1.b1	secondary	0.3	32.0	0.01649	Mo
tcs.hp2.b1	secondary	0.3	32.0	0.011597	Mo

Work in progress: geometrical wakefield due to collimators



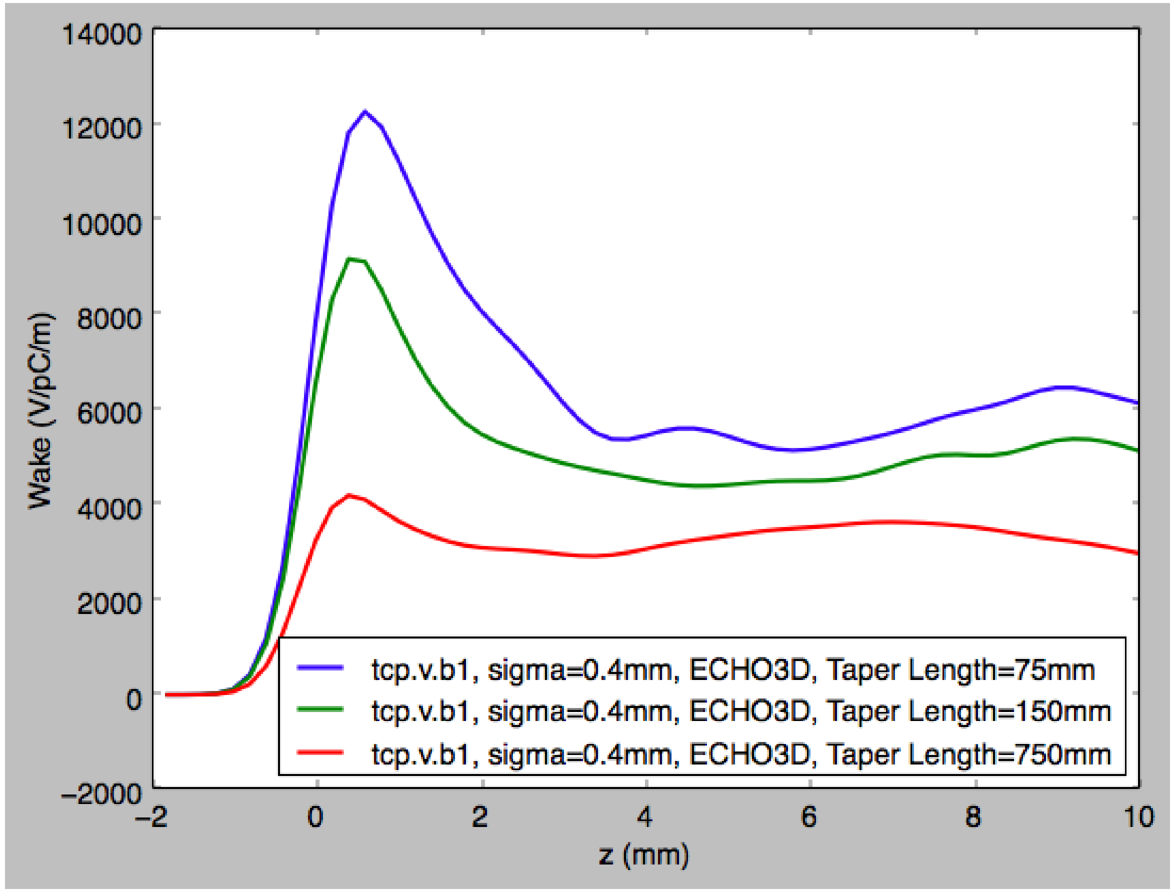


Work in progress: geometrical wakefield due to collimators

How to mitigate this geometrical contribution?

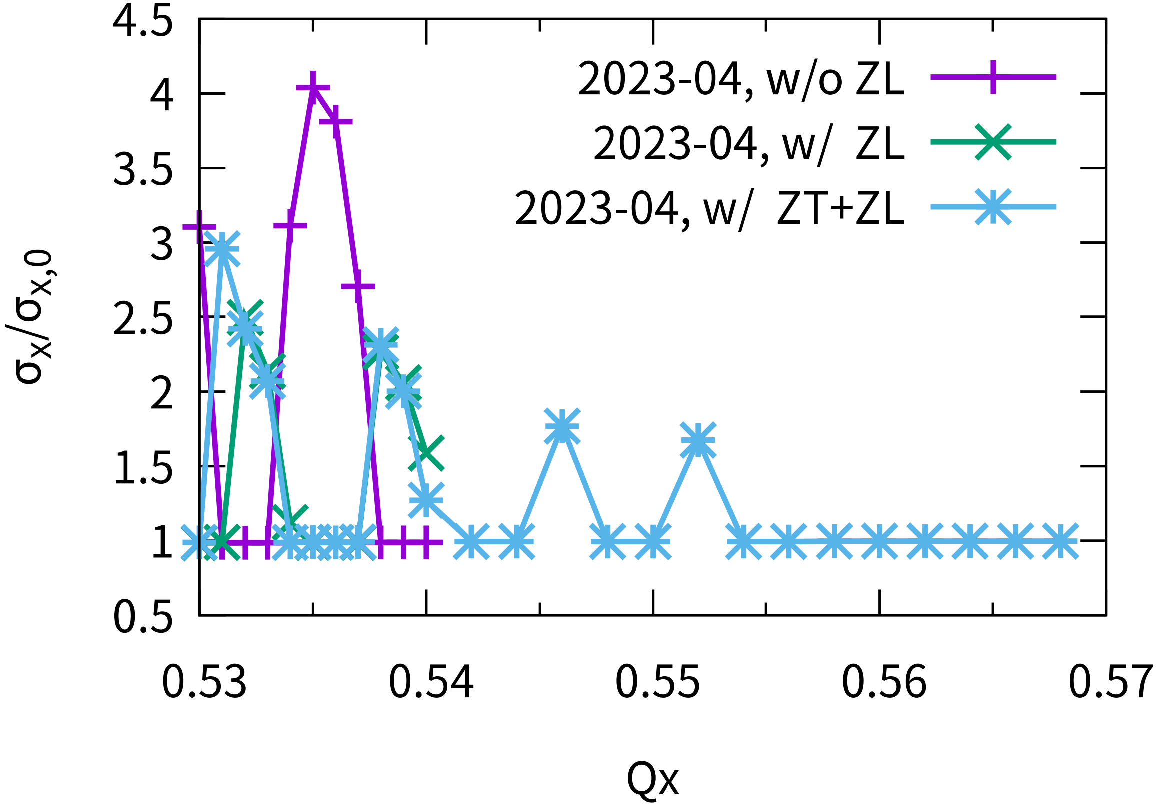
We tried to increase of the taper length, but the results were not satisfactory as expected.

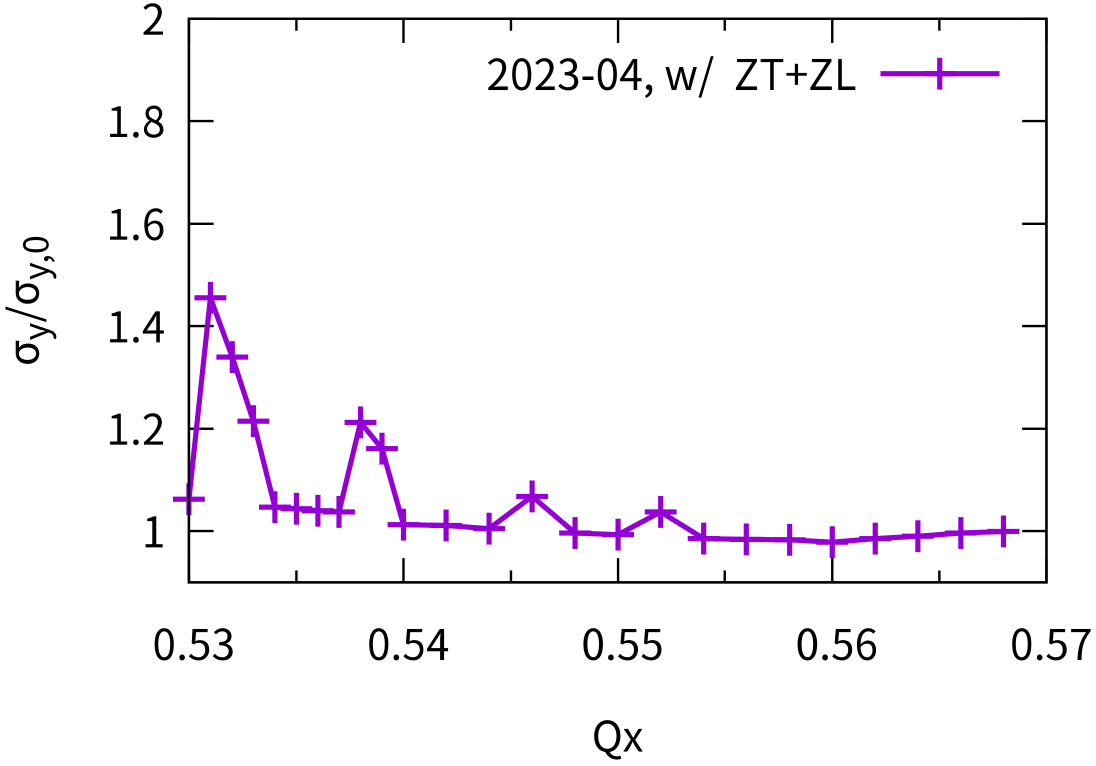
We are investigating other geometries.



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

$N_p = 1.5 \times 10^{11} \quad Q_y' = 0$





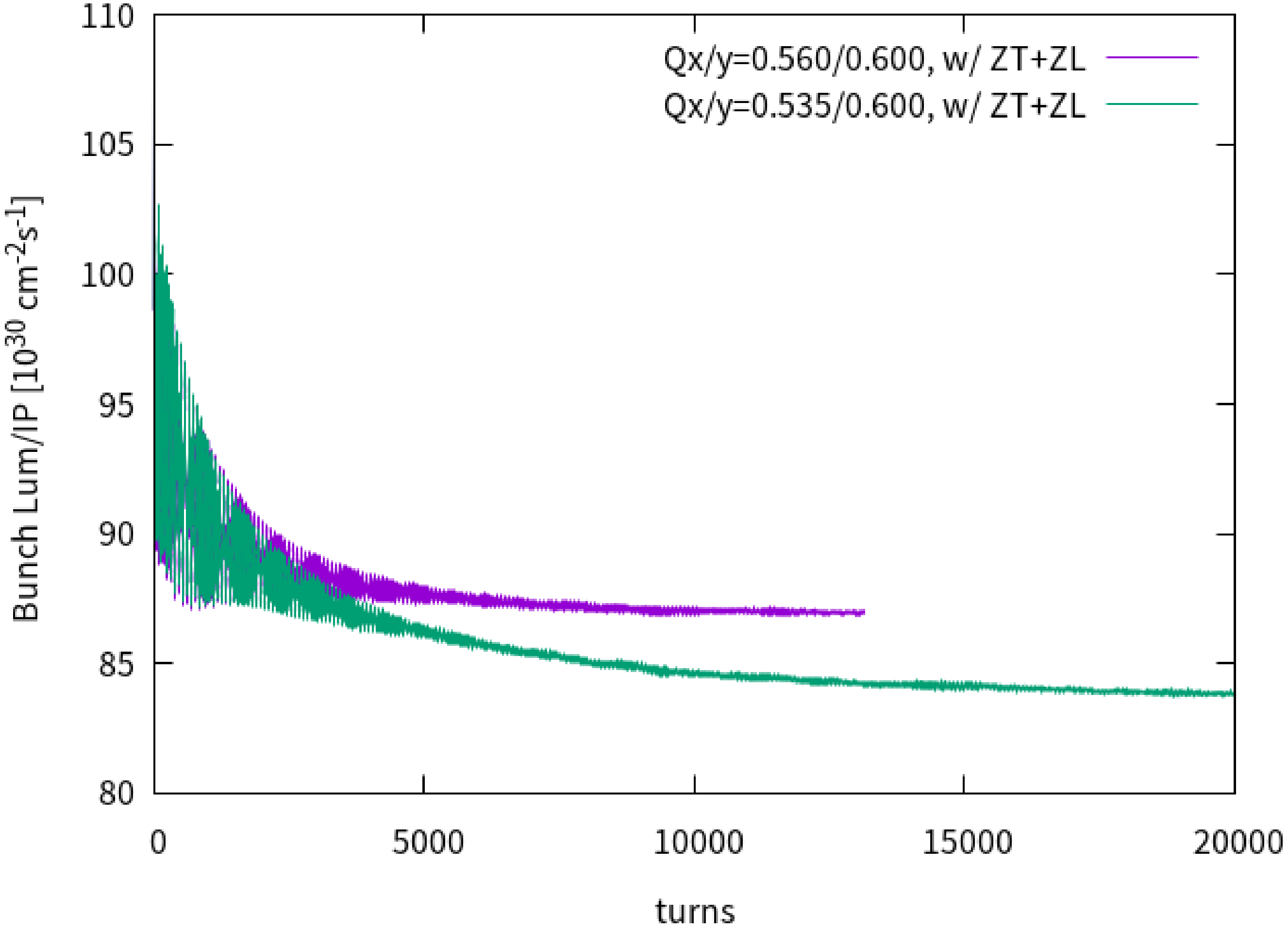
Work in progress: interplay between beam-beam and coupling impedance

$N_p = 1.5 \times 10^{11}$ $Q'_y = 0$

Nominal luminosity:

140×10^{34} cm^{-2} s^{-1}

$84 \times 10^{30} * 15880 \simeq$
133×10^{34} cm^{-2} s^{-1}



Conclusions

- FCC-ee is an ongoing project, and, as we analyse new devices, we find a continuous increase of the total machine impedance.

- On the other hand, the impedance evaluated so far already shows that collective effects play an important role for the stability of the machine.

- Particular effort must be addressed to the impedance optimization.

- Beam instability thresholds and stability regions can change according to the new impedance sources that will be gradually added. In any case we need to look for diversified mitigation solutions.

- The studies carried out 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.

Conclusions

- FCC-ee is an ongoing project, and, as we analyse new devices, we find a continuous increase of the total machine impedance.
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Thank you for your attention