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中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Collective effects for FCC-ee collider

M. Migliorati

M. Behtouei, A. Ghribi, A. Rajabi, Y. Zhang, M. Zobov

Acknowledgements: collimation, vacuum and RF groups

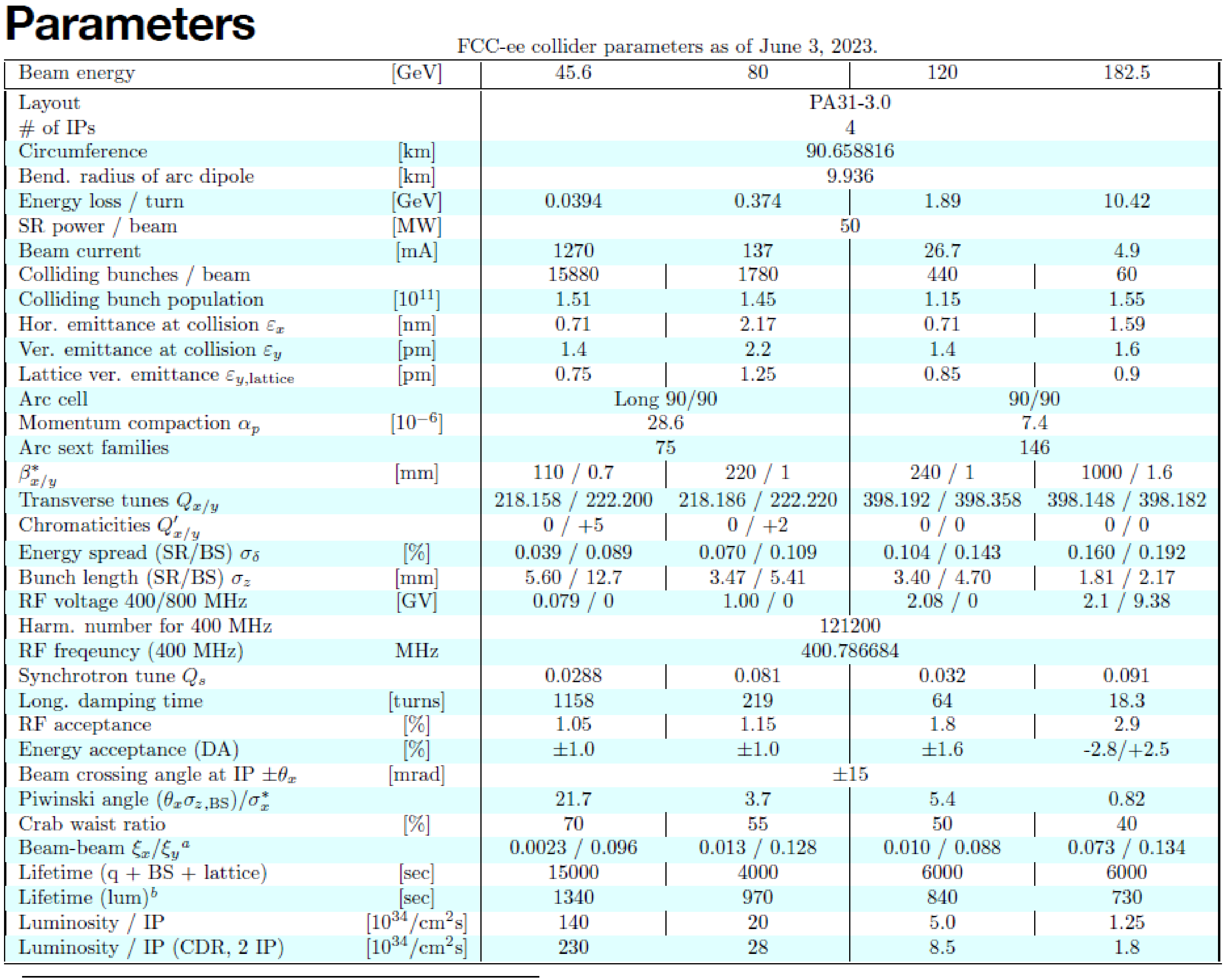
FCCIS: 'This project has received funding from the European Union's Horizon 2020 research and innovation programme under the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.'

Outline

- FCC-ee main parameters for Z-pole (mid-term review)
- Main impedance sources and their update: RW, collimators, bellows
- Wakefields and impedance model
- Collective effects and feedback system
- Conclusions

FCC-ee main parameters

We focus here on the Z machine since it is more challenging from the collective effects point of view: lowest beam energy, highest beam current, lowest emittances, and longest damping times with respect to the other machine configurations



Parameters

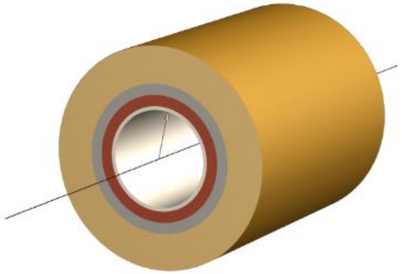
FCC-ee collider parameters as of June 3, 2023.

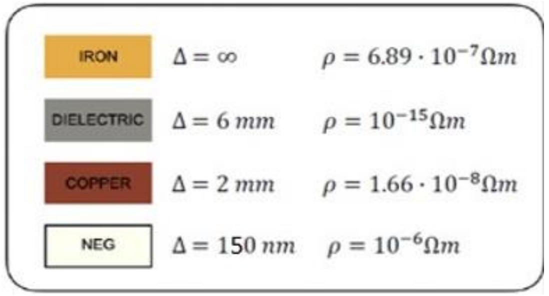
Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma_x^*$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam $\xi_x/\xi_y{}^a$		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum)^b	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

Main impedance sources

Resistive wall

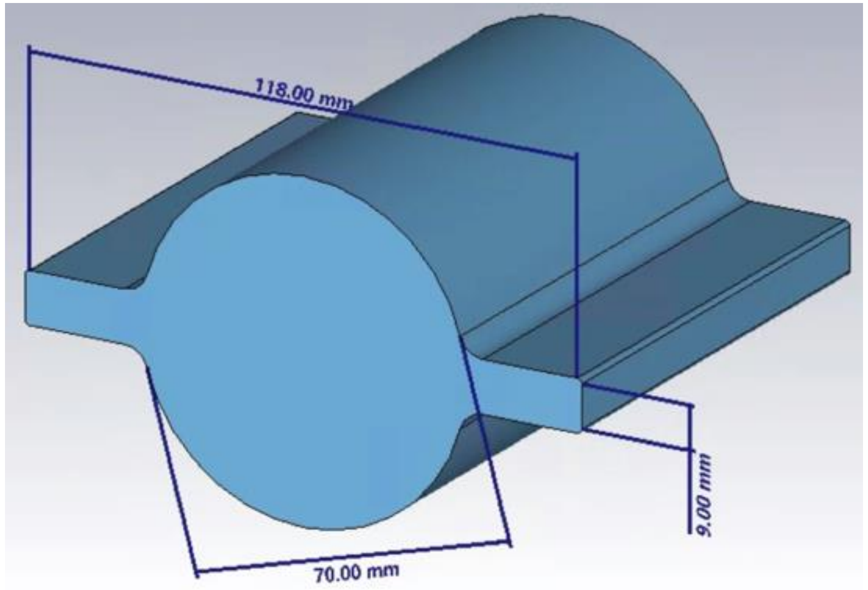
It is the largest impedance source for FCC-ee evaluated so far. NEG coating is needed to mitigate the electron cloud build-up in the positron machine and for pumping reasons in both rings.





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)

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

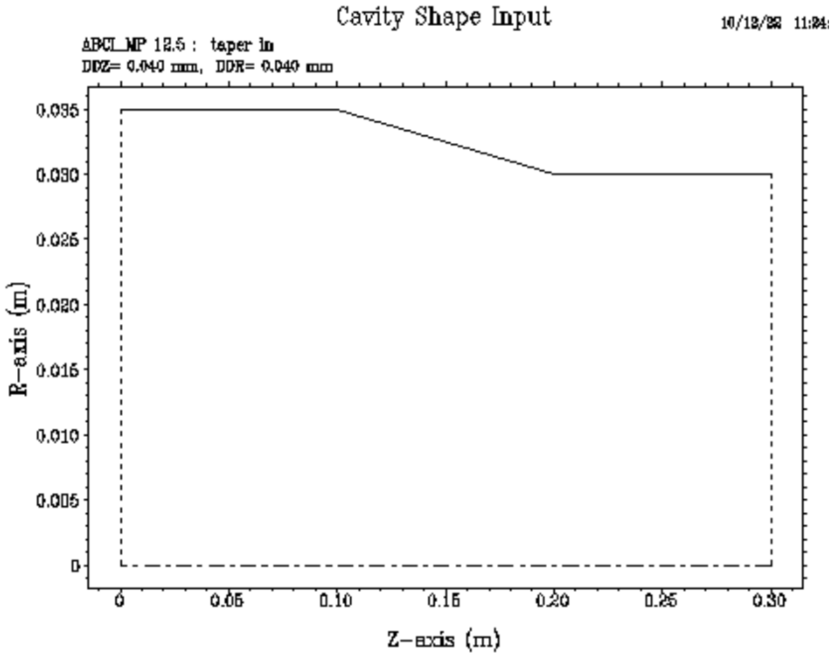
$$Z_{\perp}(\omega) = C\,\frac{Z_0}{2\pi b^3}\left\{[sgn(\omega) - i]\delta_2 - 2i\Delta\left(1 - \frac{\sigma_1}{\sigma_2}\right)\right\}$$

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 $\frac{35^3}{30^3} = 1.6 \rightarrow 60\%$

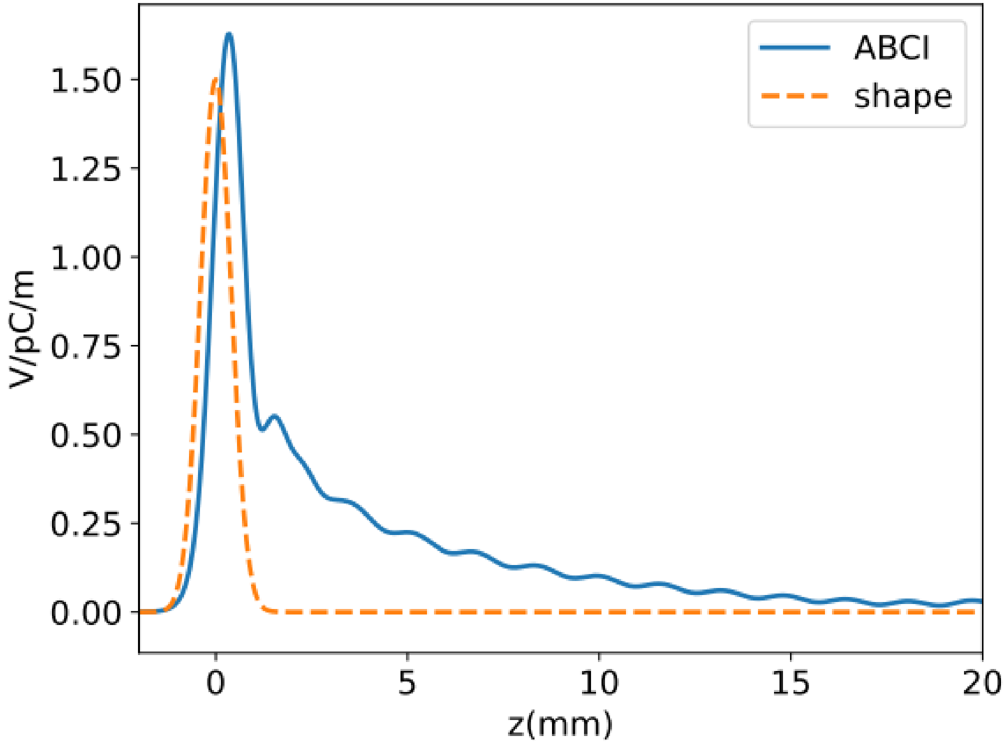
Reduction of beam pipe radius only in short straight sections (quads and sexts): 10 km of pipe with 30 mm of radius:

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

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

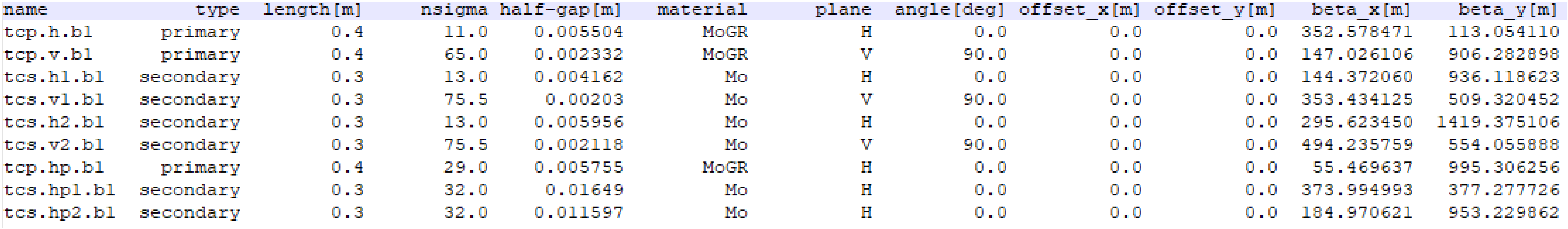


If we multiply this by 2 (double taper) and by 1500 (number of sections), we have a peak at about 5000 V/pC/m.

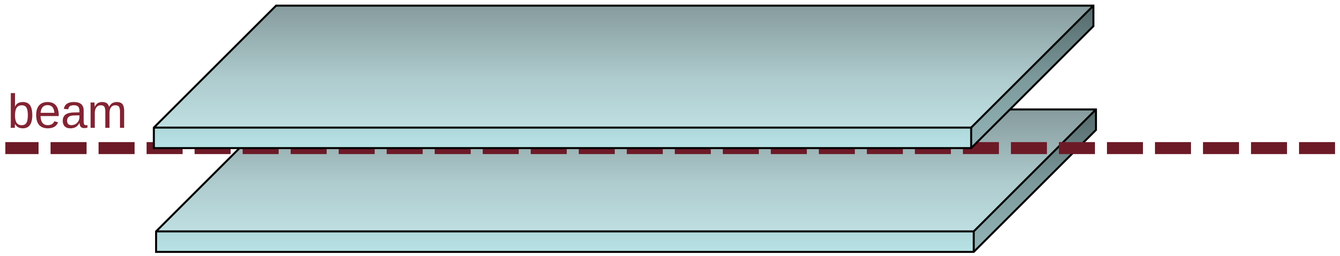
This is about 12.5% of the total transverse dipolar wake that we have evaluated so far. By increasing the taper's length it is possible to reduce this contribution.

Collimation system

Table of the beam halo collimators for the Z machine and for the 4 IPs layout.
The synchrotron collimators and masks upstream of 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



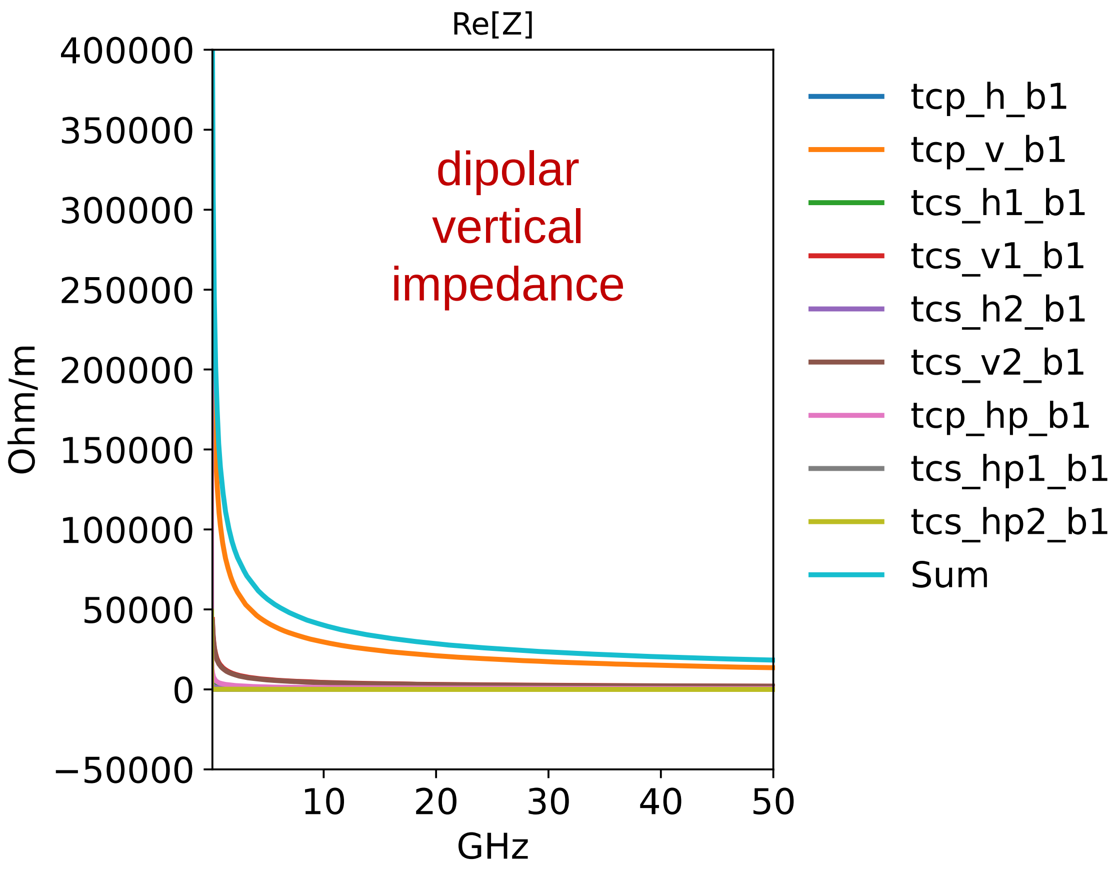
For the resistive wall contribution, we suppose parallel plates with infinite thickness and use IW2D for the impedance and wakefield evaluation.

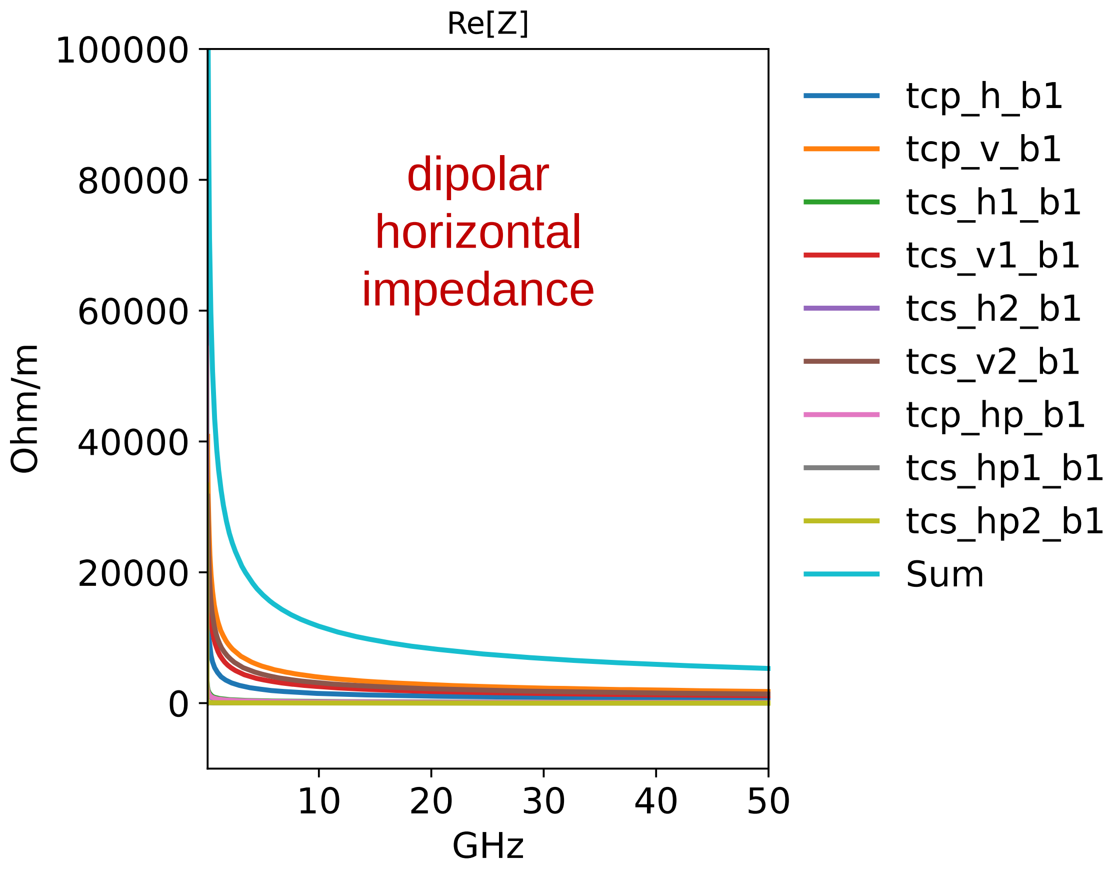
$\sigma_{MoGR} = 10^6\ S/m \qquad \sigma_{Mo} = 18.7 \times 10^6\ S/m$

Collimation system

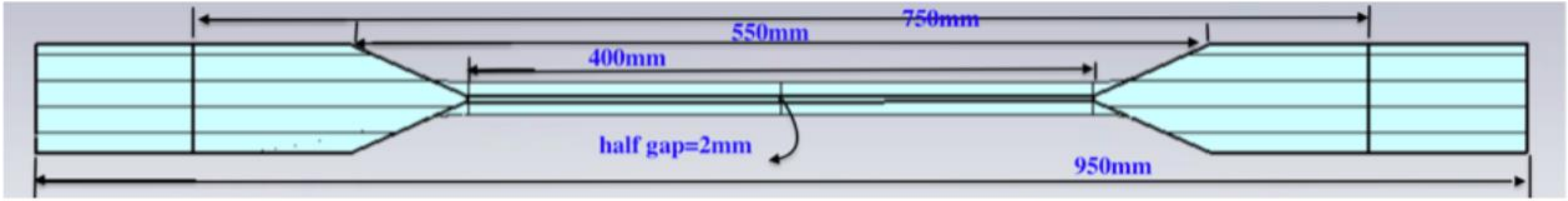
$$Z(\omega)\frac{\beta_{x,y}}{<\beta_{x,y}>} \qquad <\beta_{x,y}>=\frac{1}{C}\oint \beta_{x,y}ds$$

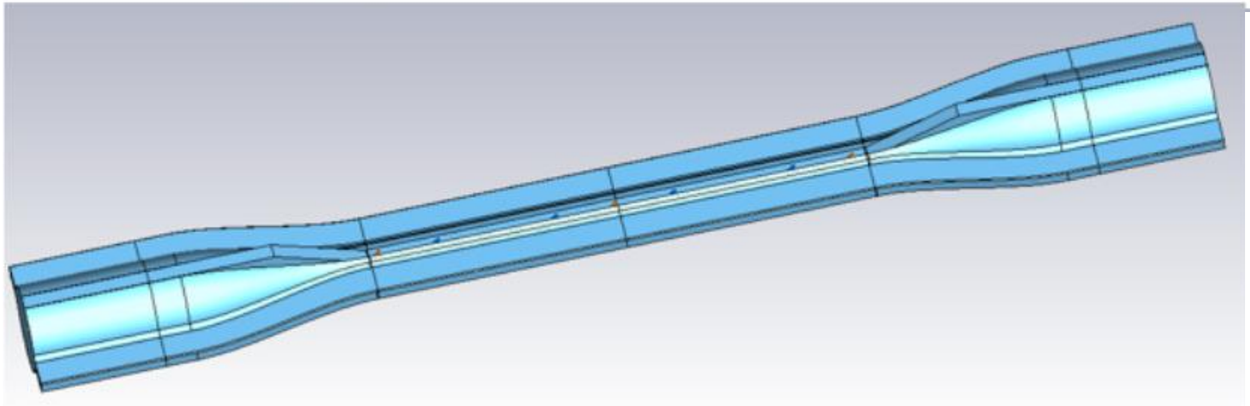
NB: the impedance of the collimators must be changed because of the new optics. We do not have the updated table yet

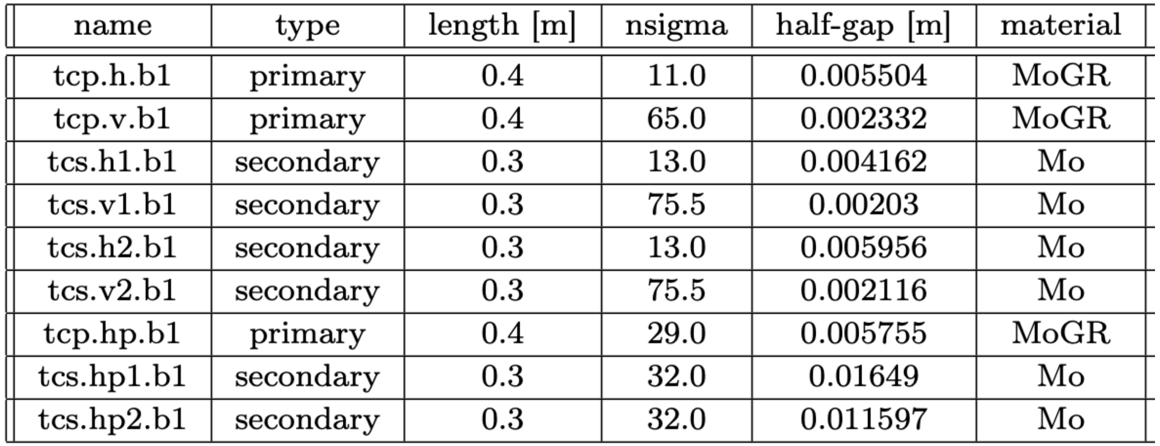




Work in progress: geometrical wakefield due to collimators

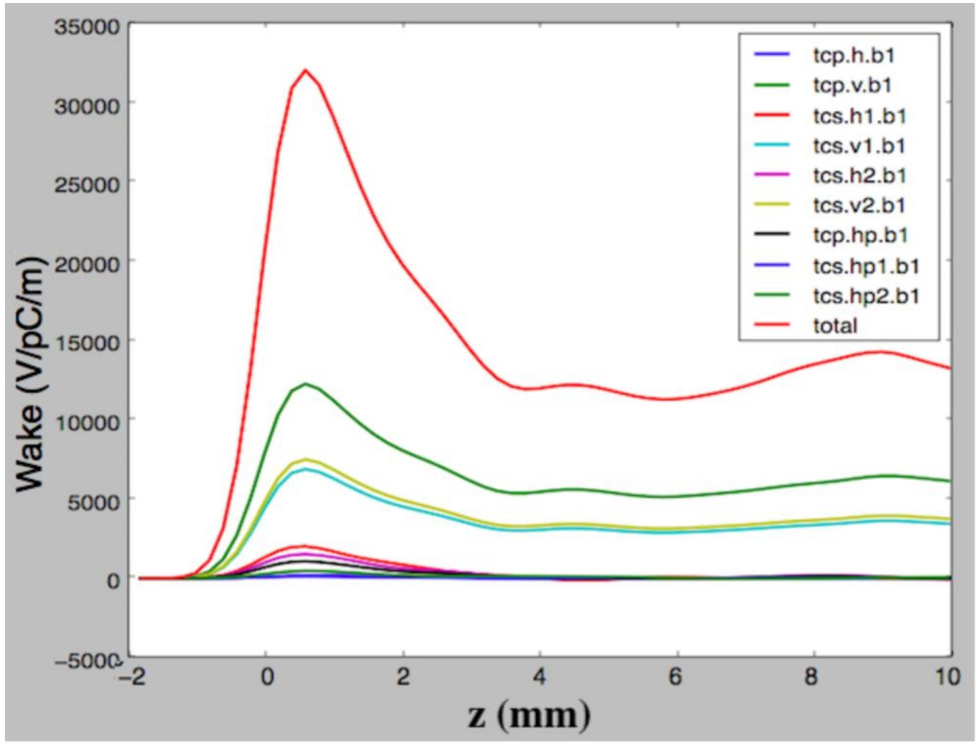


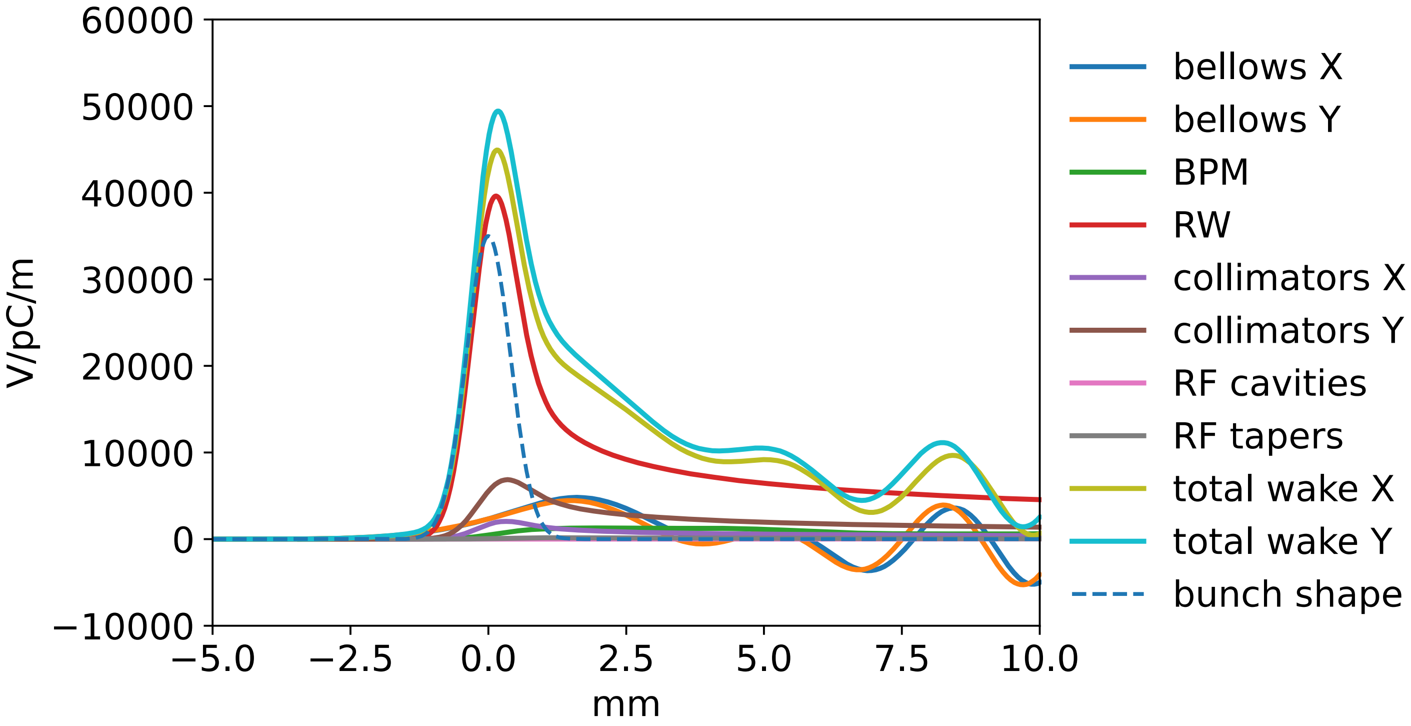




name	type	length [m]	nsigma	half-gap [m]	material
tcp.h.b1	primary	0.4	11.0	0.005504	MoGR
tcp.v.b1	primary	0.4	65.0	0.002332	MoGR
tcs.h1.b1	secondary	0.3	13.0	0.004162	Mo
tcs.v1.b1	secondary	0.3	75.5	0.00203	Mo
tcs.h2.b1	secondary	0.3	13.0	0.005956	Mo
tcs.v2.b1	secondary	0.3	75.5	0.002116	Mo
tcp.hp.b1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

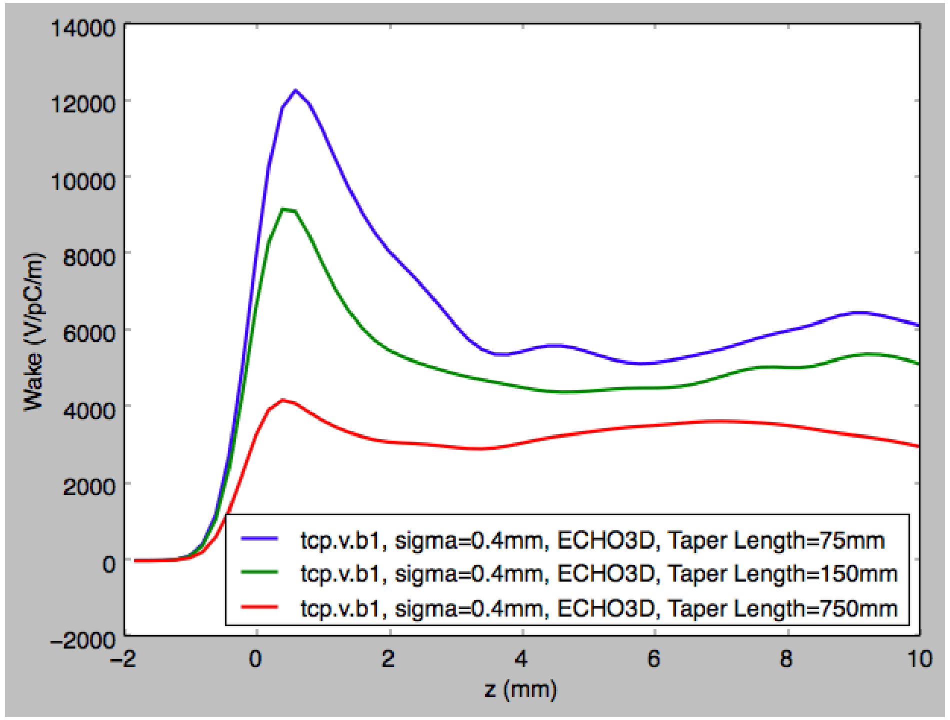




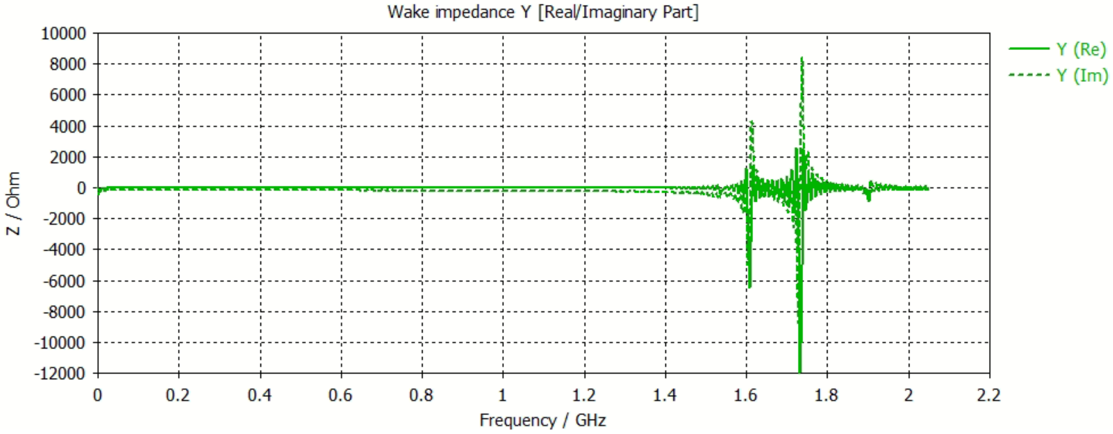
Work in progress: geometrical wakefield due to collimators

How to mitigate this geometrical contribution?

We do not have a solution yet: we tried to increase the taper length, but the results were not as satisfactory as expected.



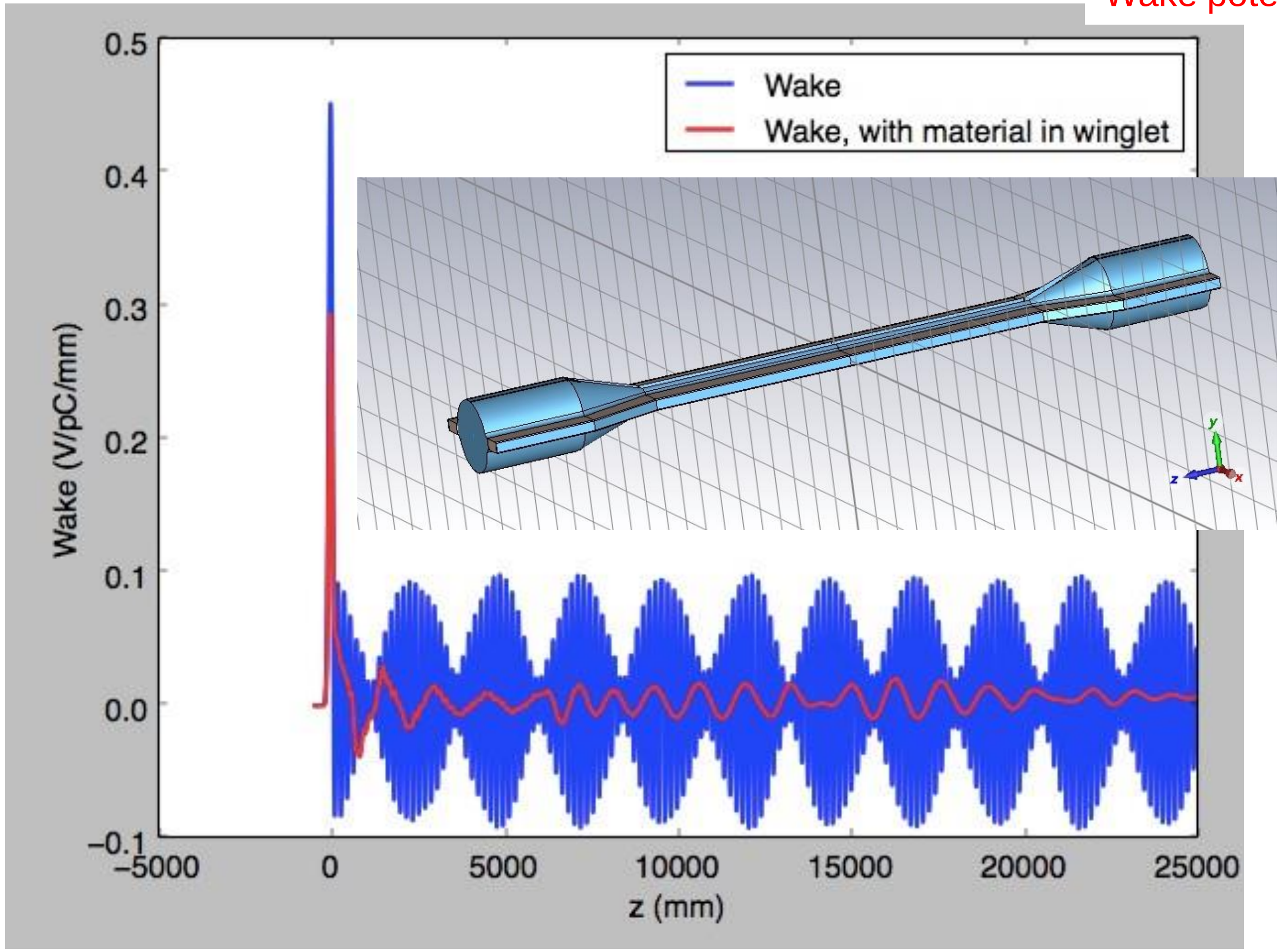
We also observed important trapped HOMs

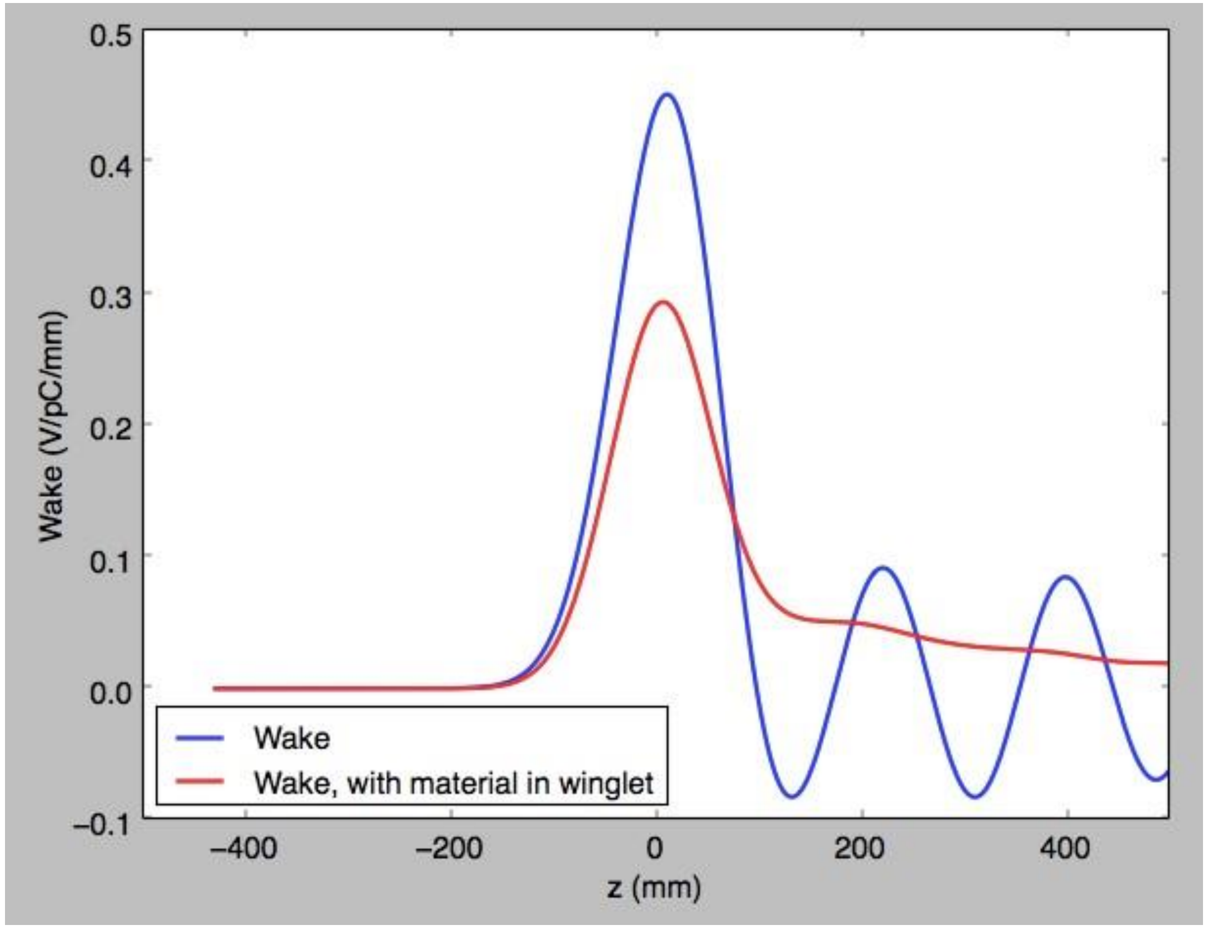


Work in progress: geometrical wakefield due to collimators

HOMs could be damped with ferrites. We tried the TT2-111R ferrite. This solution seems to reduce also the transverse broadband impedance

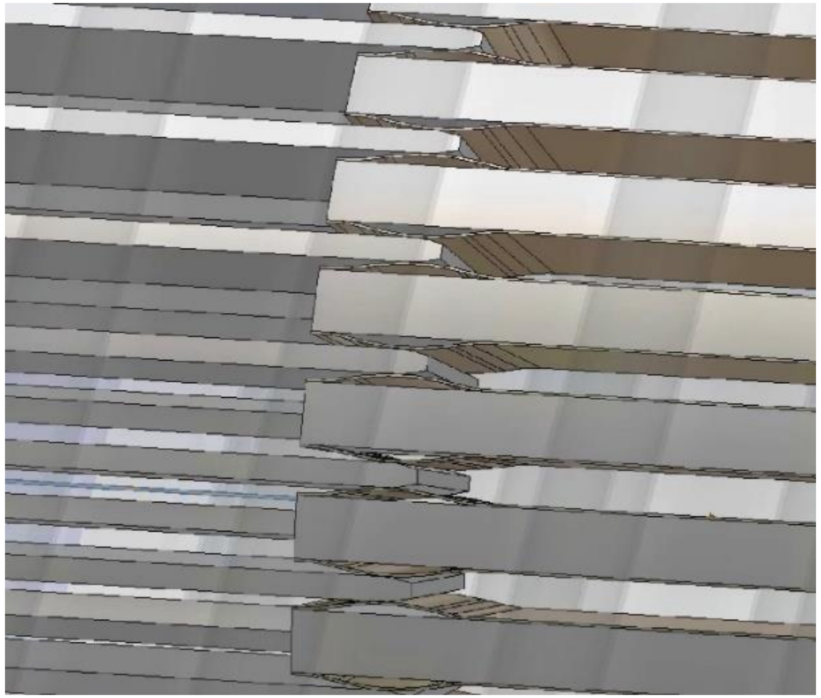
Wake potential of 50 mm Gaussian bunch

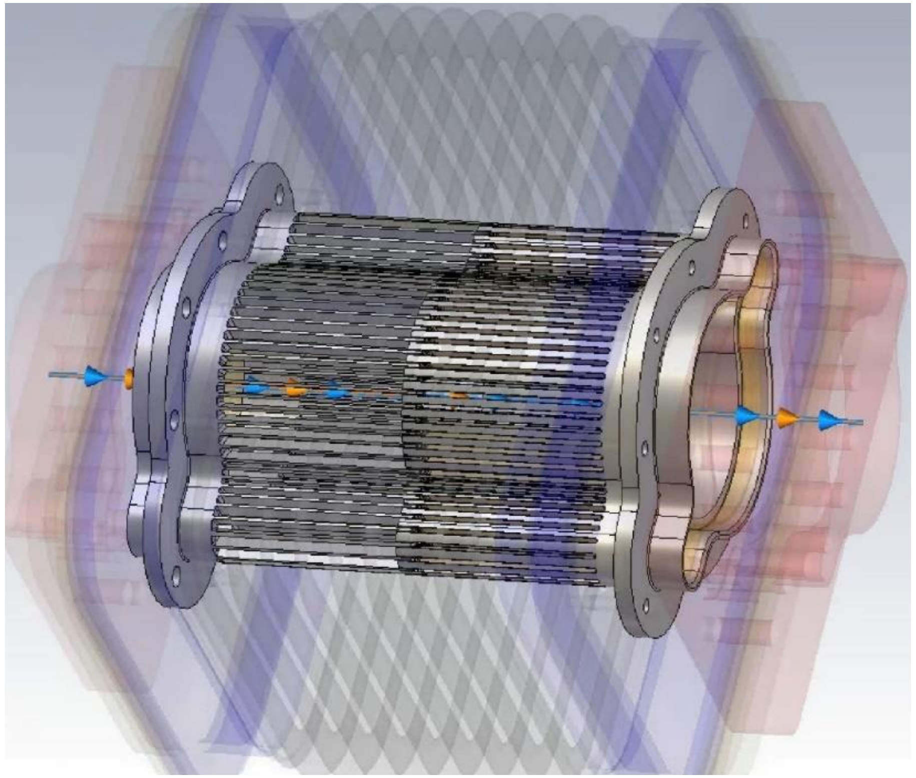




Main impedance sources

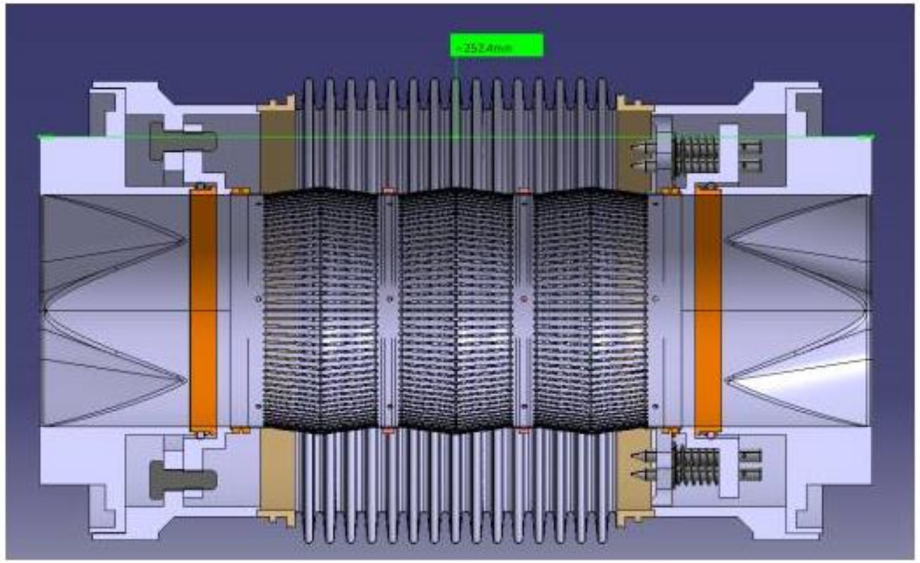
Bellows So far we used the SuperKEKB model with RF fingers with a total of 10000 bellows: 2900 dipole arcs 24 m long with bellows every 12 m plus 2900 quads/sexts sections and an additional 1000 bellows for the straight sessions.

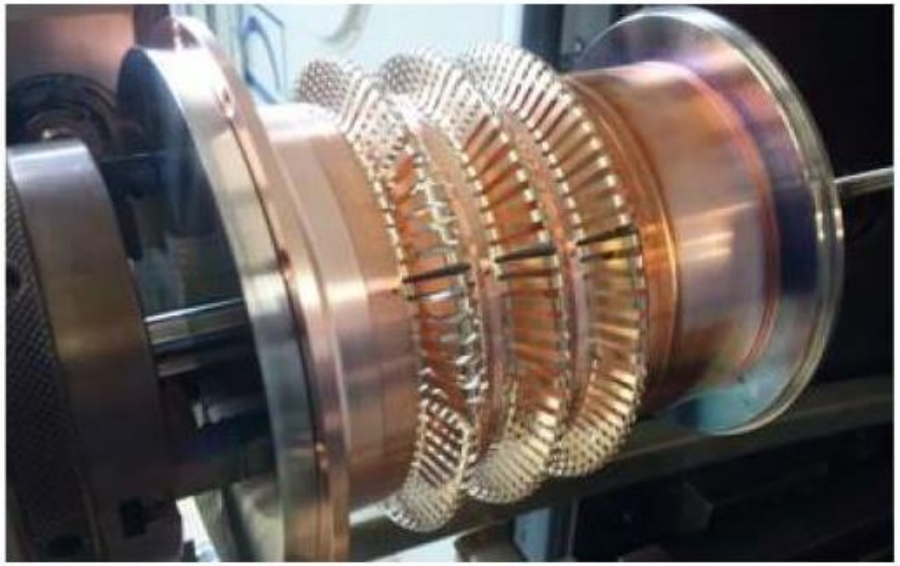


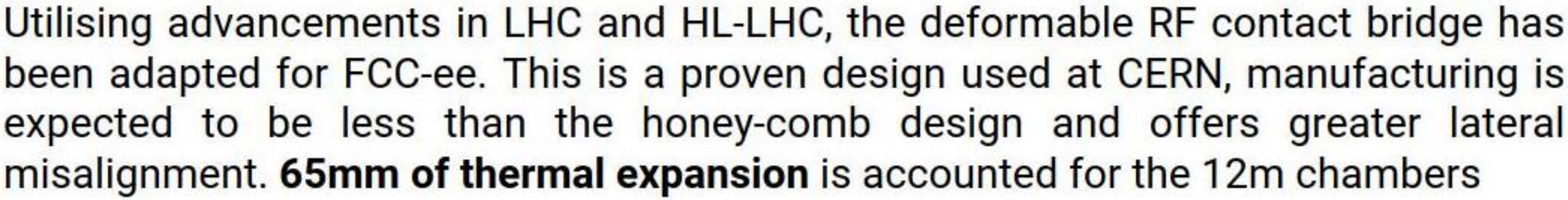


Main impedance sources

Bellows Other geometries are under investigation in the vacuum group.



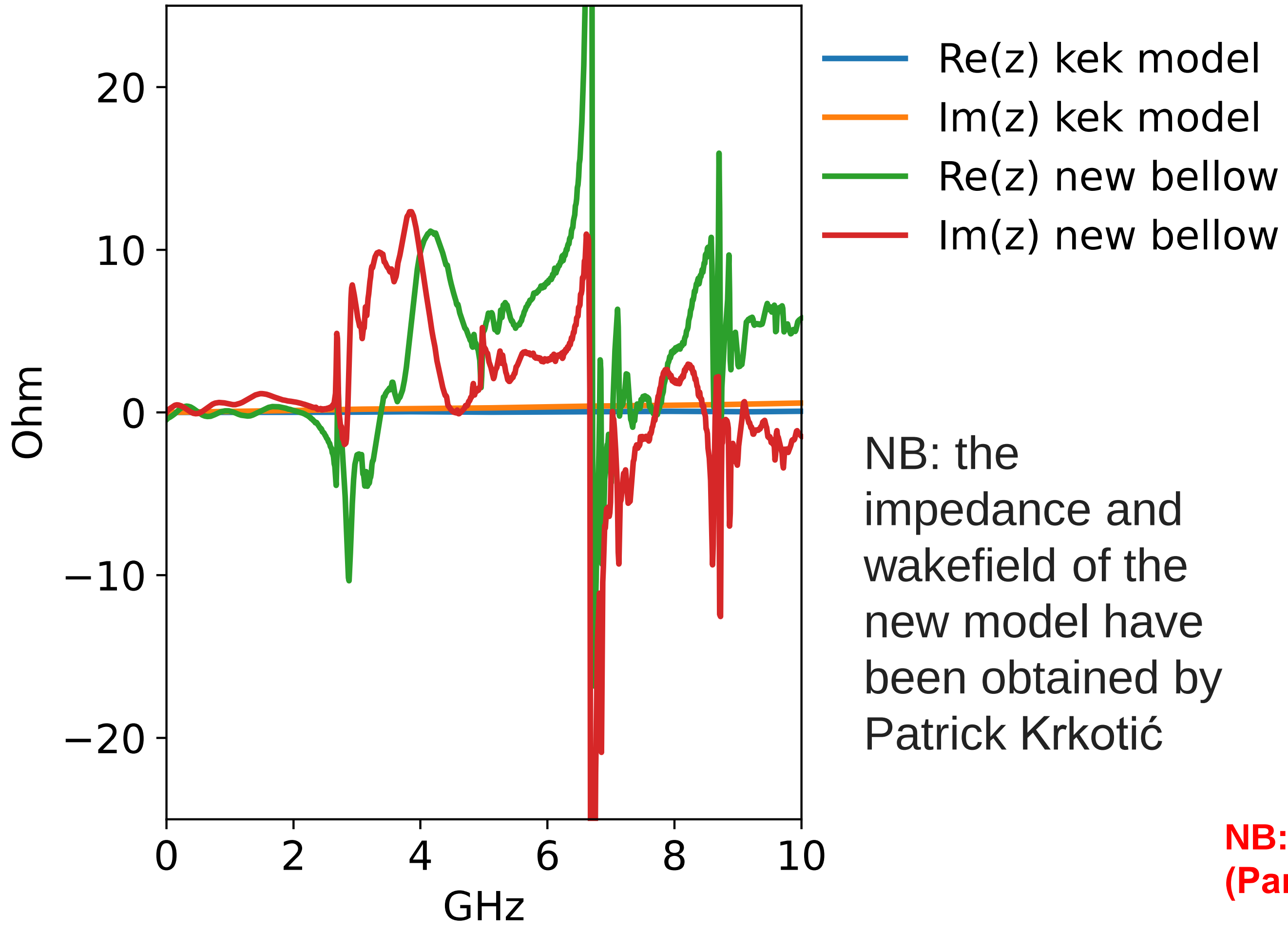



Utilising advancements in LHC and HL-LHC, the deformable RF contact bridge has been adapted for FCC-ee. This is a proven design used at CERN, manufacturing is expected to be less than the honey-comb design and offers greater lateral misalignment. **65mm of thermal expansion** is accounted for the 12m chambers

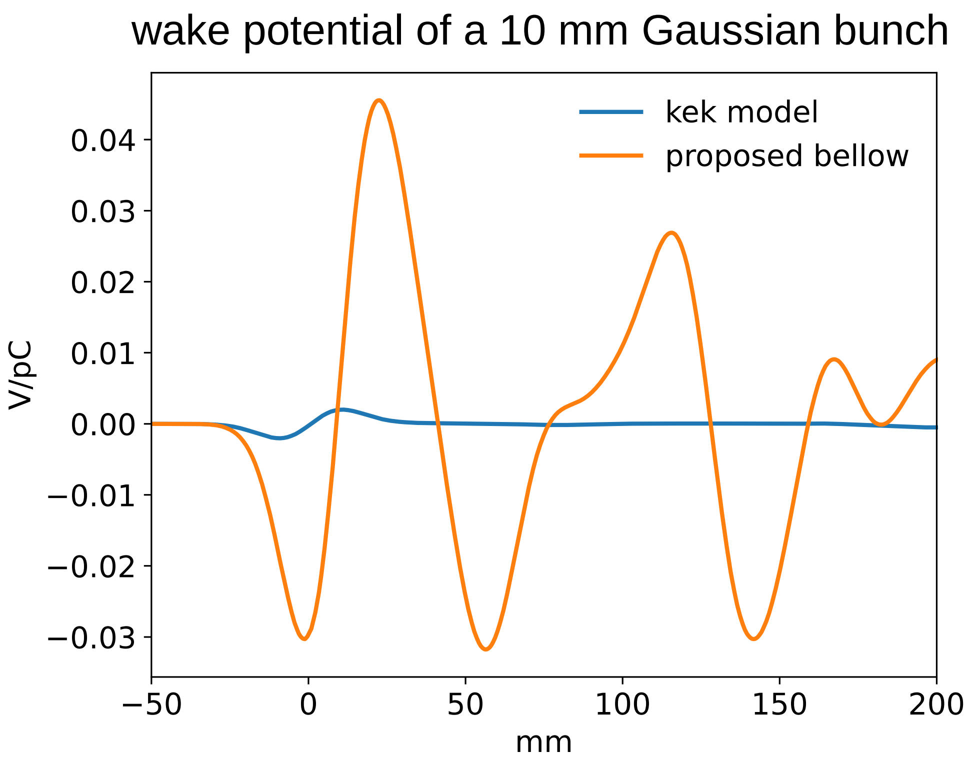
Courtesy of: S. Rorison (CERN), FCC-ee: Vacuum System Technologies R&D, poster presented at the FCC week 2023

Main impedance sources

Bellows Comparison between the SuperKEKB and the new geometry in the longitudinal plane

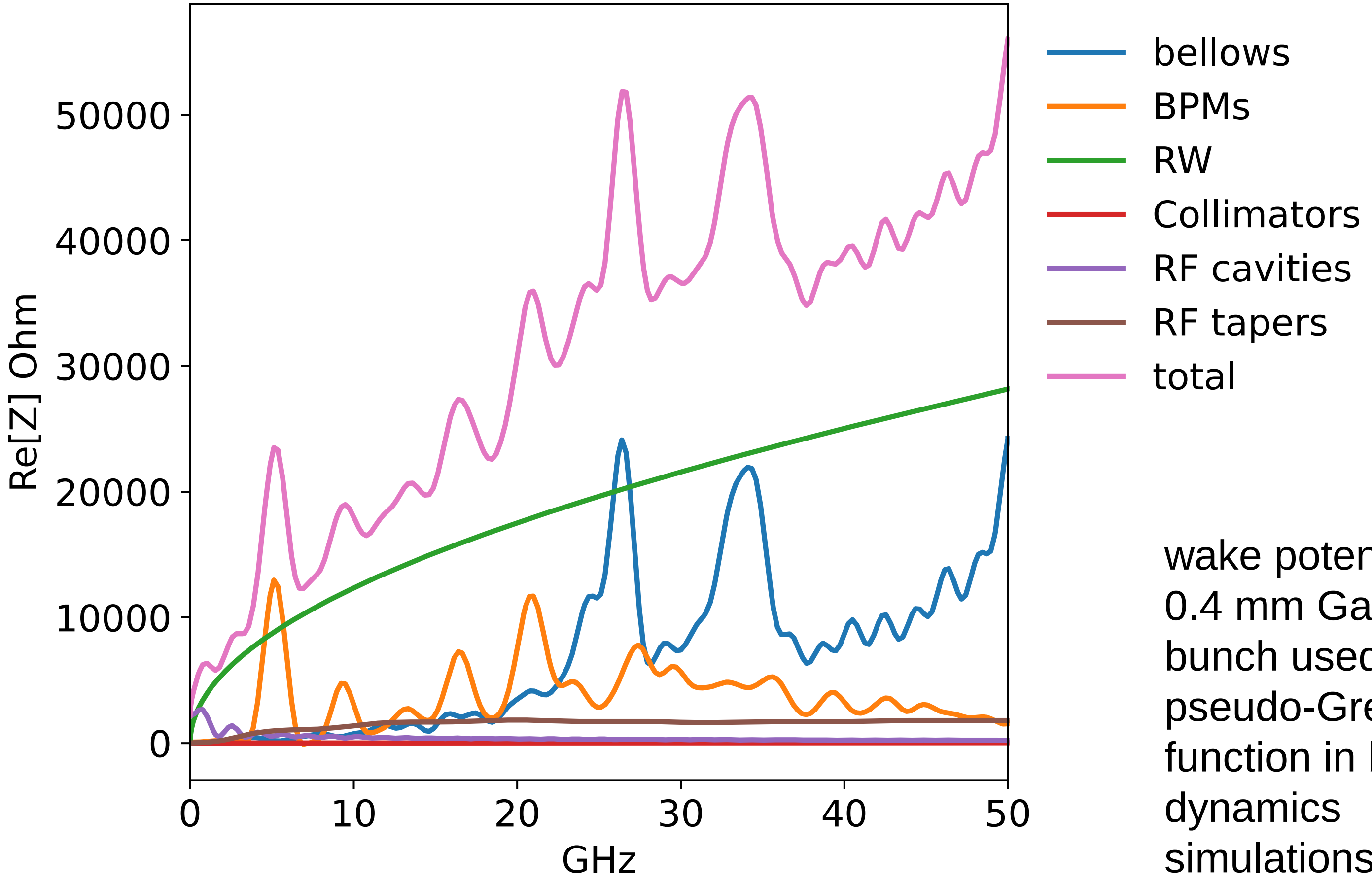


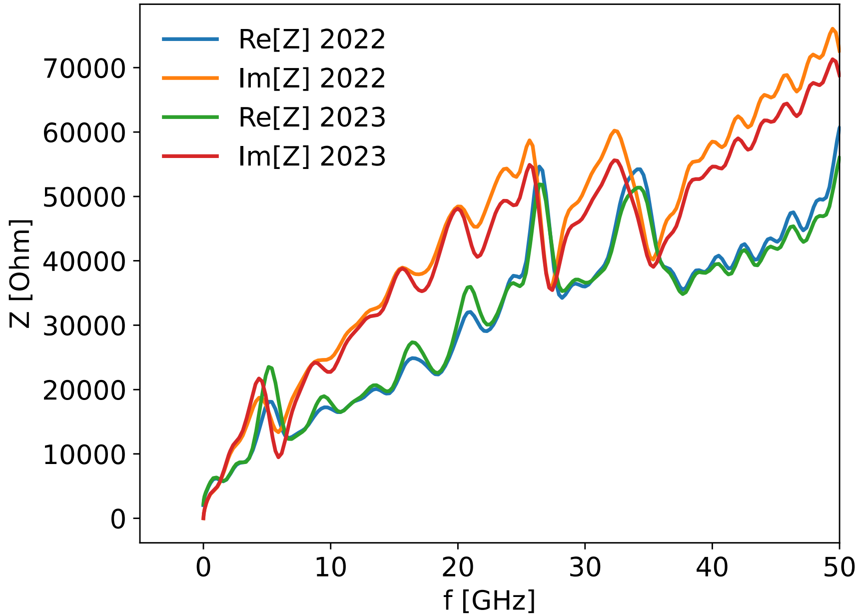
NB: the impedance and wakefield of the new model have been obtained by Patrick Krkotić



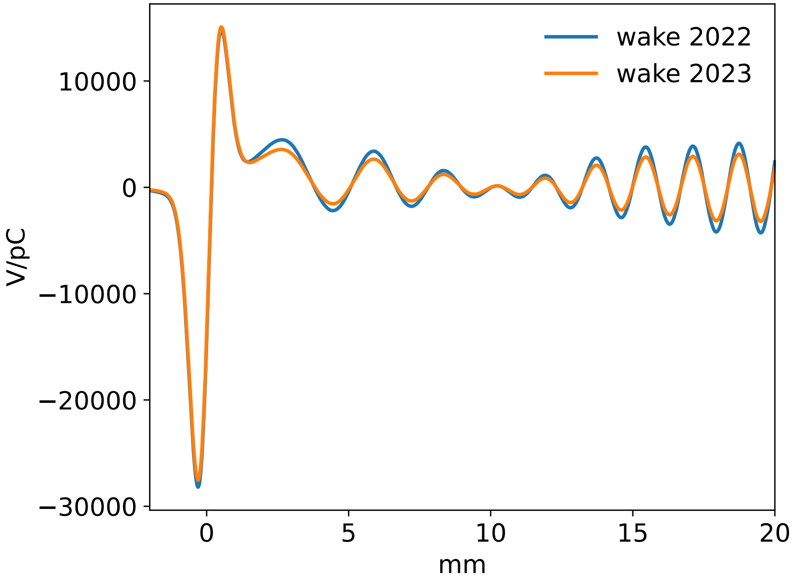
NB: Other models, such as the ESRF bellows (Pantaleo's suggestion), need to be investigated

Longitudinal impedance and wake

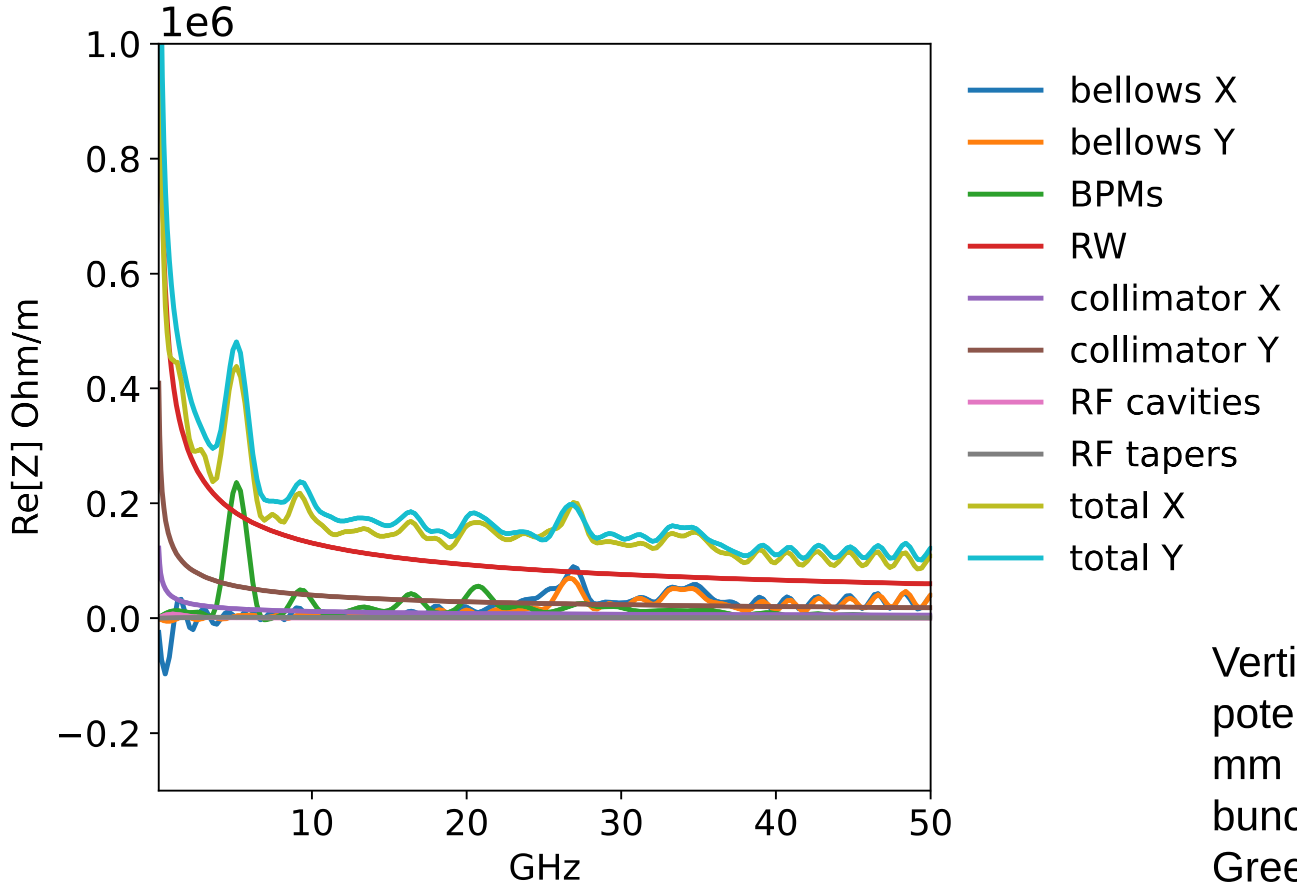


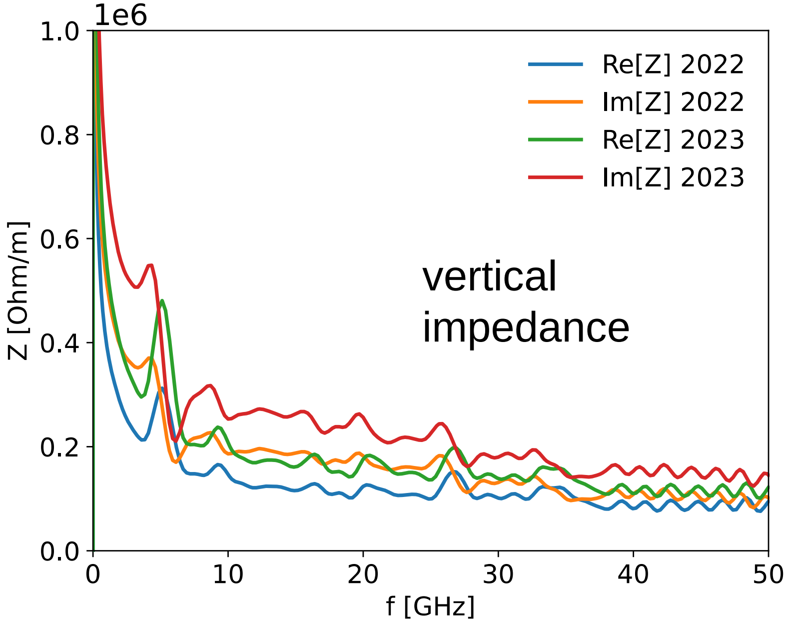


wake potential of a 0.4 mm Gaussian bunch used as a pseudo-Green function in beam dynamics simulations

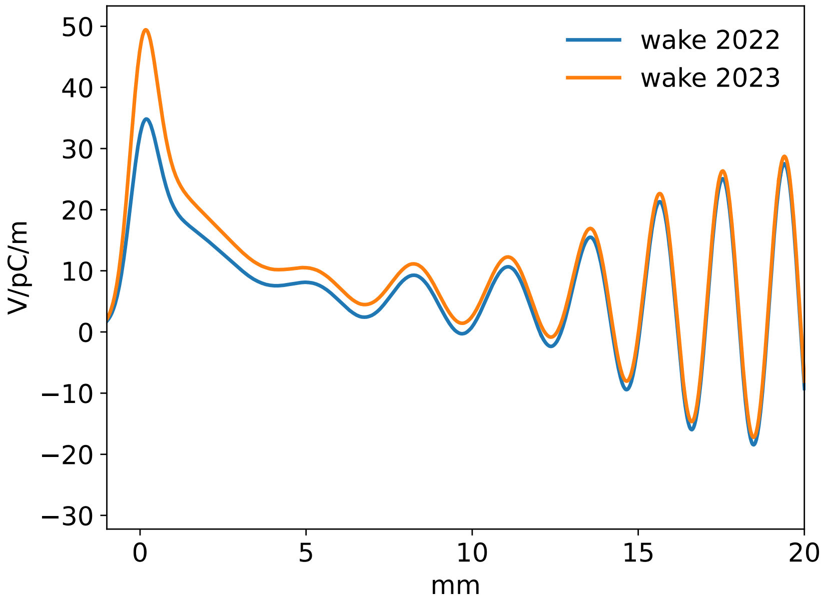


Transverse dipolar impedance and wake

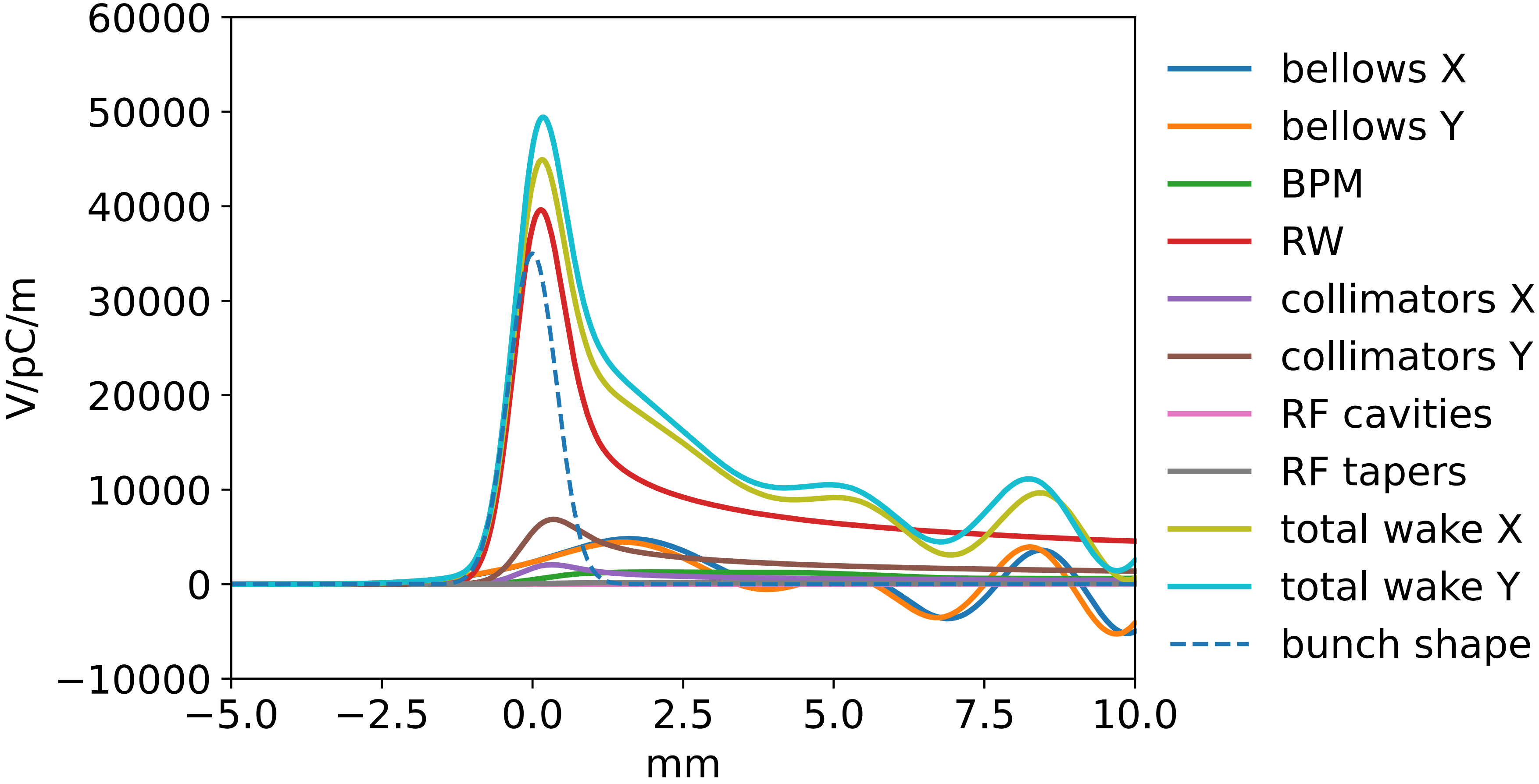




Vertical wake potential of a 0.4 mm Gaussian bunch used as a Green function in beam dynamics simulations

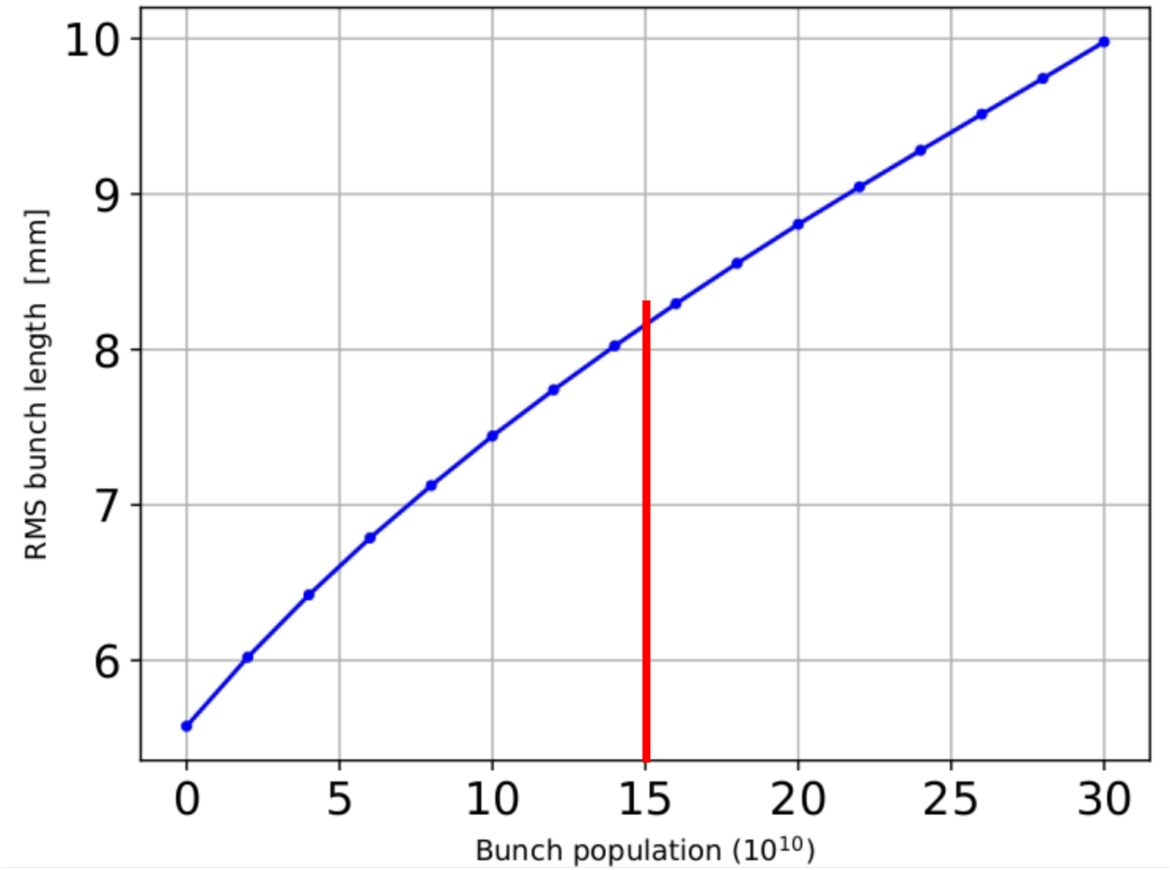


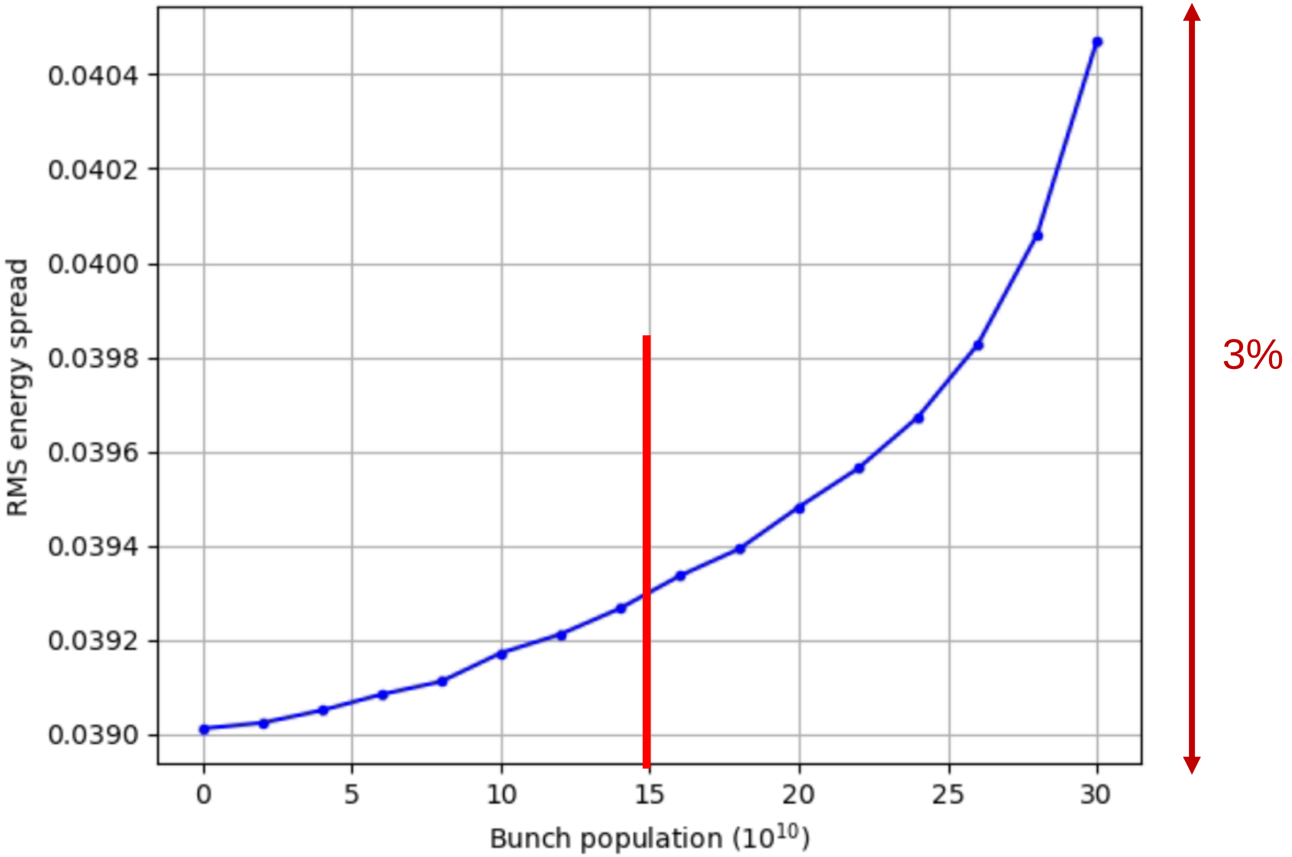
Transverse dipolar wake potential of a 0.4 mm Gaussian bunch used as Green function in beam dynamics simulations



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

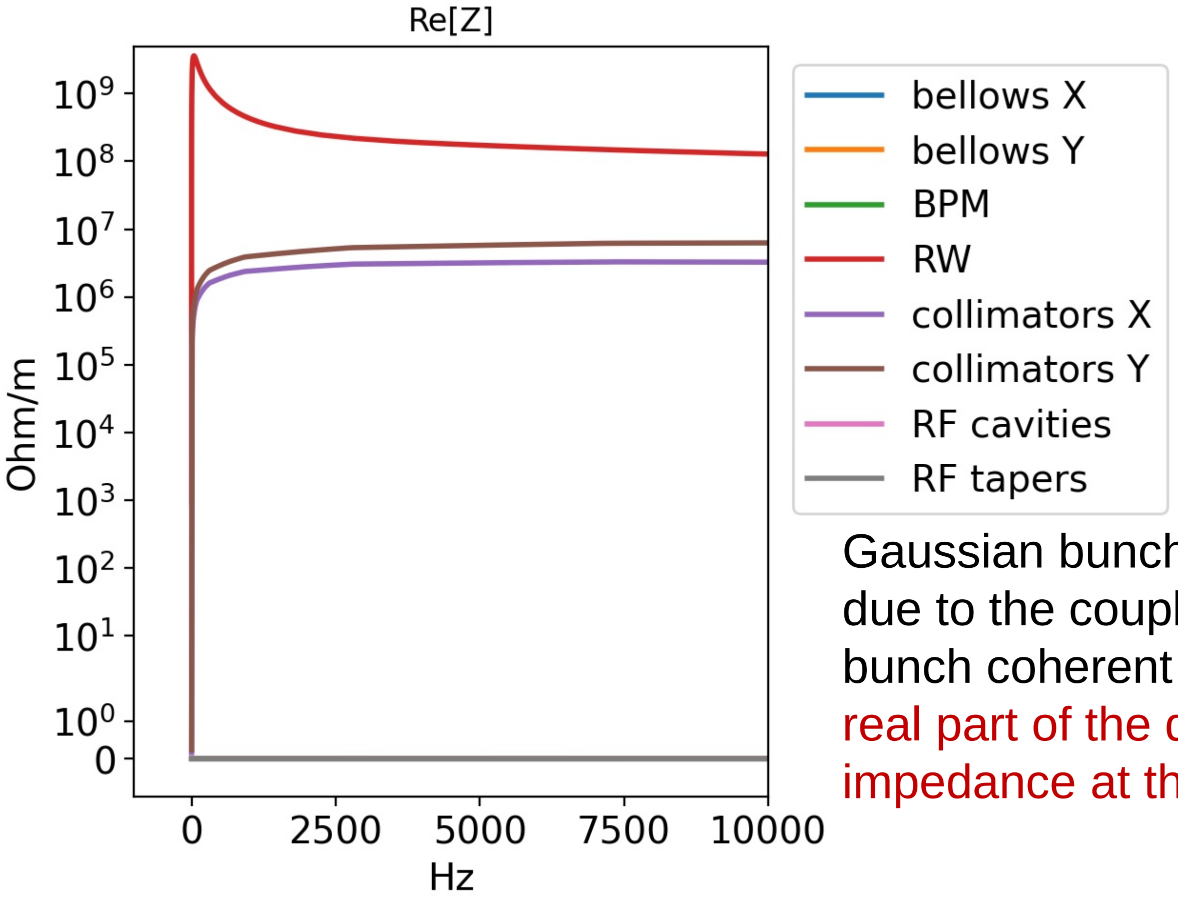
Single bunch collective effects in the longitudinal plane



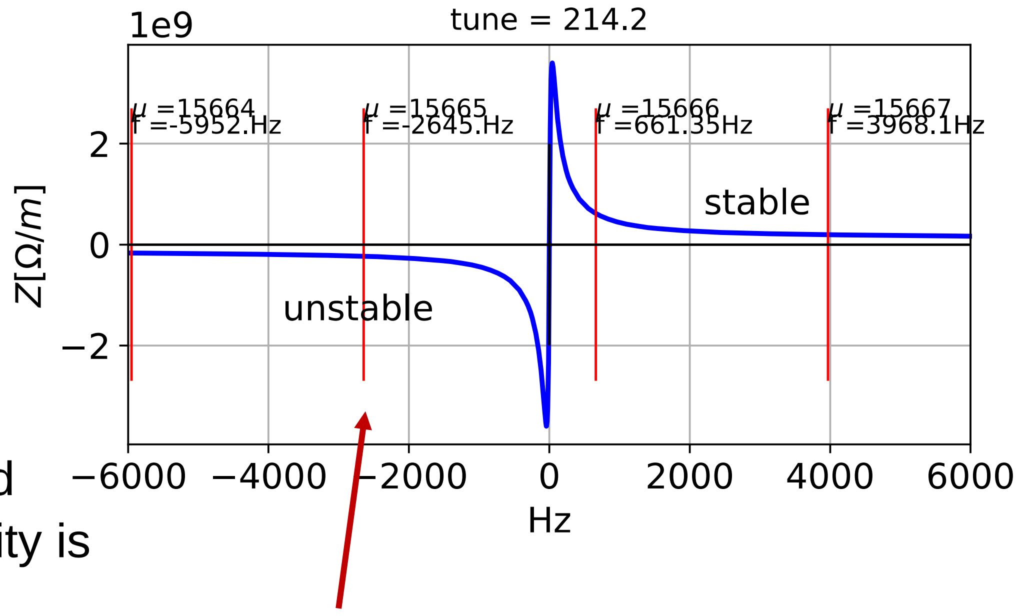


With beamstrahlung we have found that at 1.5e11 ppb: $\sigma_z = 14.0$ mm, $\sigma_p = 9\text{x}10^{-4}$ (w/ ZL)

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.

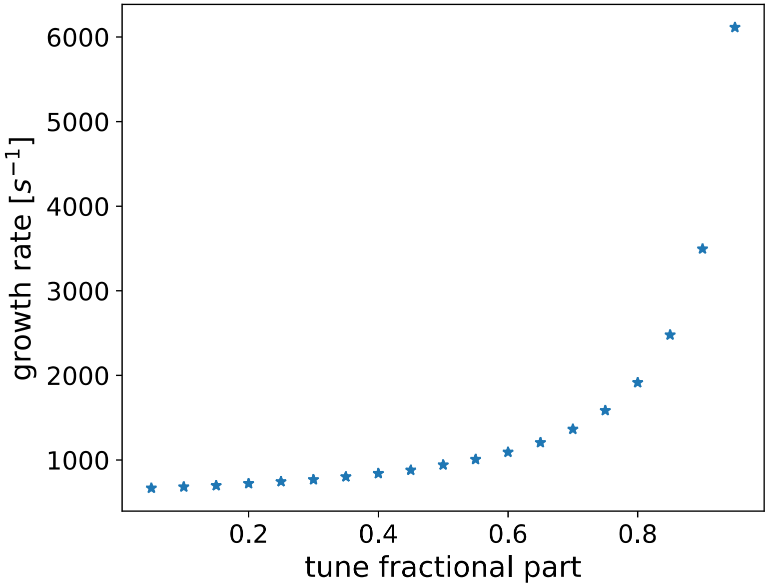


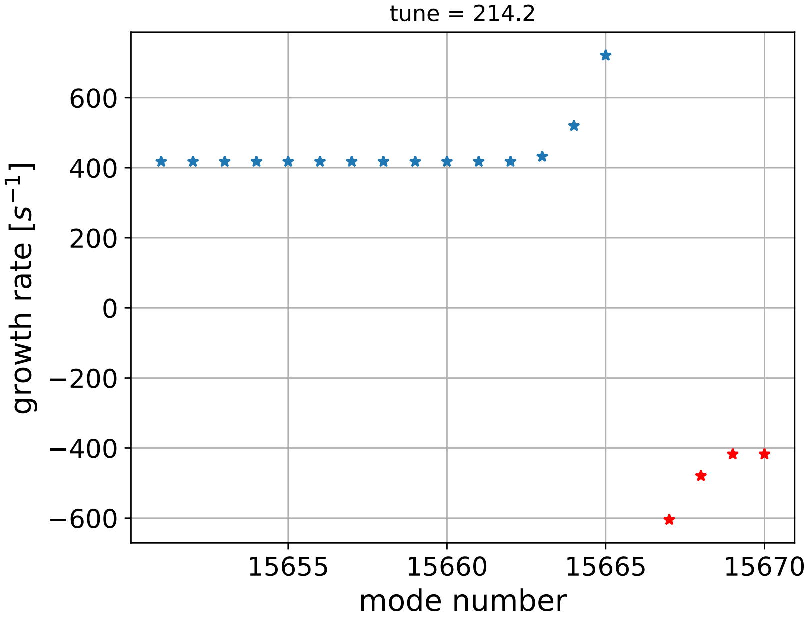
The most dangerous mode is that closest to the origin (with negative frequency)

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

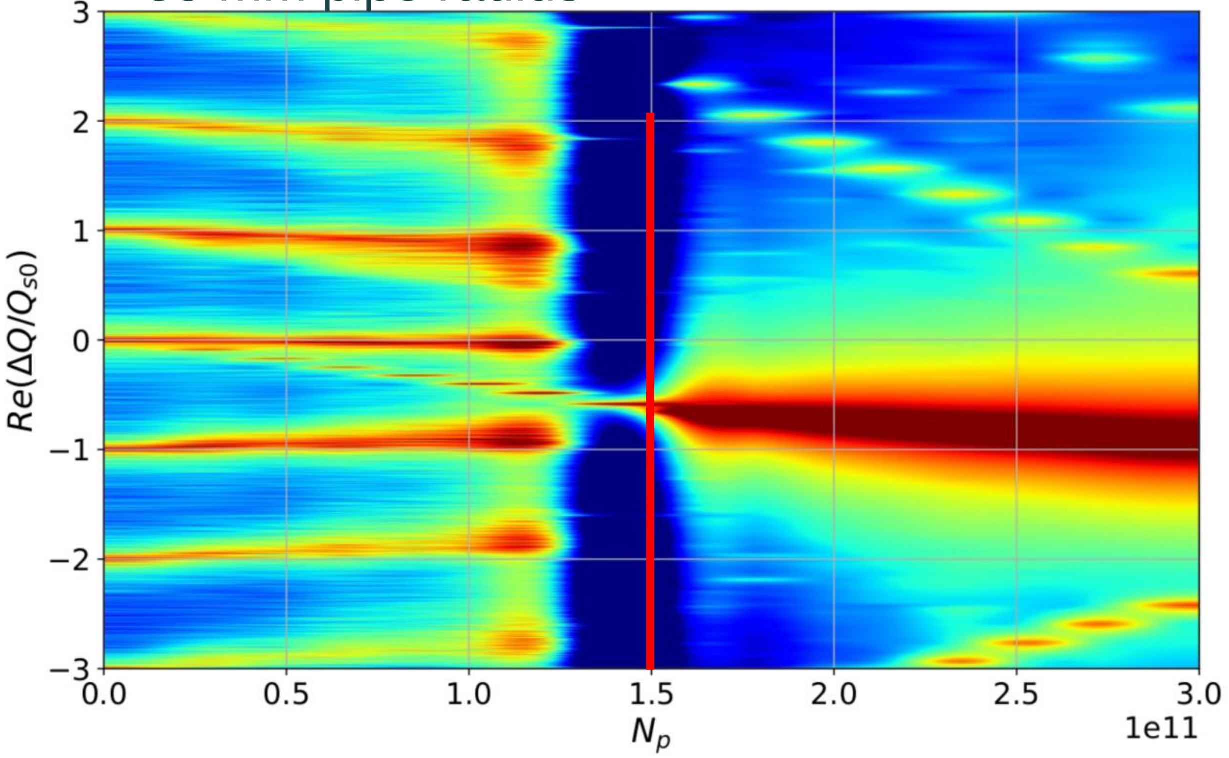
- Rise time of the most dangerous mode is about 1.4 ms (growth rate of about 700 s^{-1}).
- To suppress the TCBI, a bunch-by-bunch feedback system can be used.
- The damping time in the transverse plane should be of the order of 1 ms, similar to the damping time of the SuperKEKB feedback.
- However, 1 ms in FCC-ee corresponds to about 3 turns. We must pay attention to the design of such a feedback system.
- Additionally, there are many coupled bunch modes with a growth rate of ~ 400 s^{-1}, that is 2.5 ms.



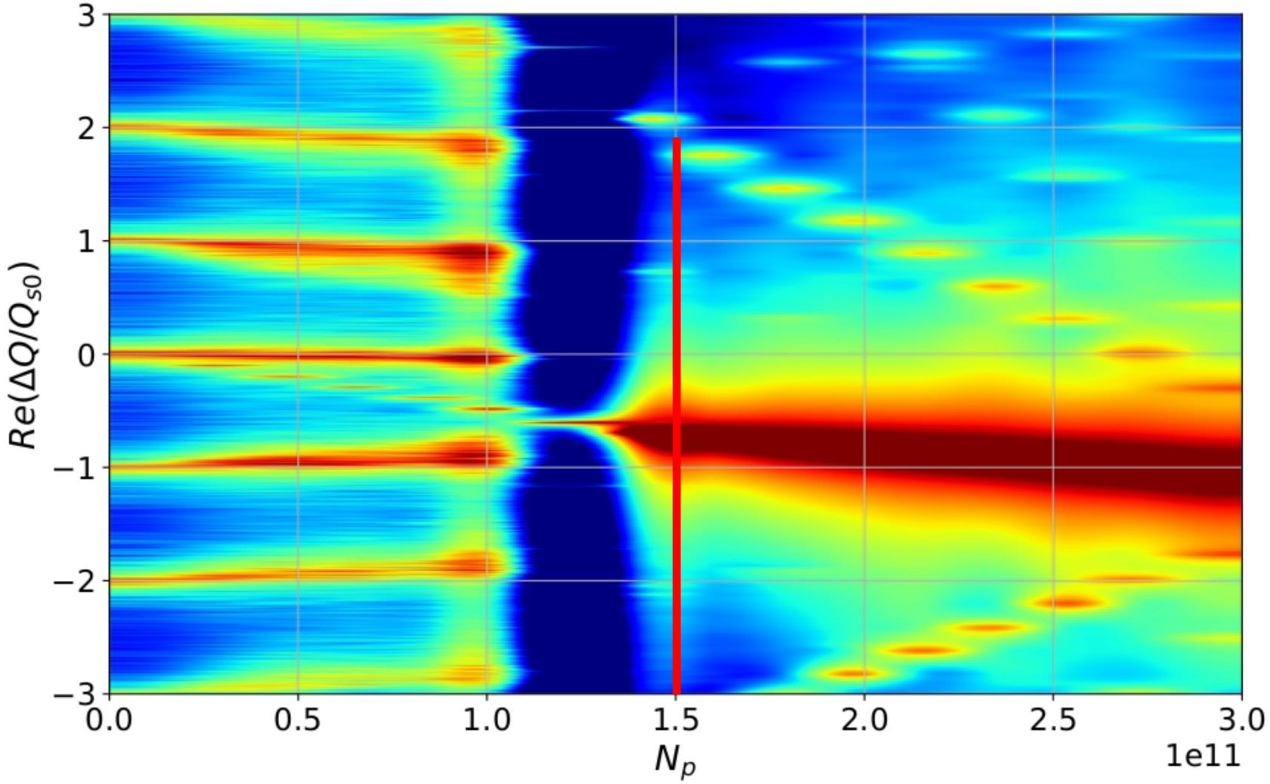


Transverse mode coupling instability

35 mm pipe radius



30 mm pipe radius

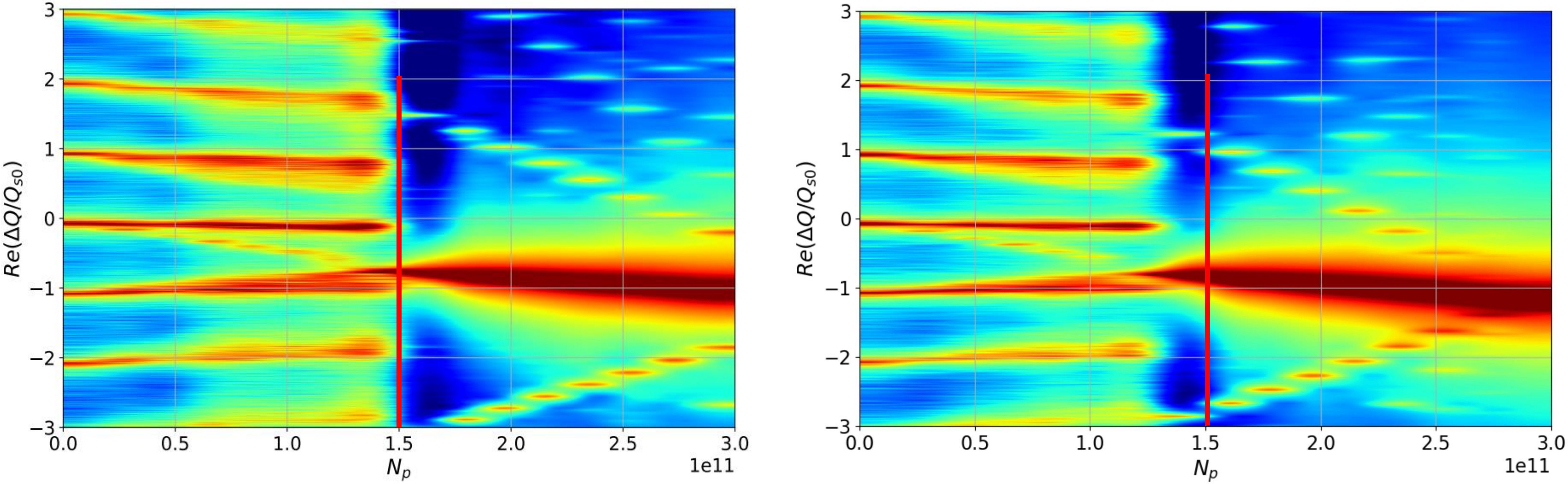


Even if the thresholds are similar, with the 30 mm radius the instability is stronger.

Single bunch collective effects in the transverse plane

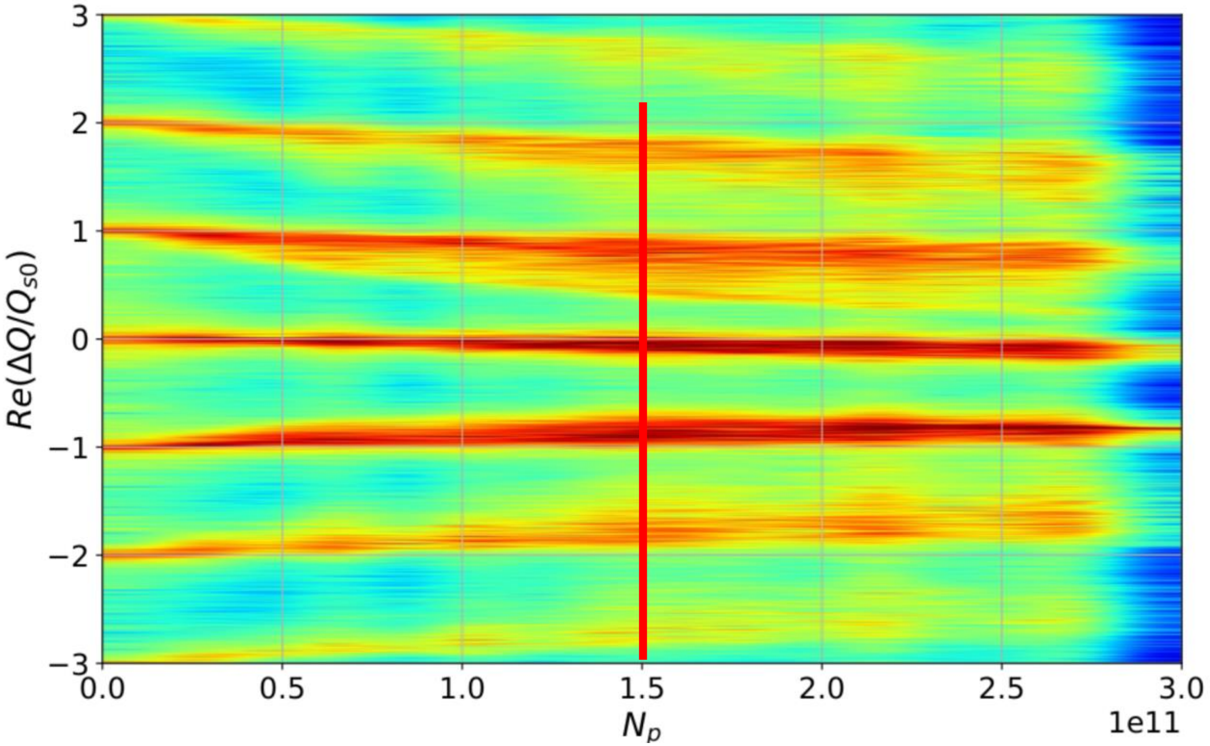
35 mm pipe radius + chroma = 5

30 mm pipe radius + chroma = 5

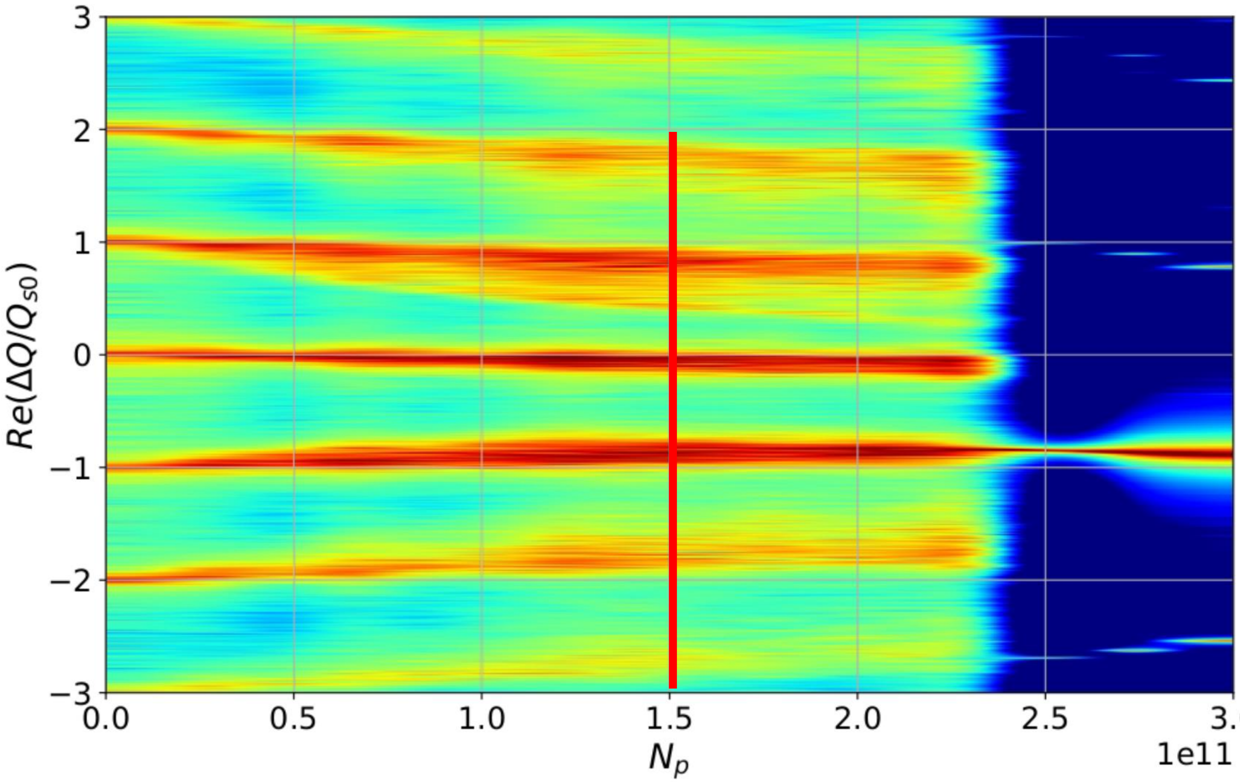


Single bunch collective effects in the transverse plane

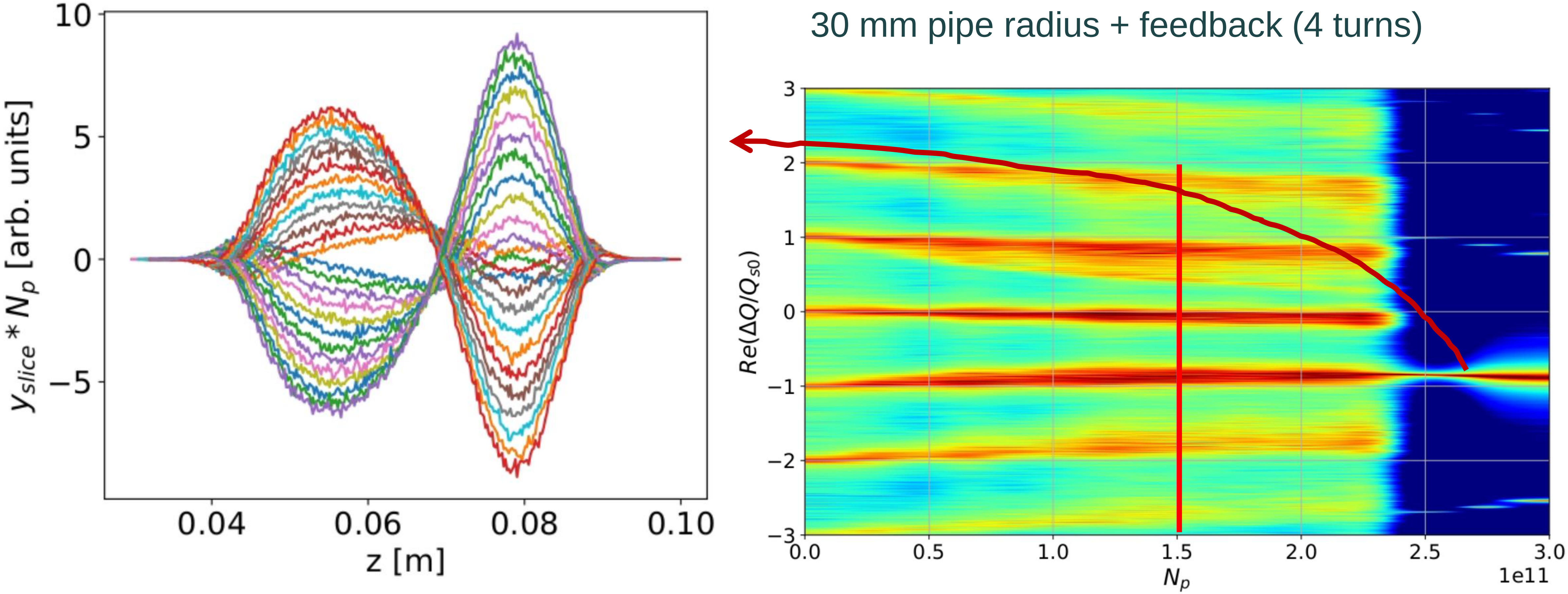
35 mm pipe radius + feedback (4 turns)



30 mm pipe radius + feedback (4 turns)

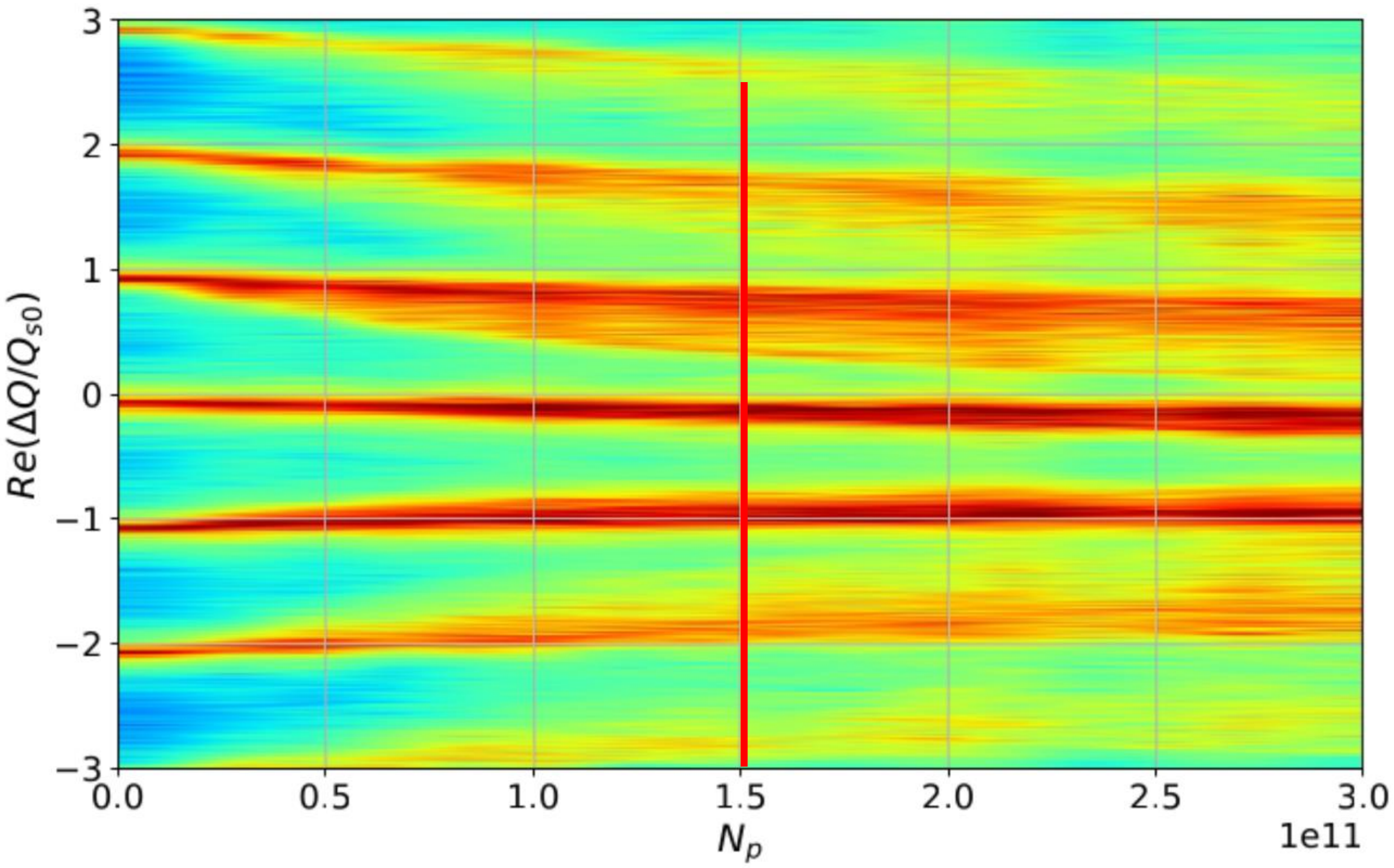


Single bunch collective effects in the transverse plane


30 mm pipe radius + feedback (4 turns)

The intra-bunch motion at 2.6×10^{11} seems to show a ‘-1 mode’ instability. At SuperKEKB the feedback induced this kind of instability, too. The problem was that simulations gave a higher instability threshold.

Single bunch collective effects in the transverse plane



30 mm pipe radius: the combination of feedback (4 turns) + chromaticity ($Q'_x = Q'_y = 5$) seems to mitigate the TMCI

Conclusions

- The design of different machine components is still in progress and the impedance model is constantly changing.
- Additionally, as we analyse new devices, the total machine impedance increases.
- On the other hand, the impedance model that we are using already shows that collective effects play an important role in the machine’s stability, and we must pay attention to impedance optimisation.
- Beam instability thresholds and mitigation efficiency that we have analyzed can change according to the new and updated impedance sources.
- The studies so far also show a strong interplay between longitudinal wakefield, transverse wakefield, chromaticity, feedback system and beam-beam (see M. Zobov presentation): each effect cannot be studied independently of the others.
- It is fundamental to look for diversified mitigation solutions for counteracting unwanted instabilities.

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Thank you for your attention