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High-intensity beam dynamics for Future Circular Collider

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and the FCC-ee collective effects study group (CERN, GANIL, IHEP, KEK)

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Activities

- The group is responsible for the impedance evaluation and single beam collective effects of FCC-ee main rings and high-energy Booster (this last in collaboration with GANIL laboratory in France).

- We have collaborations with CERN (two PhD students at the moment started to work on the machine impedance budget and on collective effects for the main rings), IHEP (Beijing), and KEK.

FCC-ee collective effects study group

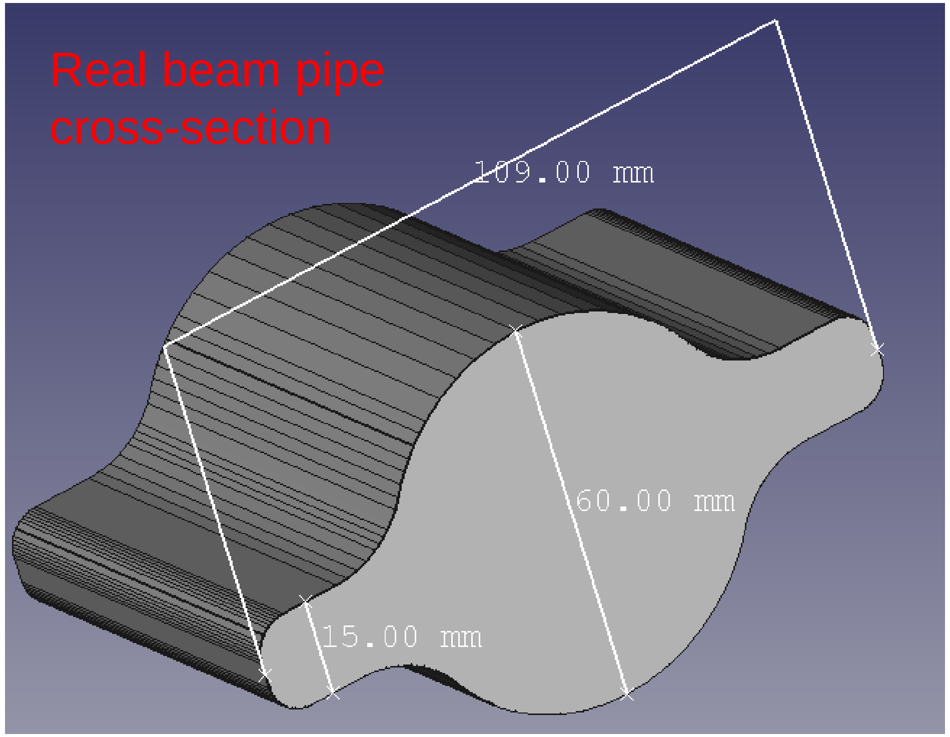
- Mauro Migliorati – Sapienza and INFN – Roma1
- Mikhail Zobov – INFN – LNF
- Yuan Zhang – IHEP – Beijing – China (interplay of impedance and beam-beam)
- Dora Gibellieri – CERN PhD – Enrolled at University of Caen – Normandie – A. Ghribi is her university supervisor, who collaborates for the collective effects in the Booster
- Carlo Zannini – CERN Supervisor of Dora
- Elena Macchia - CERN PhD started in December –enrolled at Sapienza with me as university supervisor
- Collaboration with Xavier Buffat and Roxana Soos on beam-beam
- Demin Zhou – KEK – is also starting a collaboration
- PAST CONTRIBUTIONS: C. Antuono, M. Behtouei, A. Rajabi, E. Carideo, …

Importance of the activities

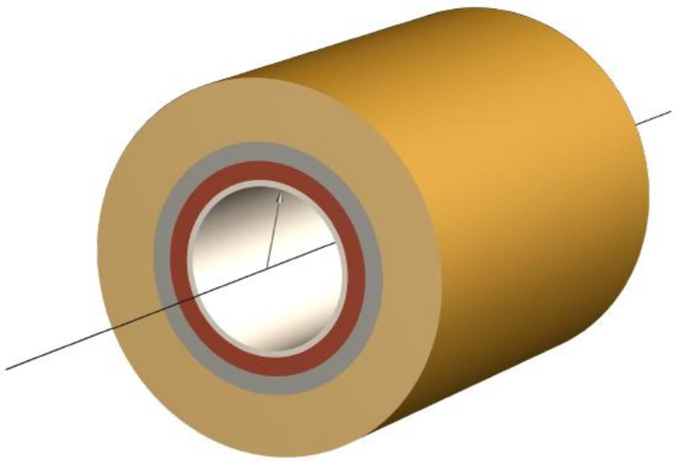
- The crab waist concept proposed and successfully tested at Frascati will be used for beam collisions in FCC-ee.
- The crab waist scheme and the extreme beam parameters at the interaction points such as low emittances, low betatron functions, high beam currents, large Piwinski angle are required to achieve the high requested luminosity in FCC-ee.
- With these parameters, new collective effects arise in beam-beam collisions, such as beamstrahlung, beam-beam head-tail instability (X-Z instability) and 3D flip-flops. Moreover, the conventional collective effects (impedance-related instabilities, electron clouds, ion effects etc.) become more severe.
- As a consequence, a careful evaluation of the machine impedance, collective effects and their interplay is mandatory to avoid collider performance deterioration and eventual beam instabilities.

Wakefields and coupling impedance: 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.



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	Δ =150 nm	$\rho = 10^{-6} \Omega m$

The contribution of the winglets to the RW impedance is small.

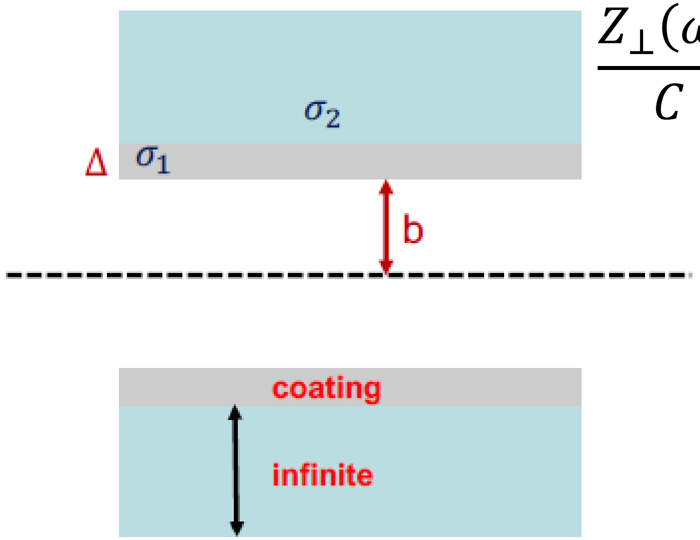
Reducing the coupling impedance in FCC-ee for the RW

- NEG coating is necessary to reduce the secondary electron yield for electron cloud mitigation and, in some cases, to help the pumping process.

Δ = coating thickness
δ_1 = skin depth coating
δ_2 = skin depth pipe

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

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



The real part of the impedances depends neither on the coating thickness nor on its conductivity (no power losses due to the coating).
The imaginary part has an additional term linear with the coating thickness.

- The lower the thickness of the coating, the lower its contribution to the (imaginary) impedance with respect to pure copper.
- Since a coating is needed, some measurements were performed at CERN to characterize NEG thin films, to find the minimum effective thickness satisfying vacuum and electron cloud requirements.
- A NEG film thickness between 100 and 200 nm, is a good candidate for coating thickness.

Wakefields and coupling impedance: collimation system

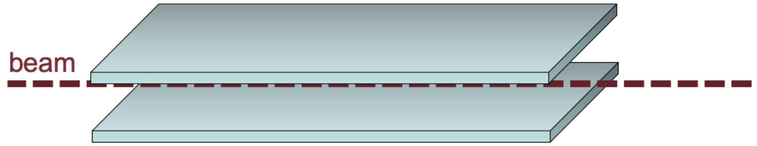
The collimation system represents a second major impedance source

beam halo collimators (form G. Broggi)

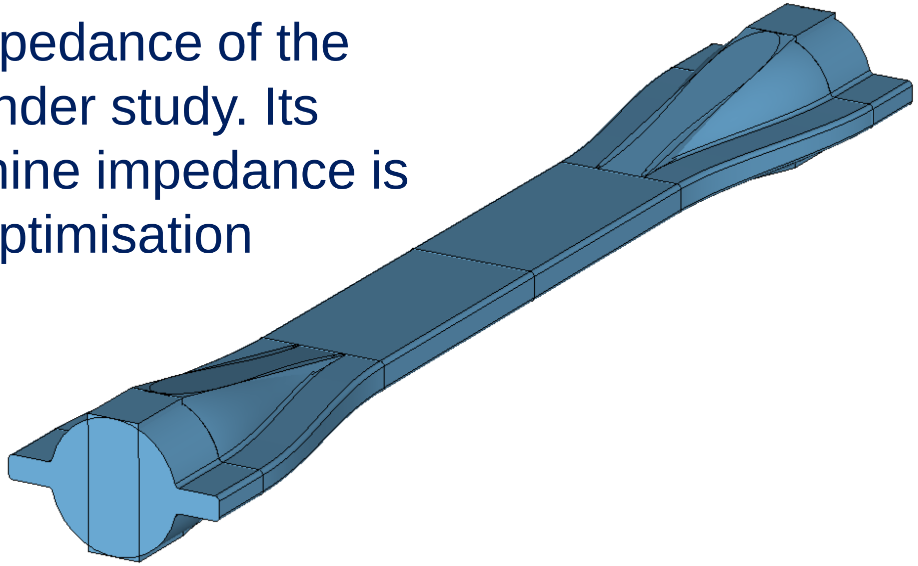
name	l (m)	$g/2$ (mm)	β_x (m)	β_y (m)
tcp.h.b1	0.25	6.7	517.46	724.70
tcp.v.b1	0.25	2.4	518.59	725.79
tcs.h1.b1	0.3	3.7	116.99	766.52
tcs.v1.b1	0.3	2.5	422.97	578.88
tcs.h2.b1	0.3	5.1	215.59	215.59
tcs.v2.b1	0.3	2.9	32.91	803.95
tcp.hp.b1	0.25	4.2	71.67	125.83
tcs.hp1.b1	0.3	4.6	63.91	193.84
tcs.hp2.b1	0.3	16.7	853.47	384.47

In the collimators' name, 'p' stands for primary (made of MoGr), 's' for secondary (made of Mo), 'v' for vertical, and 'h' for horizontal. Additionally, $l \rightarrow$ length, $g \rightarrow$ full gap.

So far, only RW contribution as parallel plates



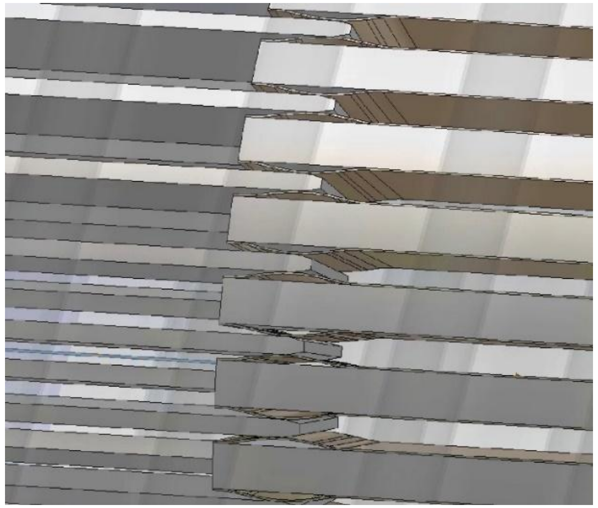
The geometrical impedance of the collimators is still under study. Its impact on the machine impedance is very high, and an optimisation study is necessary.

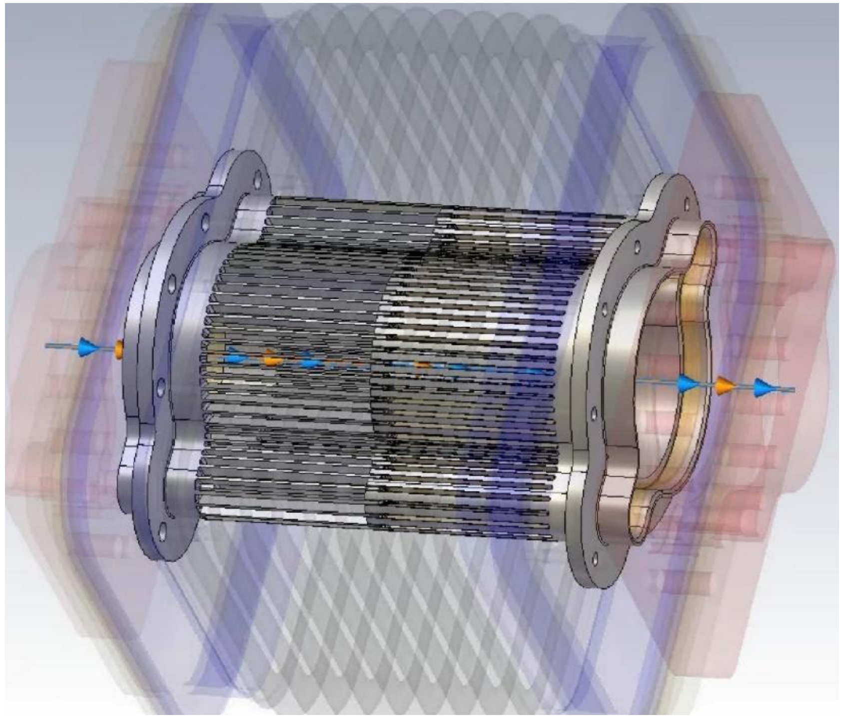


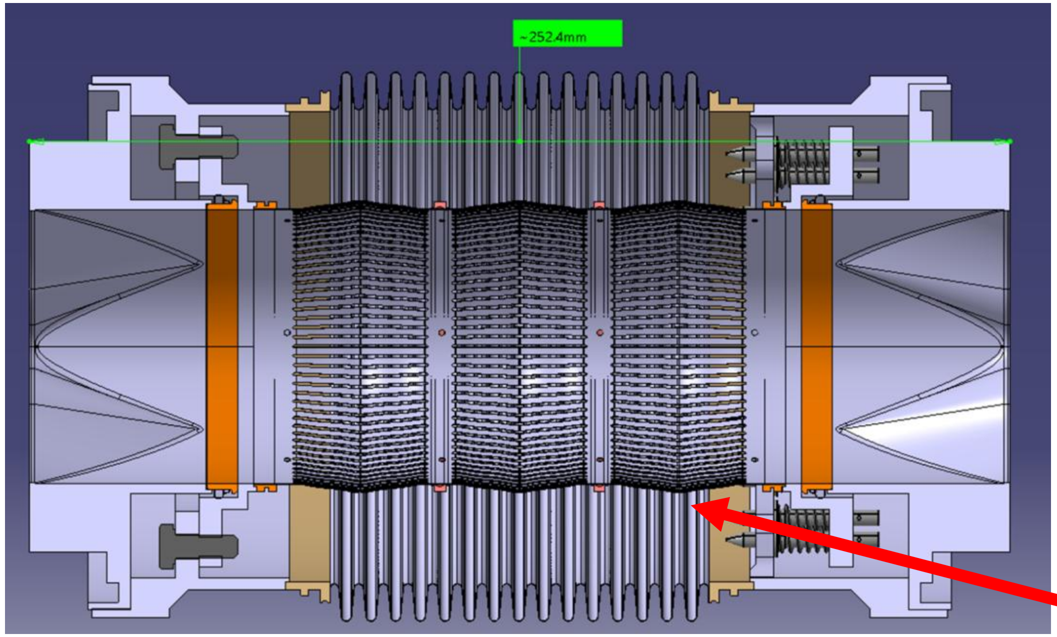
The RW impedance of 24 synchrotron radiation collimators (made of tungsten) has also been evaluated. Their contribution is much smaller than that of the beam halo collimators.

Wakefields and coupling impedance: other impedance devices

- Bellows: we are using the SuperKEKB model with sliding contacts.

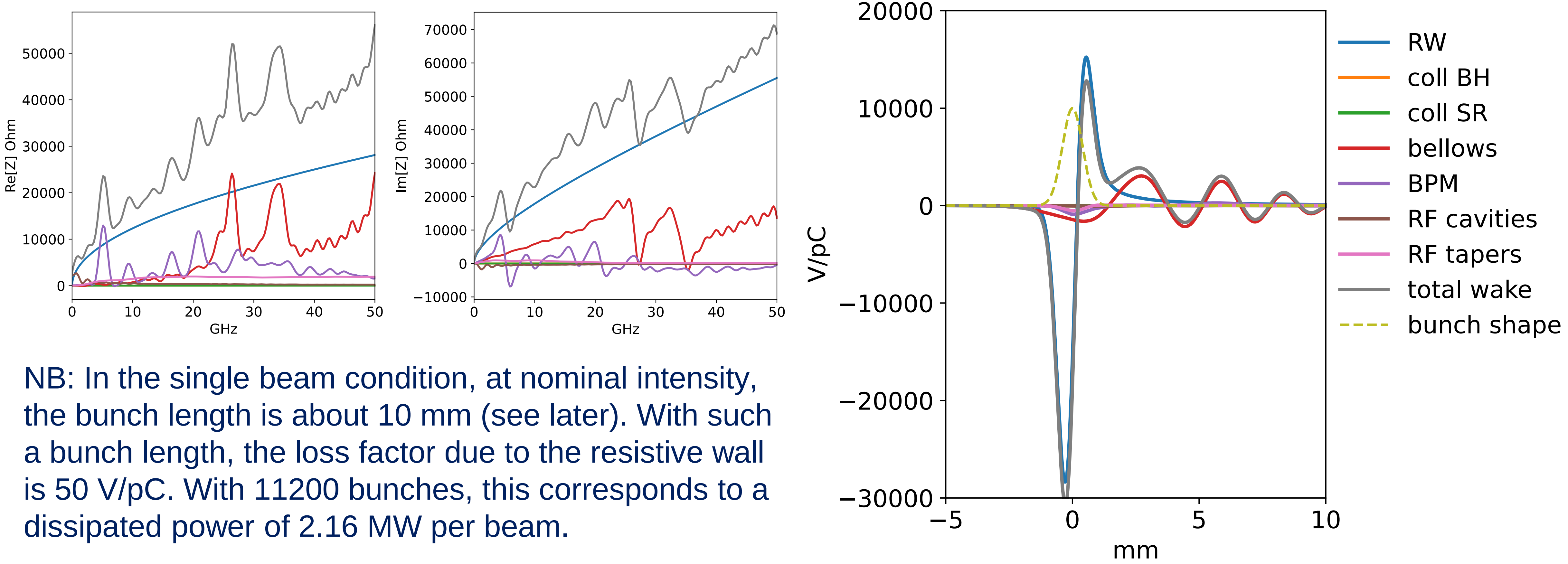






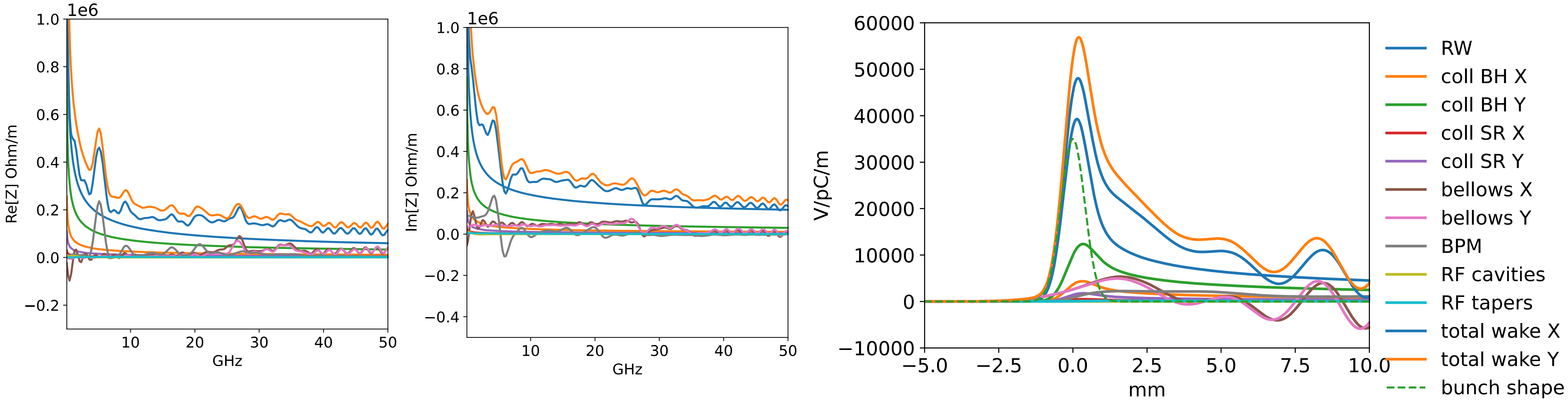
For some time, a model with deformable RF contacts (DRF) was studied (P. Krkotić, vacuum group). Such preliminary studies showed a too-high impedance.

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



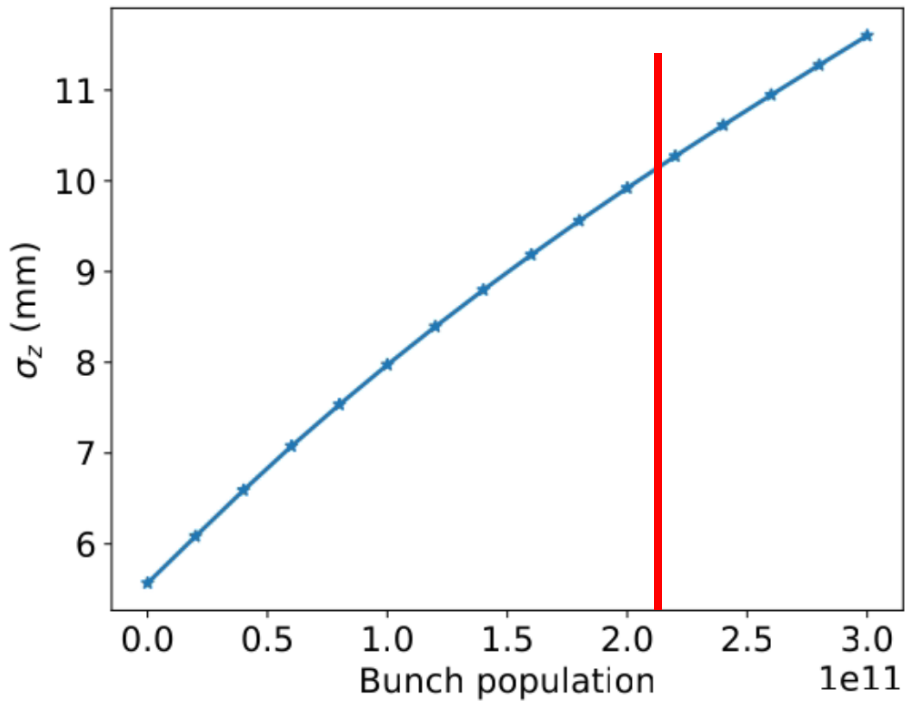
NB: In the single beam condition, at nominal intensity, the bunch length is about 10 mm (see later). With such a bunch length, the loss factor due to the resistive wall is 50 V/pC. With 11200 bunches, this corresponds to a dissipated power of 2.16 MW per beam.

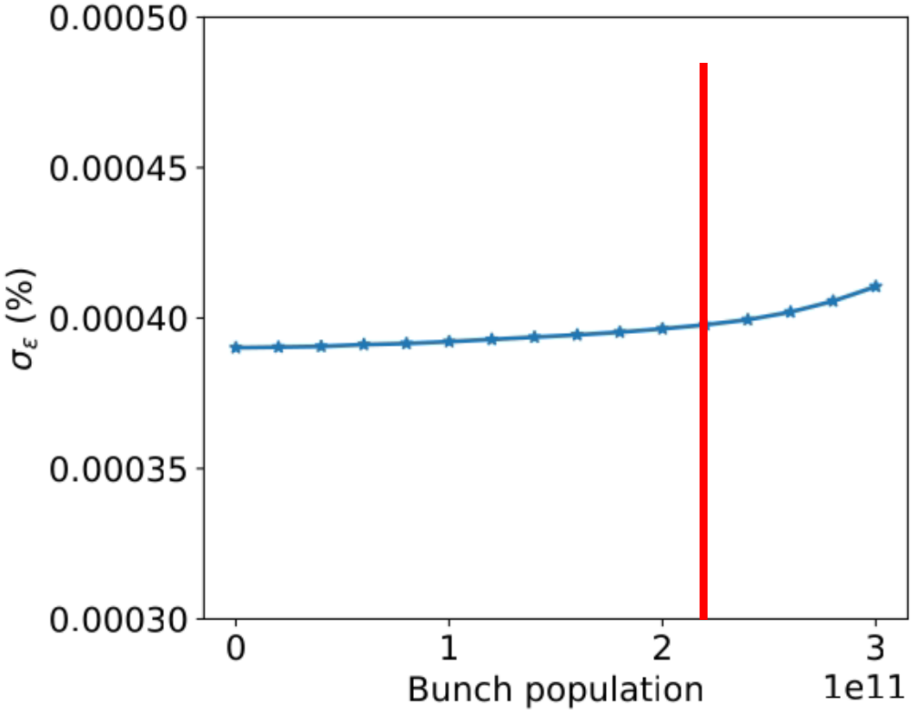
Transverse dipolar wake potential of a 0.4 mm Gaussian bunch used as Green function in beam dynamics simulations



In beam dynamics simulations we have also included the quadrupolar term (so far, about a factor of 10 smaller than the dipolar impedance).

Collective effects in longitudinal plane: single beam and potential well distortion

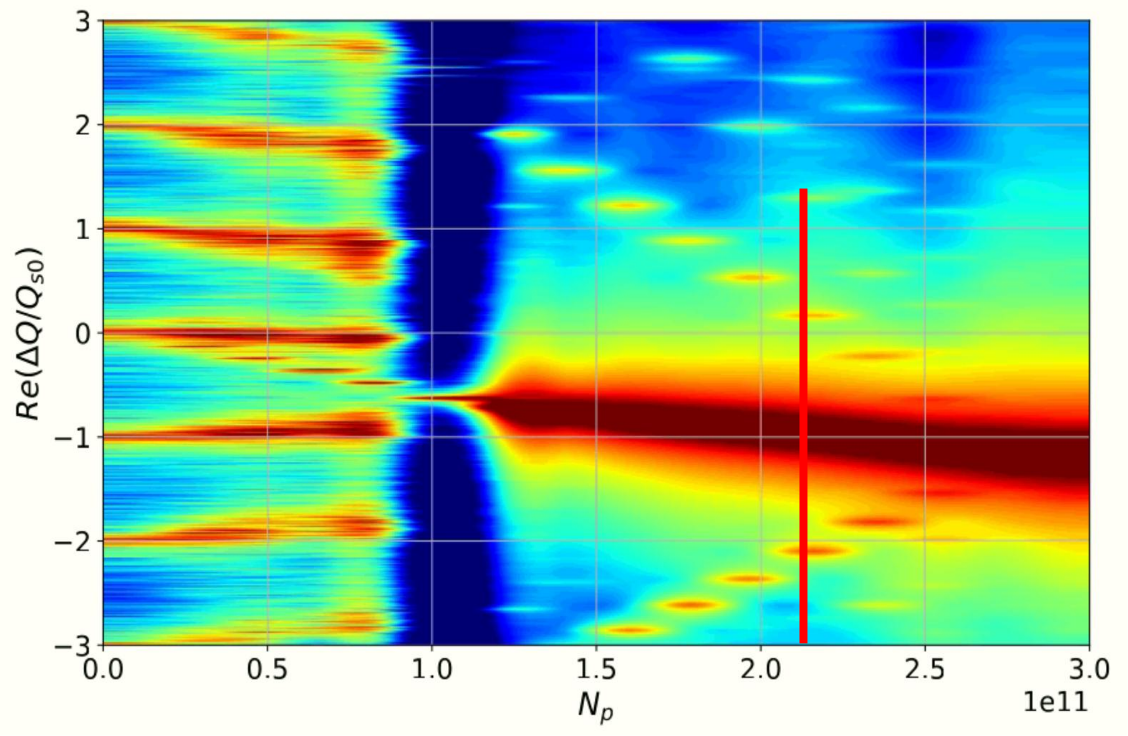




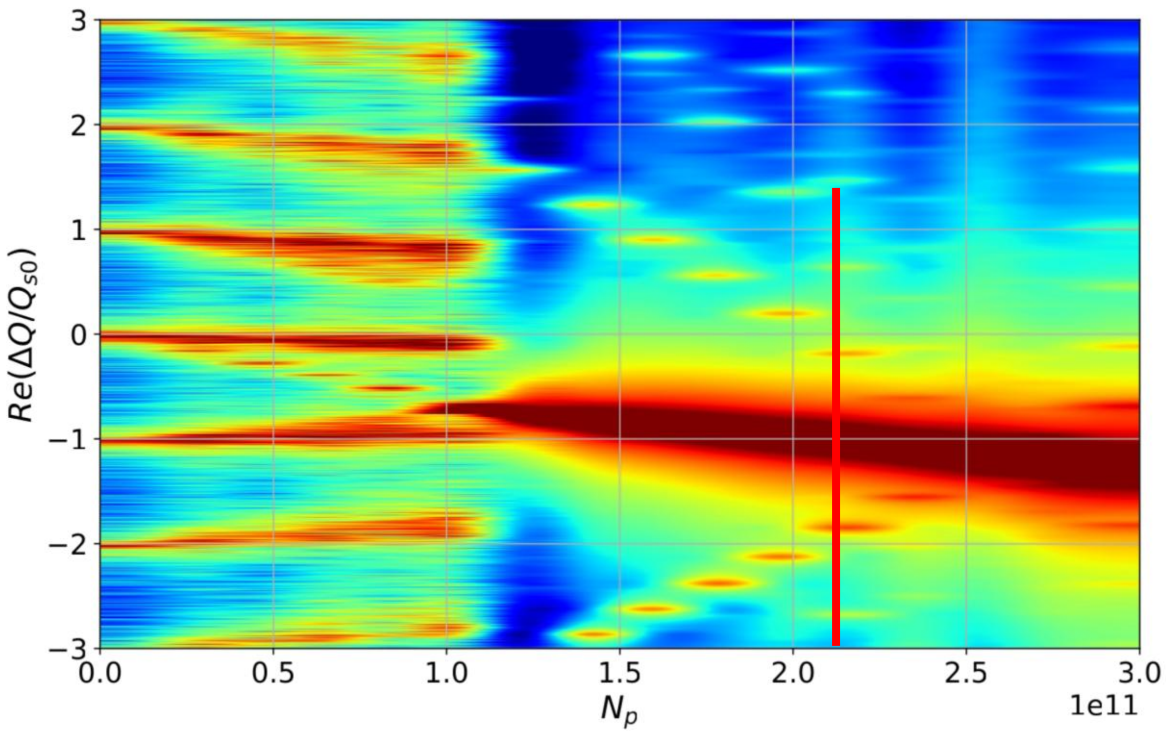
At the nominal bunch population, we are below the microwave instability threshold.

Collective effects in transverse plane: TMCI

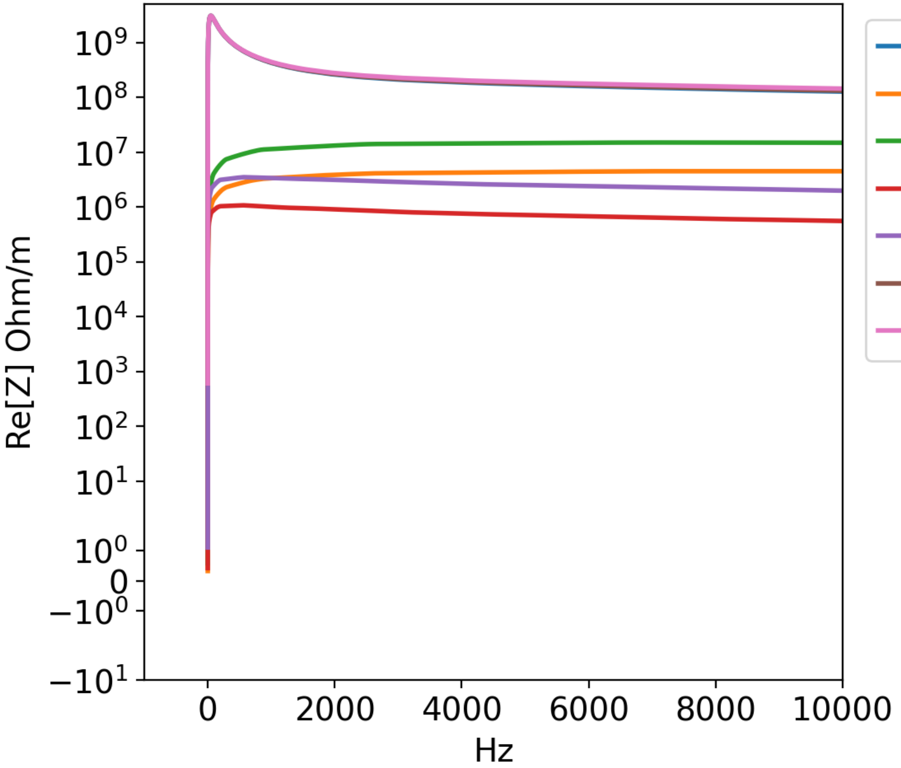
No chromaticity, no feedback system



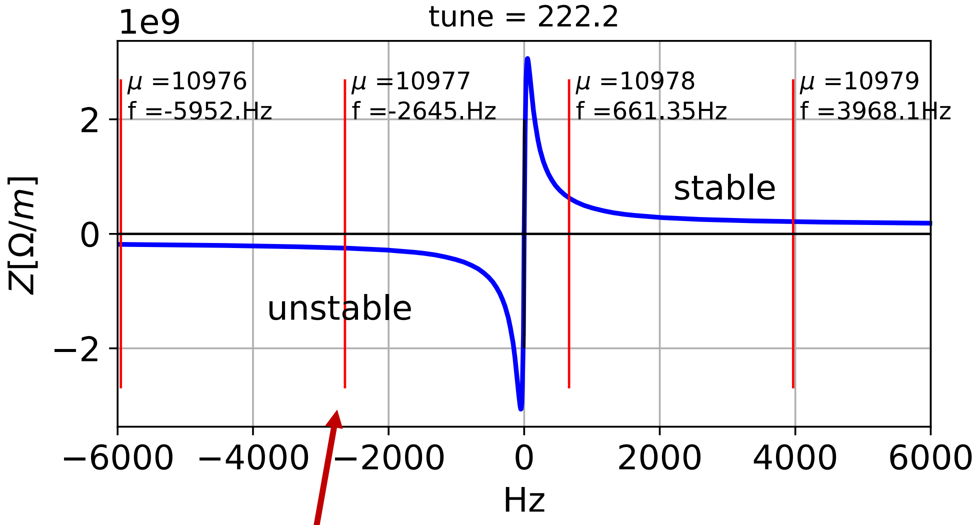
chromaticity = 2, no feedback system



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.

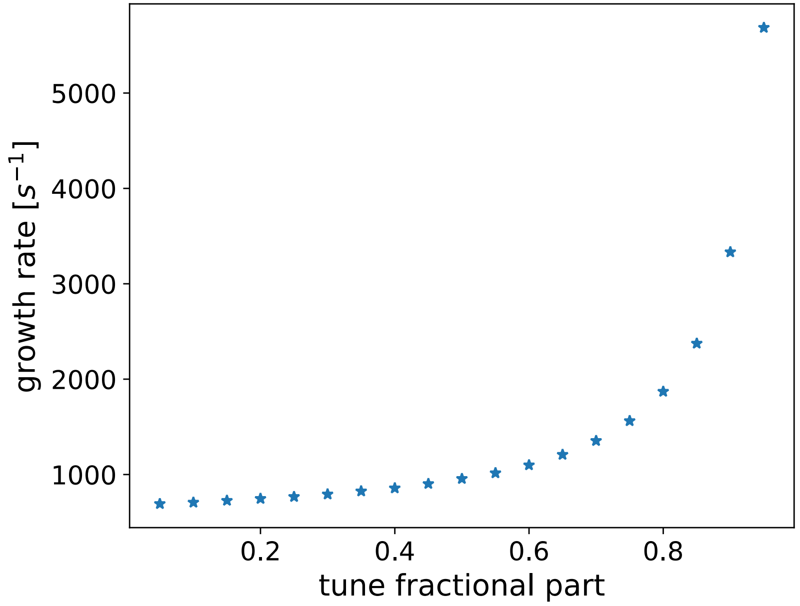


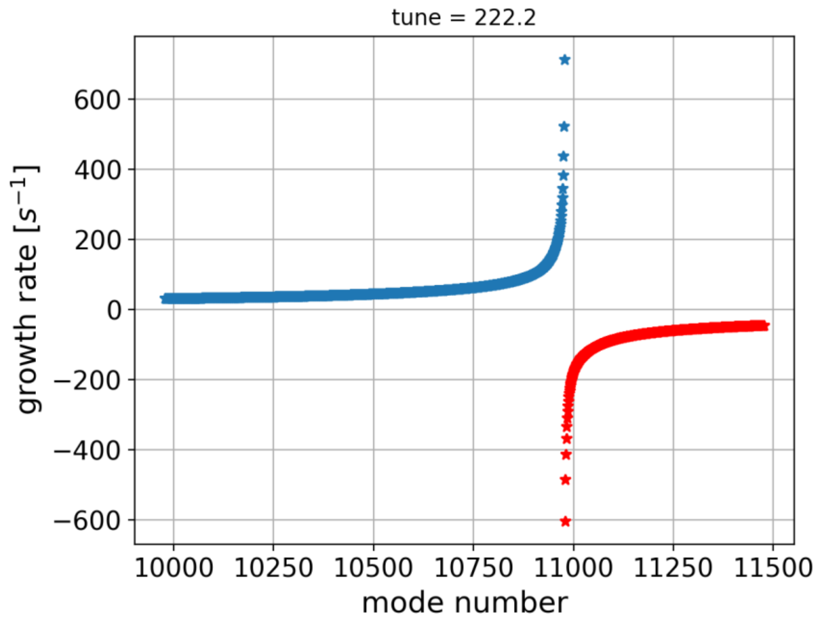
The most dangerous mode is that closest to the origin (with negative frequency)

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

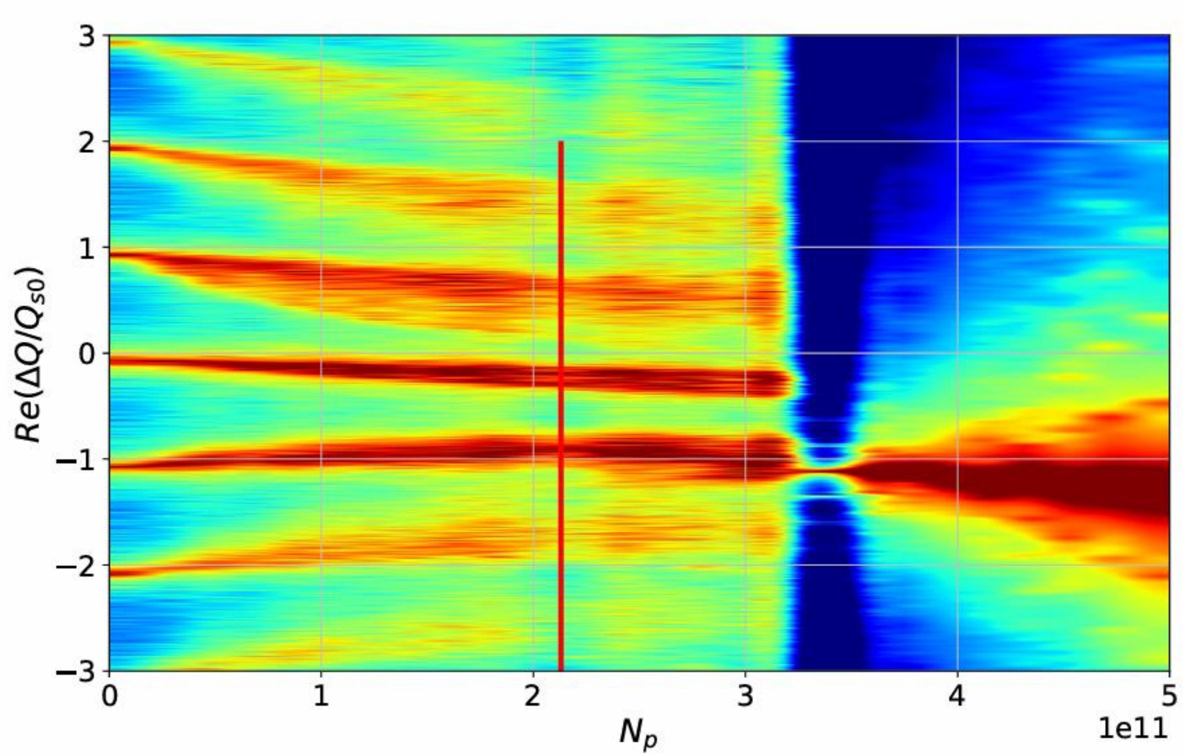
- The rise time of the most dangerous mode is about 1.3 ms (growth rate of about 750 s^{-1}).
- To suppress the TCBI, a bunch-by-bunch feedback system can be used.
- The damping time in the transverse plane should be 1 ms, similar to the damping time of the SuperKEKB feedback.
- However, 1 ms in FCC-ee corresponds to about 3 turns. We must pay attention to the design of such a feedback system.
- Additionally, some hundreds of unstable coupled bunch modes must be damped.





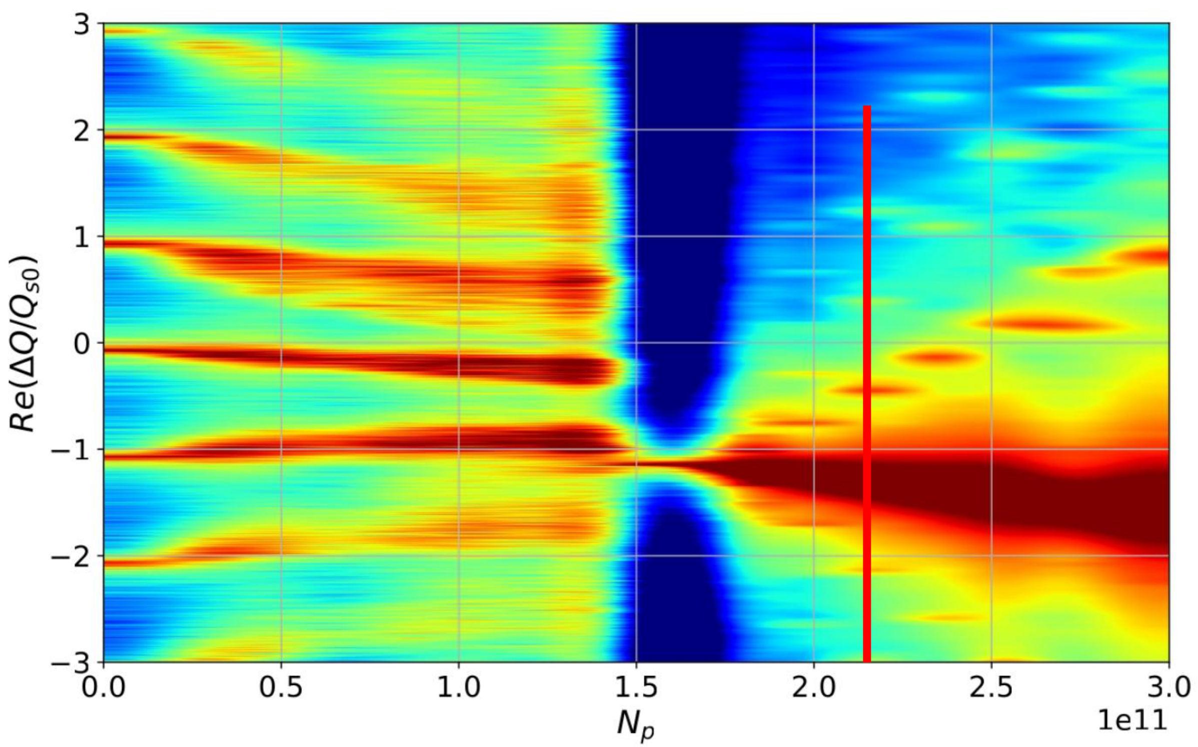
Collective effects in transverse plane: TMCI

chromaticity = 5, feedback system on (4 turns)

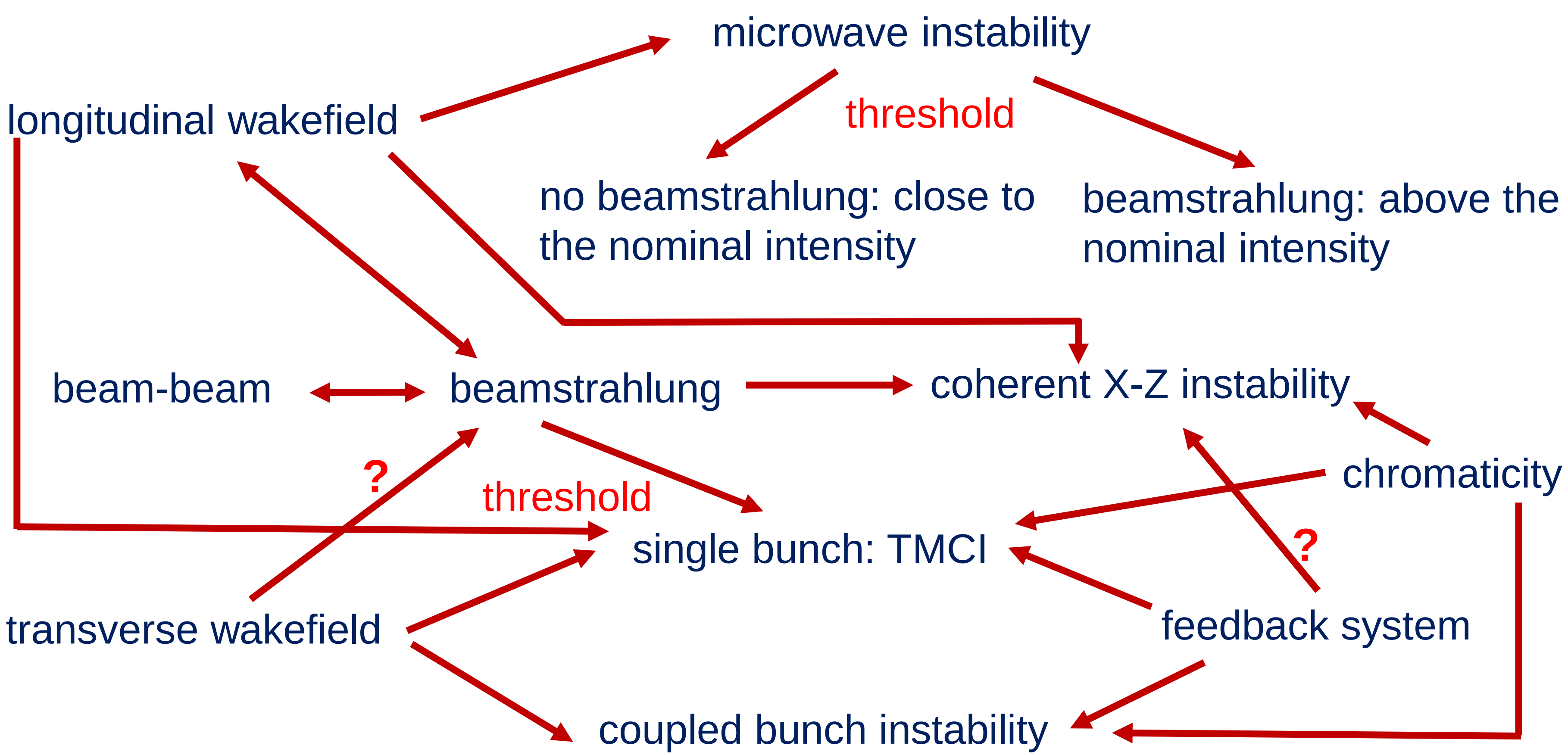


We still miss several impedance devices. Some of them could be important (as the geometric contribution of the collimators).

Double impedance, chromaticity = 5, feedback system on (4 turns)



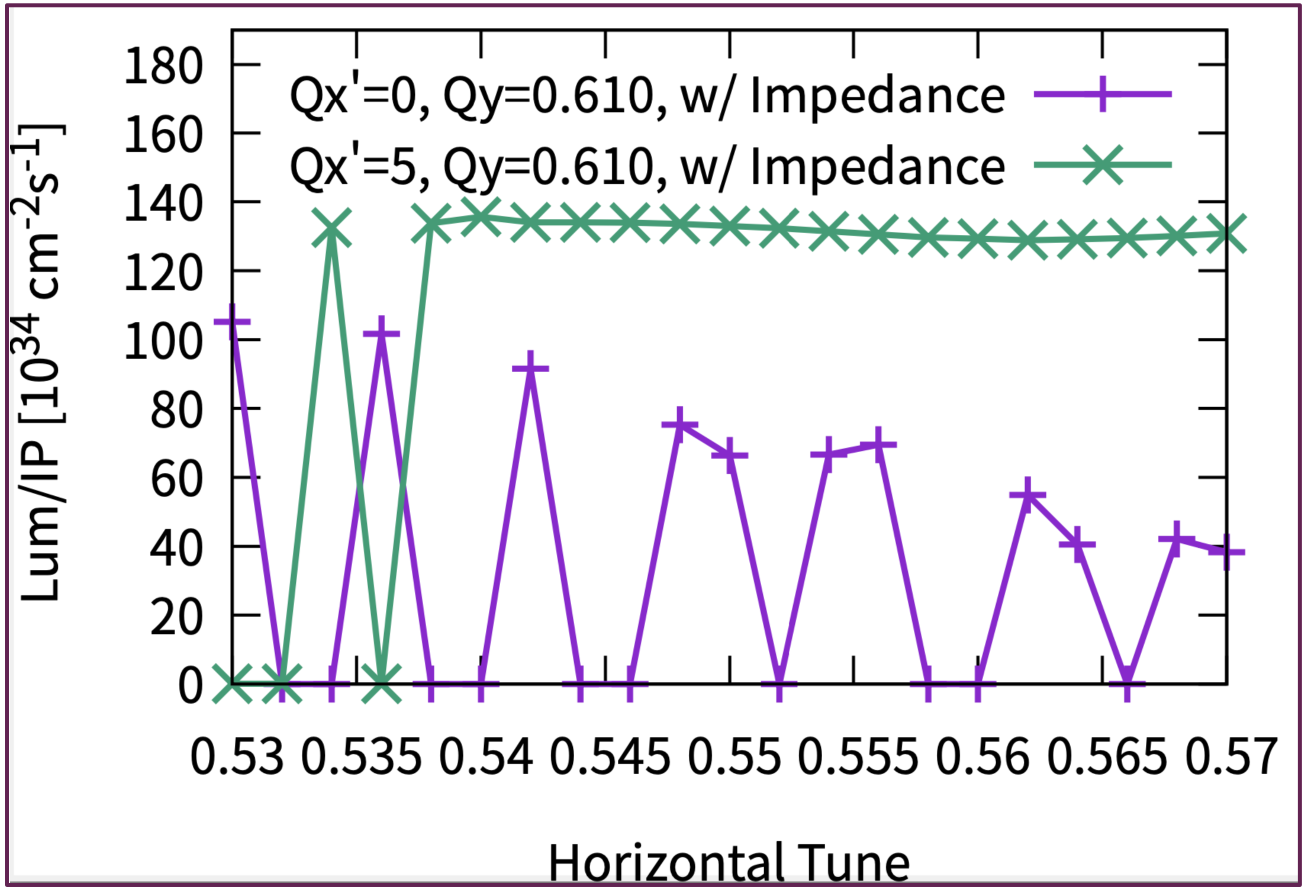
The interplay between different collective effects for FCC-ee



Interplay between beam-beam and coupling impedance

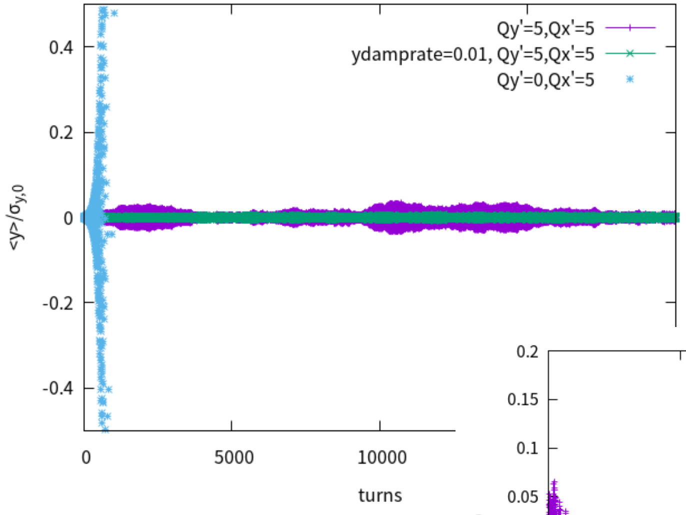
A positive chromaticity has a beneficial effect on the beam-beam. Self-consistent simulations show a luminosity per IP close to the nominal value of 141 x 10^{34} $cm^{-2}s^{-1}$ by properly choosing the collider working point.

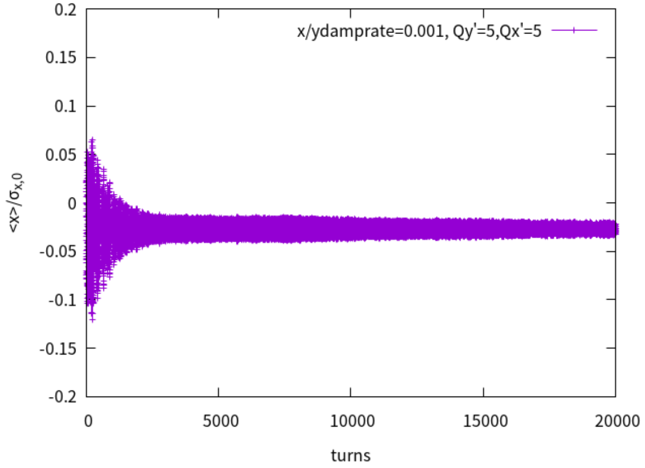
Y. Zhang, IHEP, Beijing, China

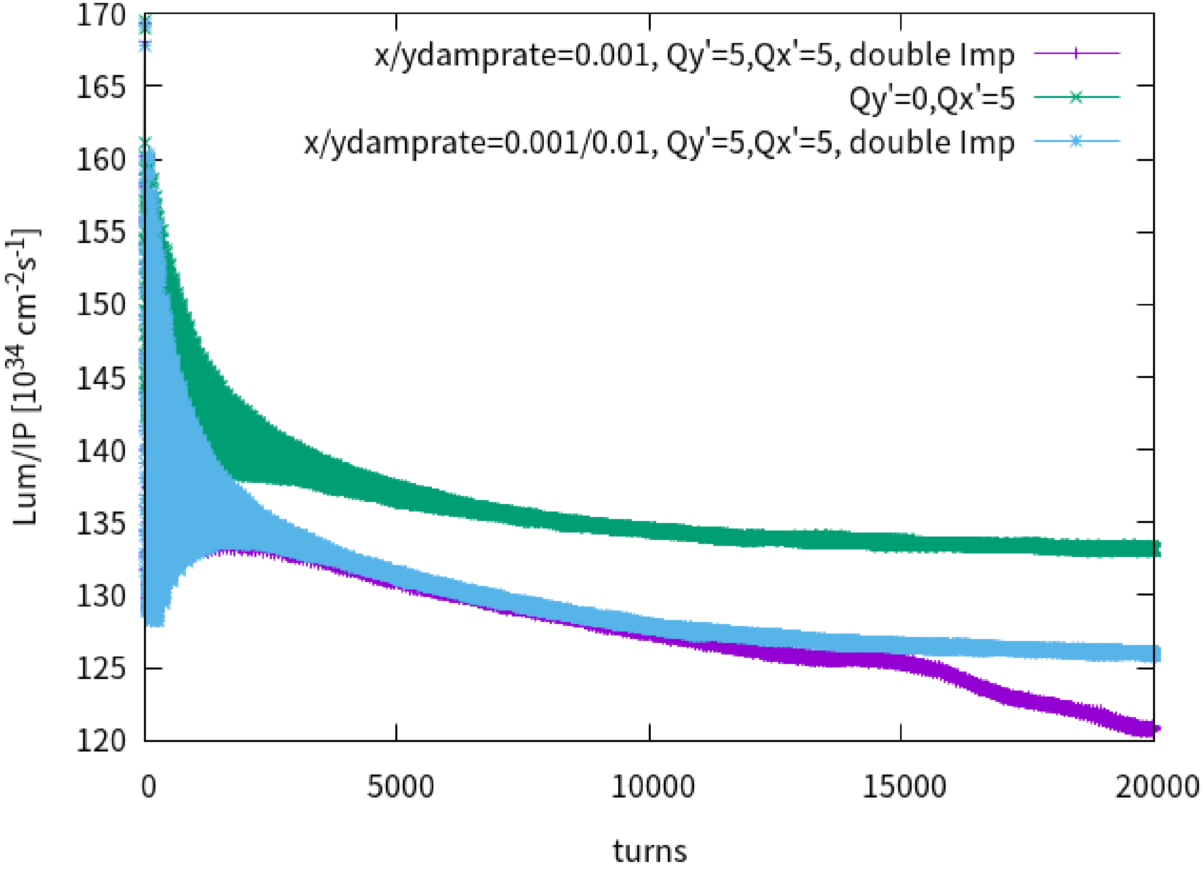


Missing impedance and mitigation tools

There seems to be a mitigation effect when beam-beam and beamstrahlung are included in simulations: with damping times y/x of 25/250 turns, $Q'_{xy} = 5$, and a proper choice of the tunes, the beams seem to be quite stable (Y. Zhang, work in progress …).







Conclusions

- With the continuous refinement of the FCC design, the coupling impedance budget evolves alongside updates to vacuum chamber components.

- Beam instability thresholds and stability regions can change according to the new impedance sources that will be gradually added.

- It is fundamental to look for impedance optimization and diversified mitigation solutions for counteracting collective effects.

- 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.

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Thank you for your attention