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# FCC-ee single beam collective effects (and interplay with beam-beam)


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**and the FCC-ee collective effects study group**



Acknowledgements: collimation, vacuum and RF groups, Xsuite code developers, …

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# Outline

- FCC-ee main parameters (baseline)
- Wakefields and coupling impedance
- Collective effects: longitudinal and transverse planes
- Feedback system
- Interplay between beam-beam and coupling impedance
- Missing impedance and mitigation tools

# FCC-ee main parameters (baseline)

| Parameter | Value |
|---|---|
| Circumference (km) | 90.658816 |
| Beam energy (GeV) | 45.6 |
| Bunch population ($10^{11}$) | 2.14 |
| RF frequency (MHz) | 400 |
| RF Voltage (MV) | 79 |
| Energy loss per turn (GeV) | 0.0391 |
| Longitudinal damping time (turns) | 1158 |
| Momentum compaction factor $10^{-6}$ | 28.6 |
| Horizontal tune/IP | 54.5395 |
| Vertical tune/IP | 55.55 |
| Synchrotron tune | 0.0288 |
| Emittance Hor (nm)/Vert (pm) | 0.71/1.9 |
| Bunch length (mm) (SR/BS)* | 5.6/15.4 |
| Energy spread (%) (SR/BS)* | 0.039/0.109 |
| Piwinski angle (BS)* | 26.4 |
| $\xi_x/\xi_y$ | 0.0022/0.097 |
| $\beta^*$ Hor (m)/Vert (mm) | 0.11/0.7 |
| Luminosity/IP ($10^{34}$/cm$^2$s) | 141 |

*SR: synchrotron radiation, BS: beamstrahlung

# FCC-ee main parameters (baseline)

The main difference with respect to FCC week 2023 is the bunch population:

$$N_p: 1.51 \times 10^{11} \rightarrow 2.14 \times 10^{11}$$

… and the RW dipolar impedance increased by 60% …

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|---|---|
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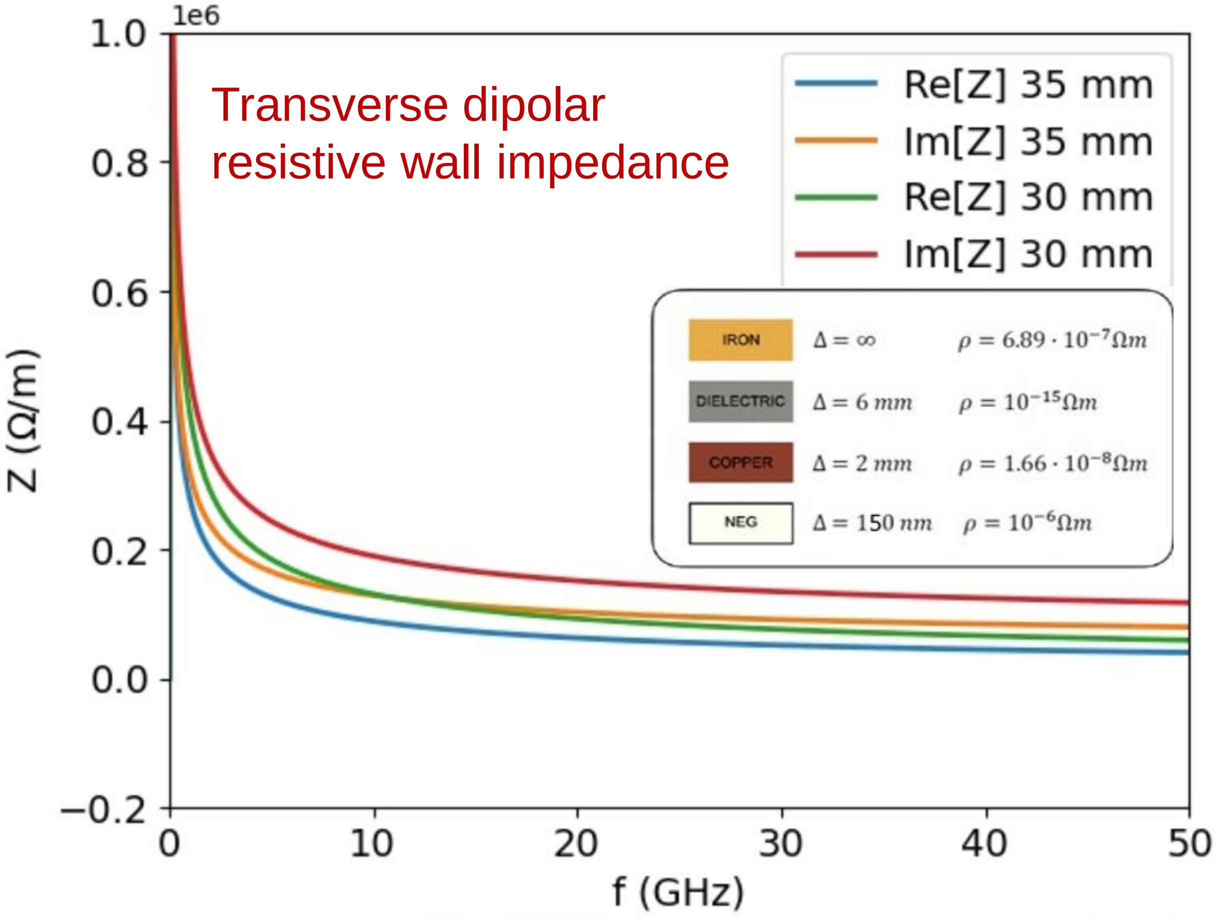
*SR: synchrotron radiation, BS: beamstrahlung

## Wakefields and coupling impedance: resistive wall

Due to the high power consumption requested for driving quadrupole and sextupole magnets, the new FCC-ee baseline foresees a beam pipe radius *b* reduced from 35 to 30 mm.

Since the transverse RW impedance is proportional to $b^{-3}$, we find an increase in this contribution of about 60%.

Additionally, we need to evaluate the impact of this reduced radius on other machine devices, such as BPMs and bellows.



# Wakefields and coupling impedance: collimation system

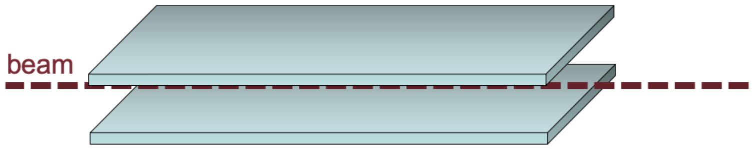
## With the updated parameter list and optics, also the collimation system is changed

beam halo collimators (form G. Broggi)

| name | $l$ (m) | $g/2$ (mm) | $\beta_x$ (m) | $\beta_y$ (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.

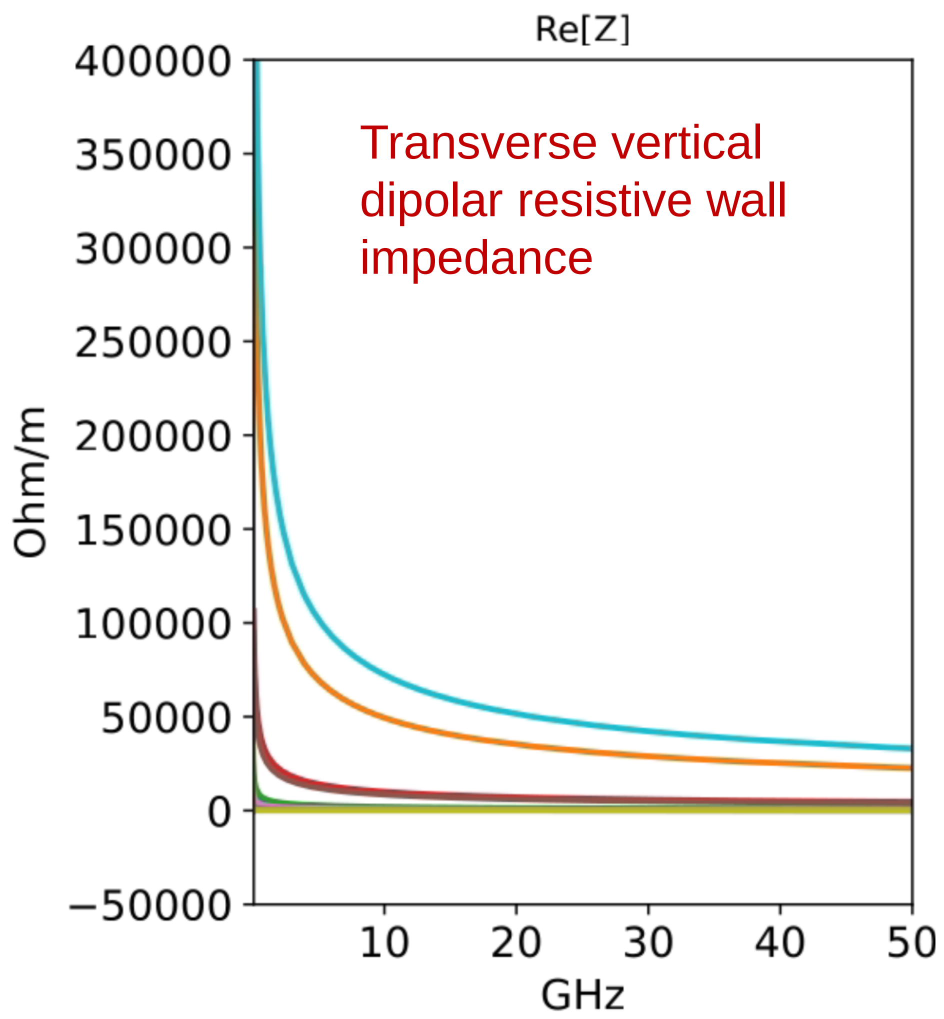
So far, only RW contribution as parallel plates

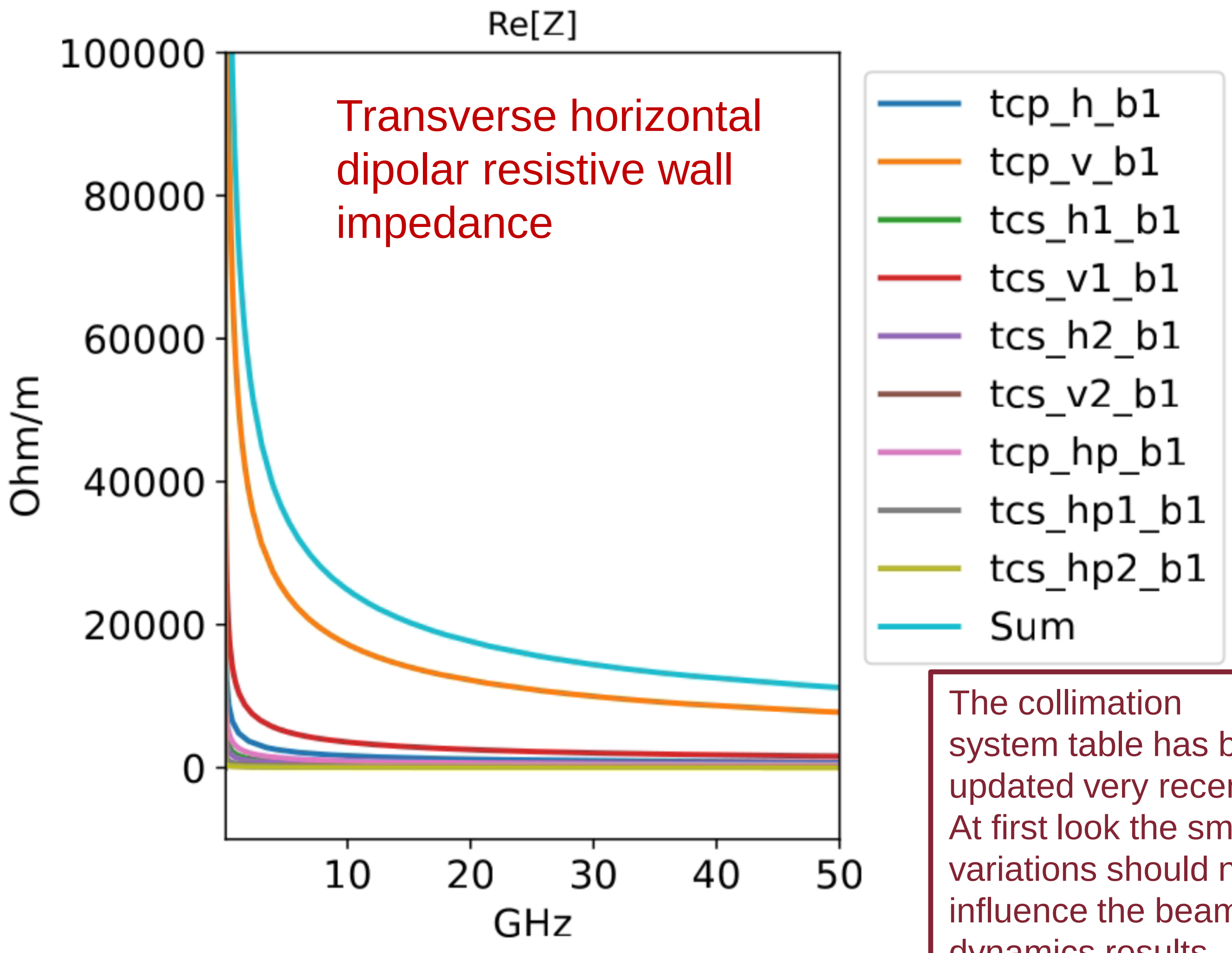



This gives the highest resistive wall transverse dipolar impedance contribution in both the horizontal and vertical planes, having the smallest gap and a very high local beta function.

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.

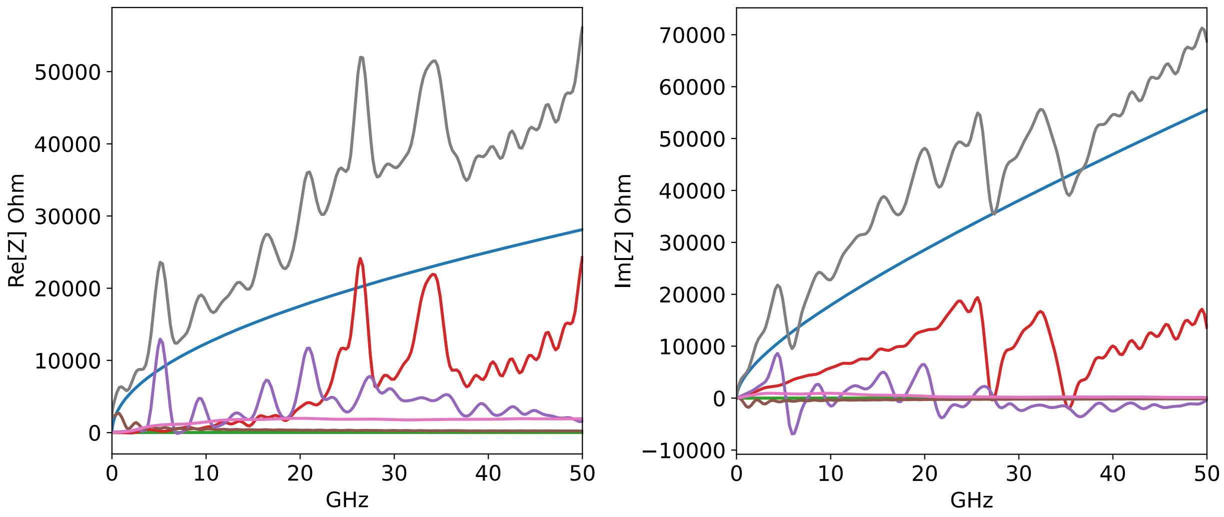
# Wakefields and coupling impedance: collimation system

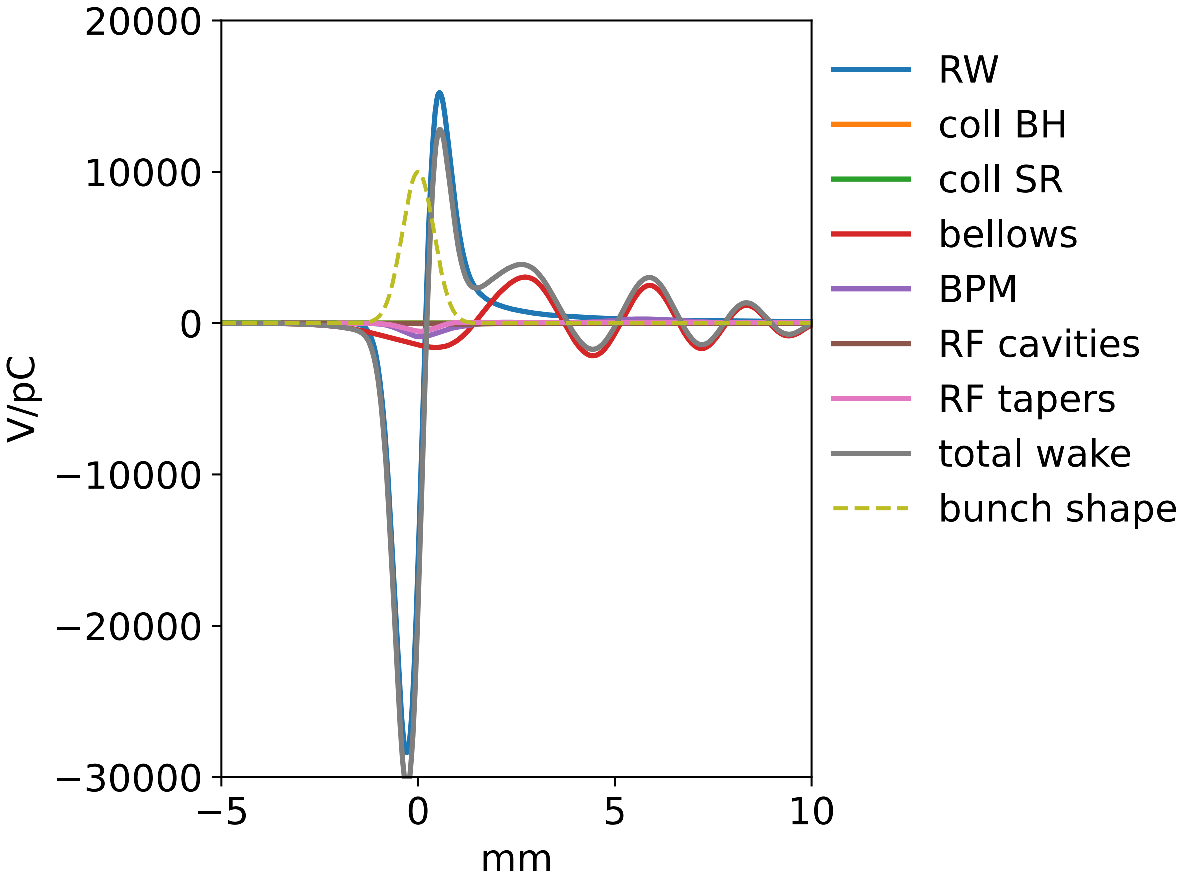



The collimation system table has been updated very recently. At first look the small variations should not influence the beam dynamics results.

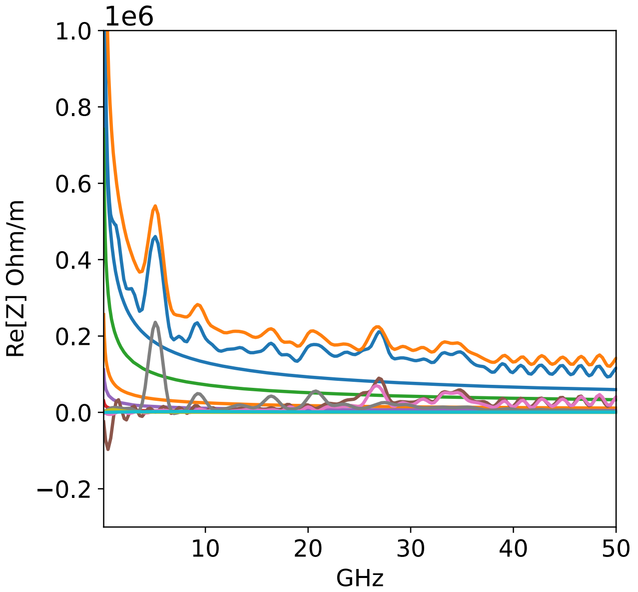
# Longitudinal impedance and wake potential of a 0.4 mm Gaussian bunch used as Green function in beam dynamics simulations

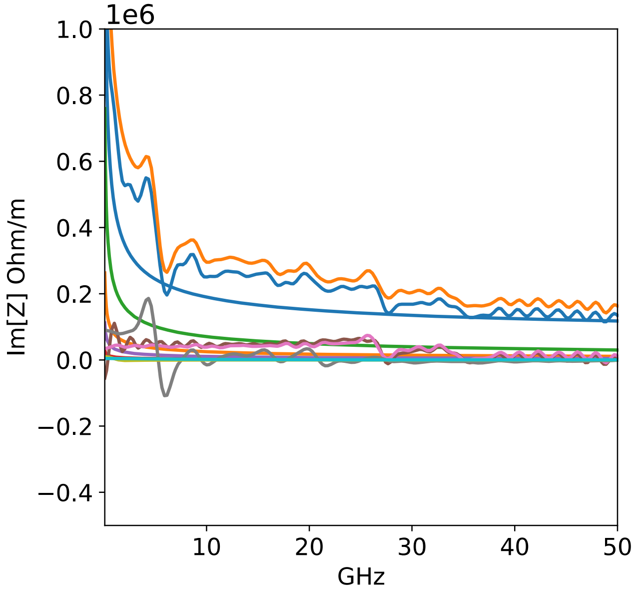


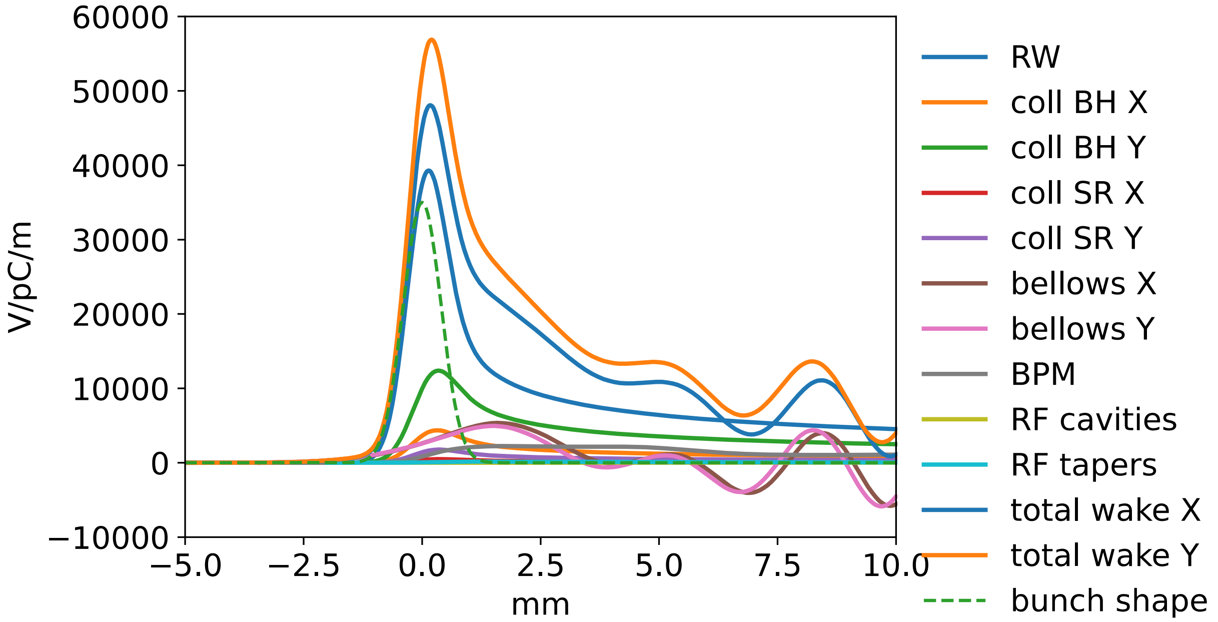




NB: In the single beam condition, at nominal intensity, the bunch length is about 10 mm (see later). With such a bunch length, the loss factor due to the resistive wall is 50 V/pC. With 11200 bunches, this corresponds to a dissipated power of 2.16 MW per beam.

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



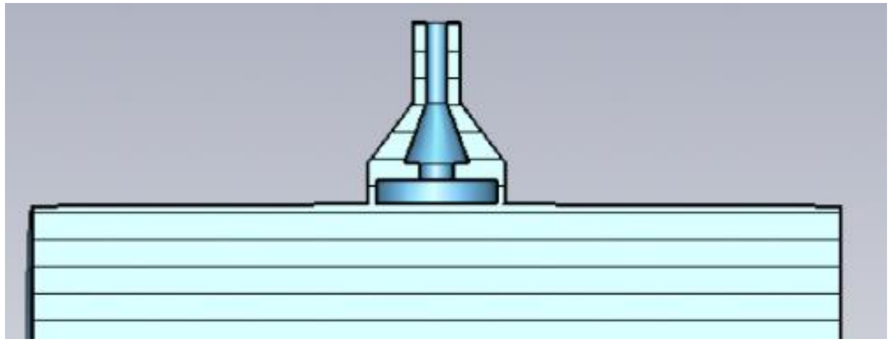




In beam dynamics simulations we have also included the quadrupolar term (so far, about a factor of 10 smaller than the dipolar impedance).

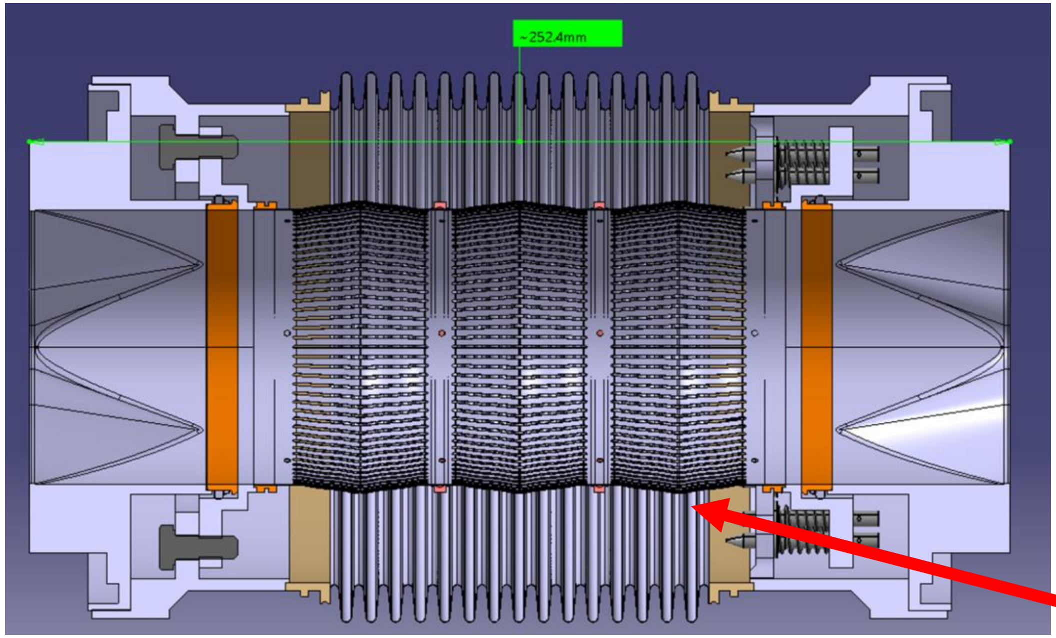
# Wakefields and coupling impedance: open questions

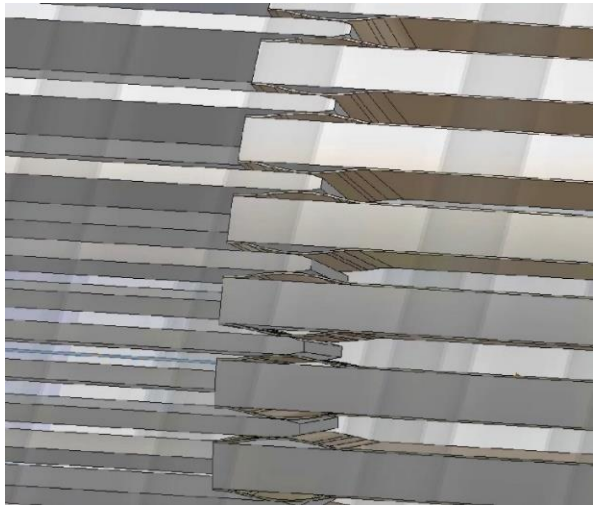
- Collimators 1: can we reduce the impedance of the tcp.v.b1 by changing its position (local beta function) and aperture?
- Collimators 2: can we reduce the length of the beam halo collimators?
- Collimators 3: we are working on the geometrical impedance starting from a scaled SuperKEKB model.
- **We are collaborating with other groups to address the above points**
- BPMs: we are using a model scaled from DA$\Phi$NE, with a cylindrical button with a diameter of 15 mm and a thickness of 3 mm. This gives a trapped mode around 6 GHz, but the device is not optimized. An interaction with the BI group is needed.

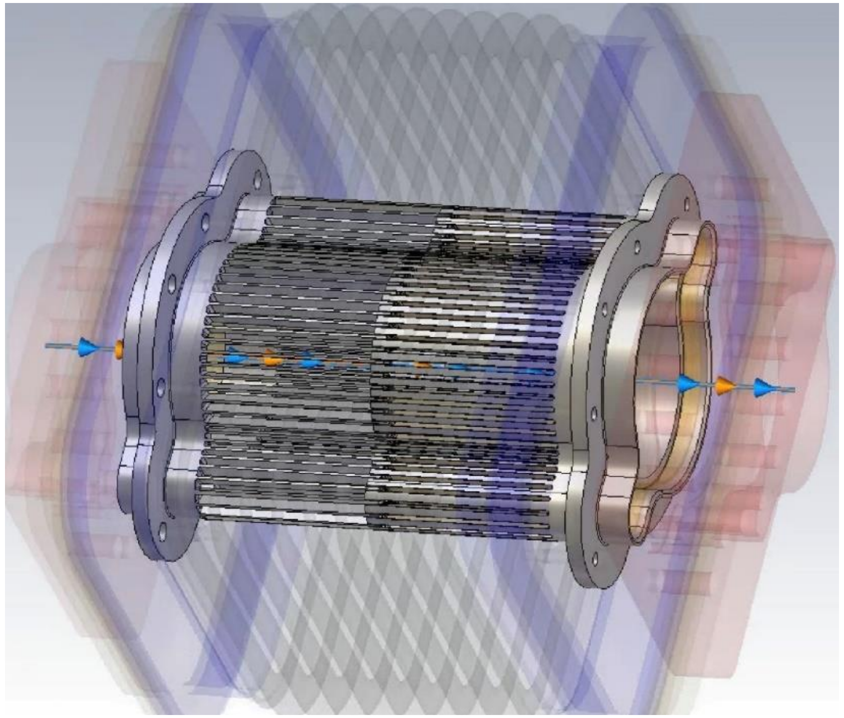


# Wakefields and coupling impedance: open questions

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

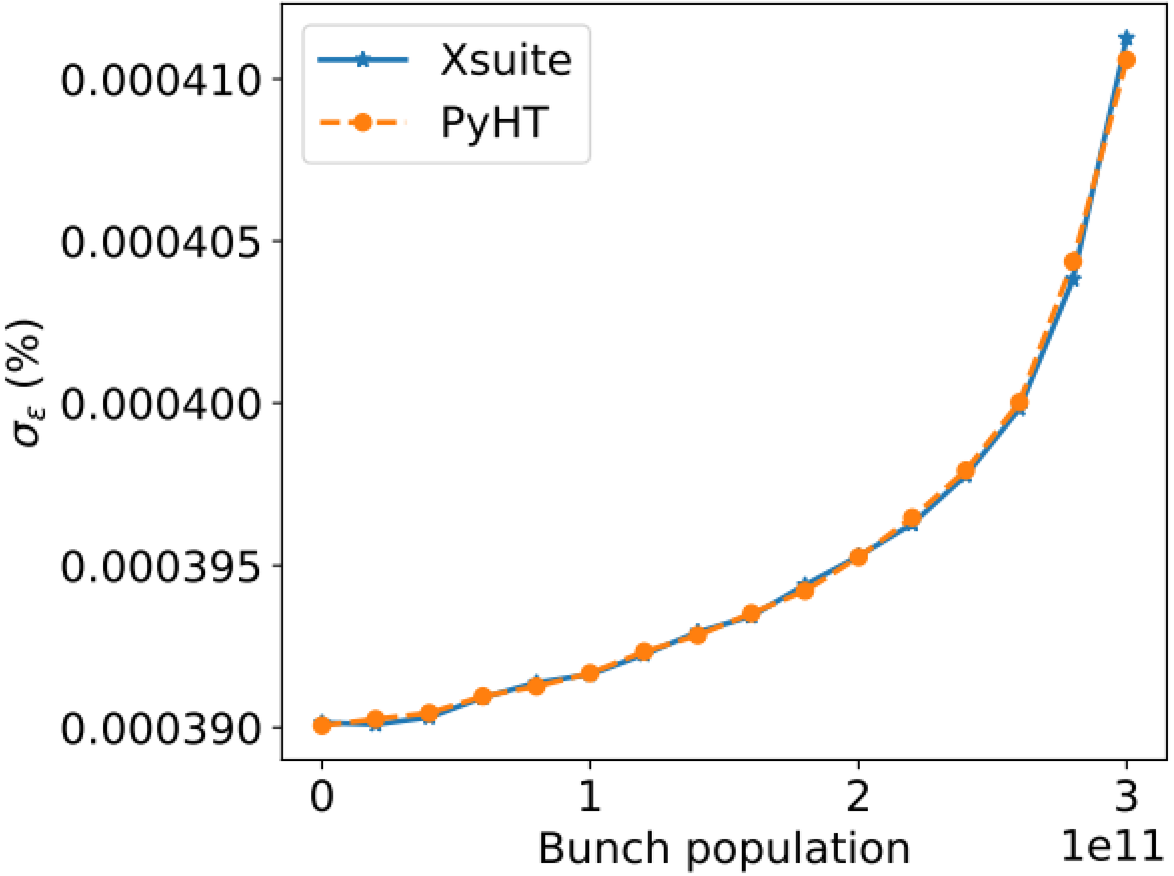


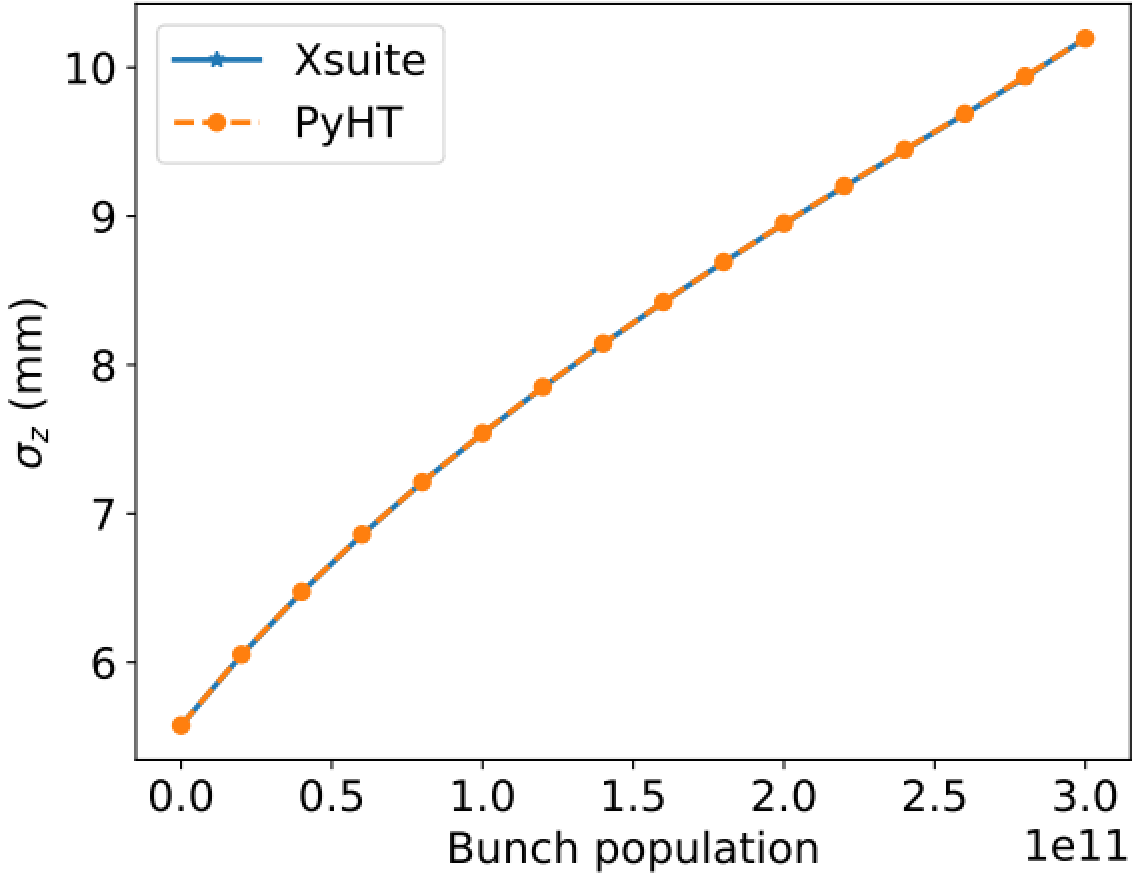





For some time, a model with deformable RF contacts (DRF) was studied (P. Krkotić, vacuum group). Such preliminary studies showed a too-high impedance.

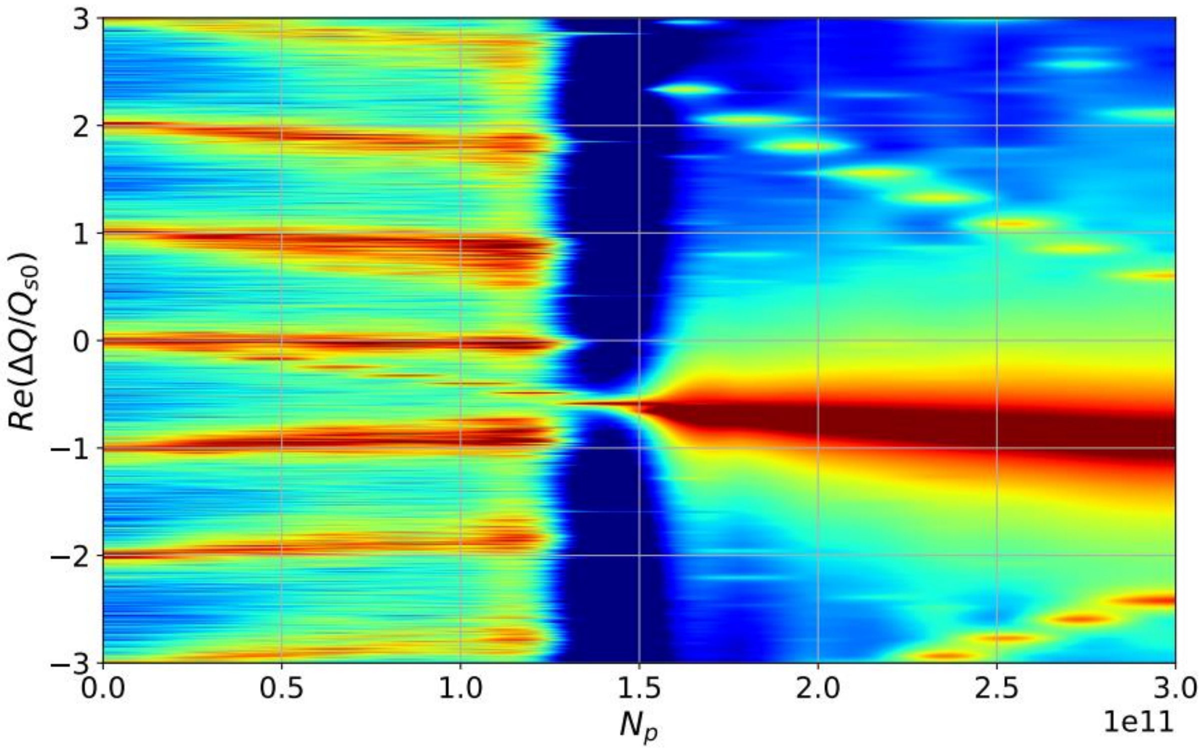
# Beam dynamics simulations: PyHT vs XSuite



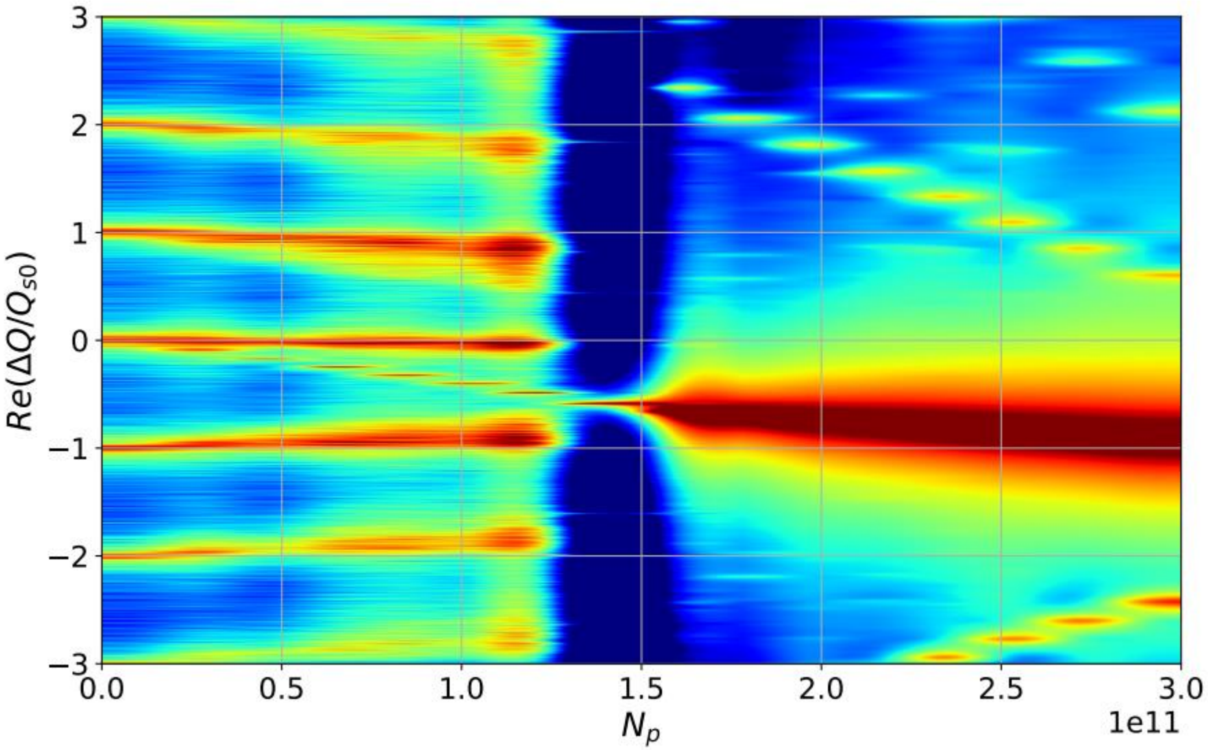



# Beam dynamics simulations: PyHT vs XSuite

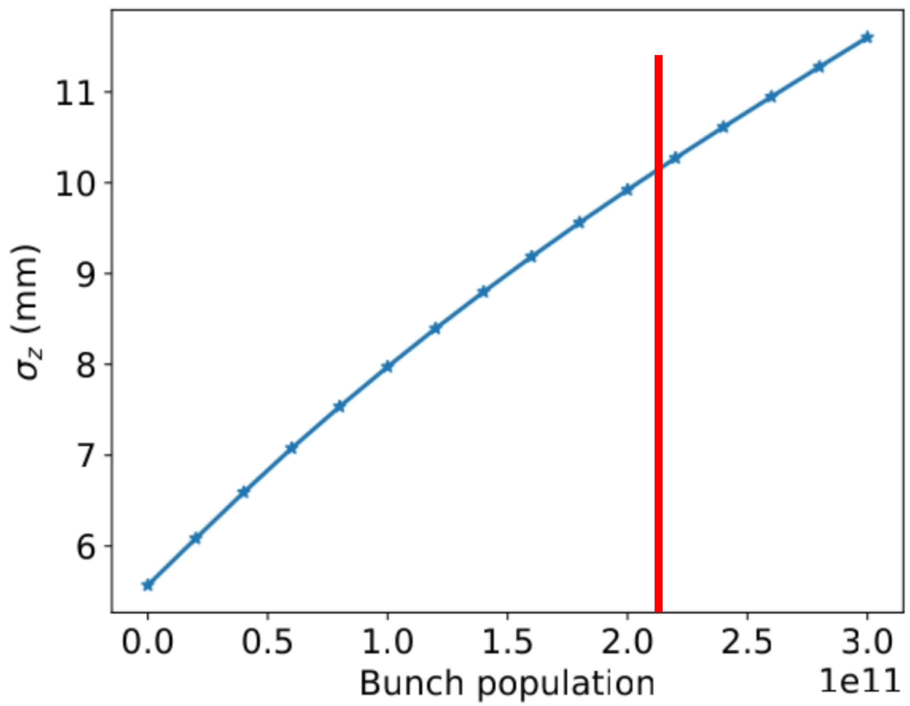
Xsuite y-plane

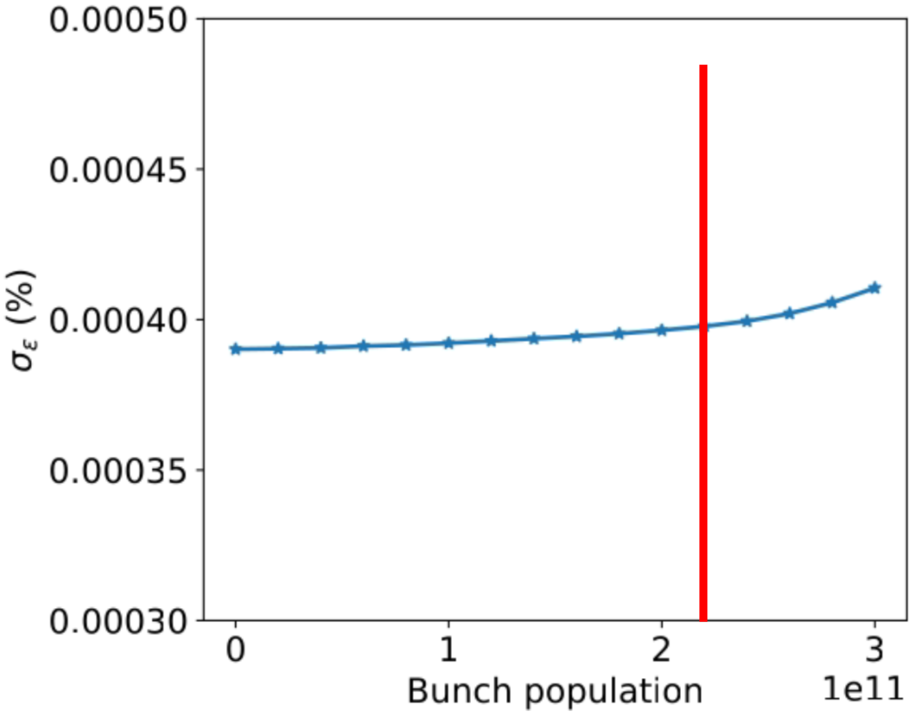



PyHT y-plane



# Collective effects in longitudinal plane: potential well distortion




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

# Impact of high-frequency ($k \gg 1/\sigma_z$) CSR and RW impedances on MWI

## (D. Zhou – KEK)

- CSR impedance:
  - A scaling law can be used to estimate CSR effects
  - The threshold bunch current is proportional to $1/h$ ($h$ is the half chamber height = 30 mm), but independent of the bending radius of dipoles [1,2]

$$(I_b)_{th} = \frac{0.384 \cdot 4\pi(E/e)\eta\sigma_\delta^2\sigma_z}{Z_0 h}$$

  - The critical frequency corresponding to the above threshold is

$$k_{th} = 2\sqrt{\frac{\rho}{h^3}}$$

  - With beamstrahlung (BS): $(I_b)_{th} = 10.2$ mA, $N_p = 1.9 \times 10^{13}$ at $k_{th}$=38500 m$^{-1}$ ($f_{th}$=1.8 THz)
  - Without BS: $(I_b)_{th} = 0.47$ mA, $N_p = 9 \times 10^{11}$ (scales as $\sigma_\delta^2\sigma_z$)

- RW impedance:
  - Copper + NEG coating
  - Instability analysis is performed according to [2,3]
  - With beamstrahlung (BS): $(I_b)_{th}$ = 0.61 m, $N_p = 1.16 \times 10^{12}$ at $k_{th}$= 19800 m ($f_{th}$=0.94 THz)
  - Without BS: $(I_b)_{th}$=0.029 mA, $N_p = 0.54 \times 10^{11}$ (scales as $\sigma_\delta^2\sigma_z$)

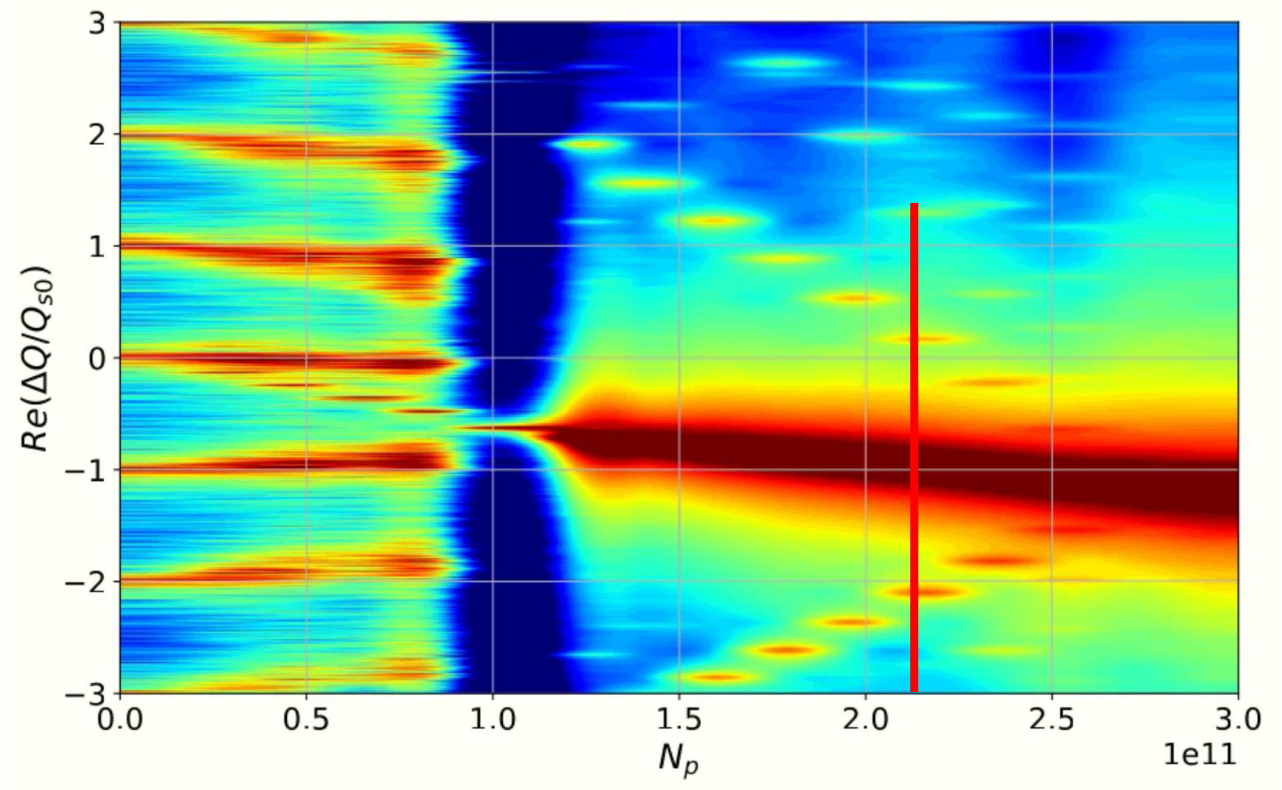

[1] Y. Cai, “Theory of microwave instability and coherent synchrotron radiation in electron storage rings”, IPAC’11.

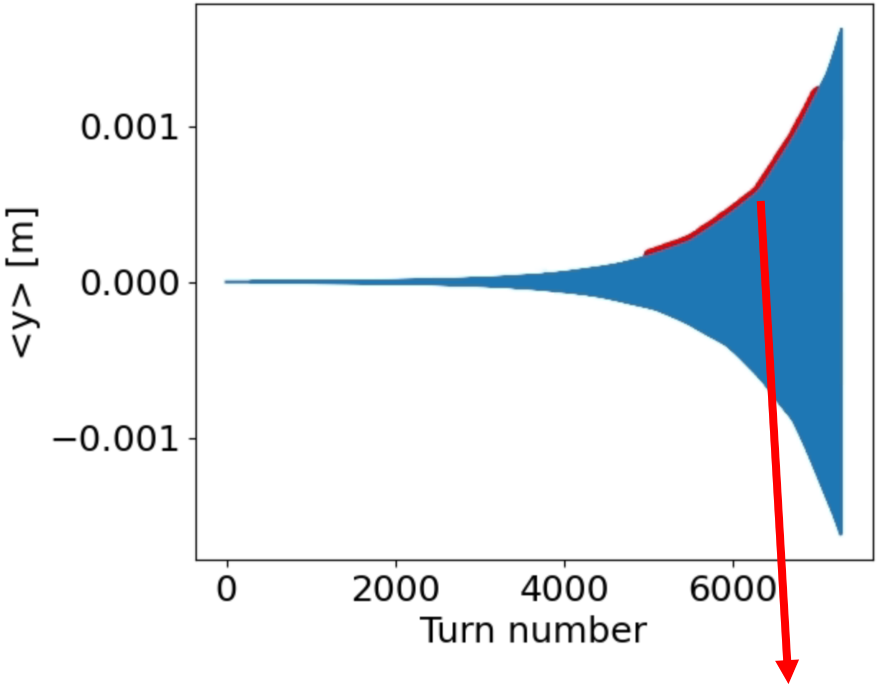
[2] D. Zhou et al., “Coherent synchrotron radiation instability in low-emittance electron storage rings”, To be published (2024).

[3] D. Zhou, et al., Phys. Rev. Accel. Beams **26**, 051002 (2023).

# Collective effects in transverse plane: TMCI

No chromaticity, no feedback system



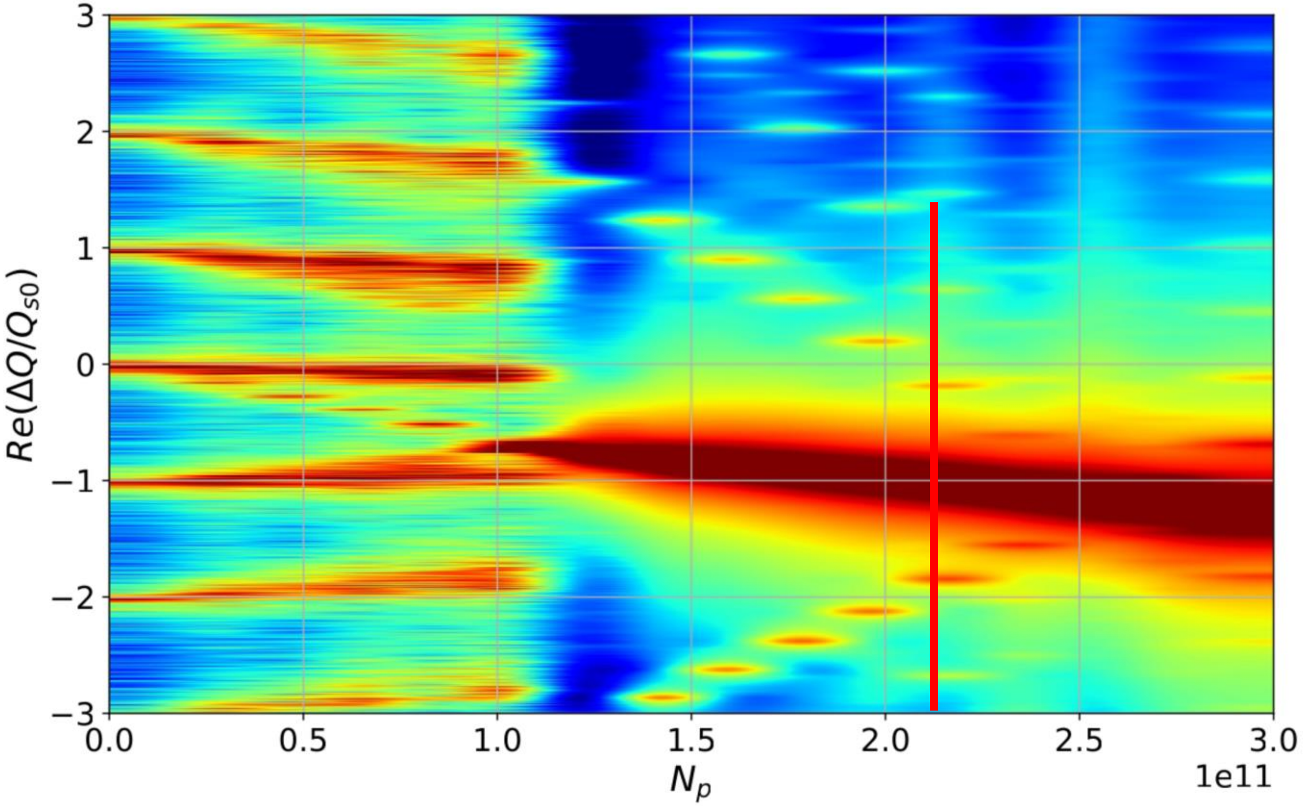

**Rise times:**

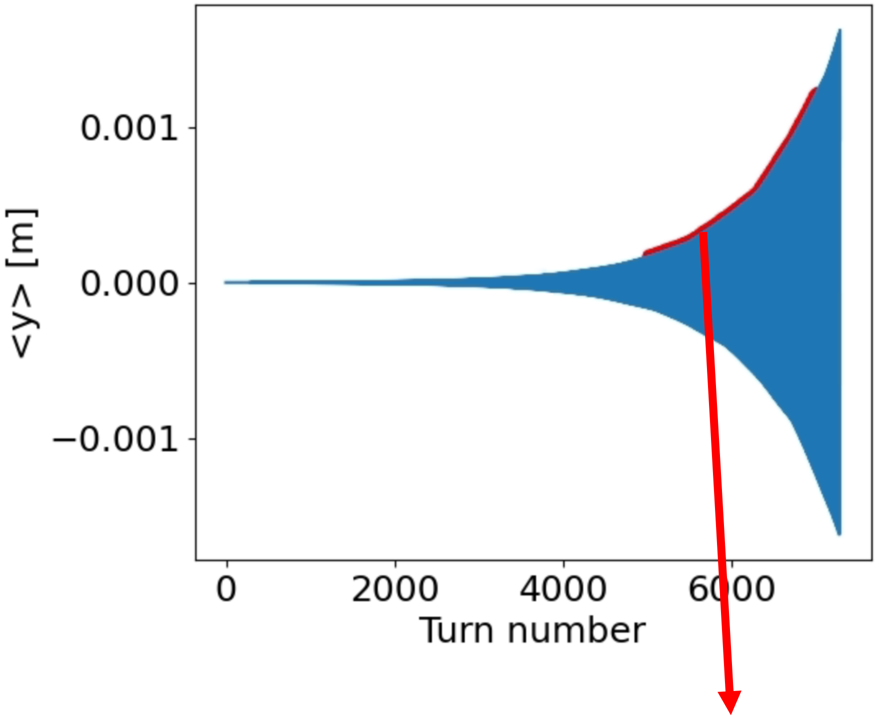
$N_p = 1.0 \times 10^{11} \rightarrow \simeq 300$ **ms**

$N_p = 1.2 \times 10^{11} \rightarrow \simeq 16.4$ **ms**

# Collective effects in transverse plane: TMCI

chromaticity = 2, no feedback system



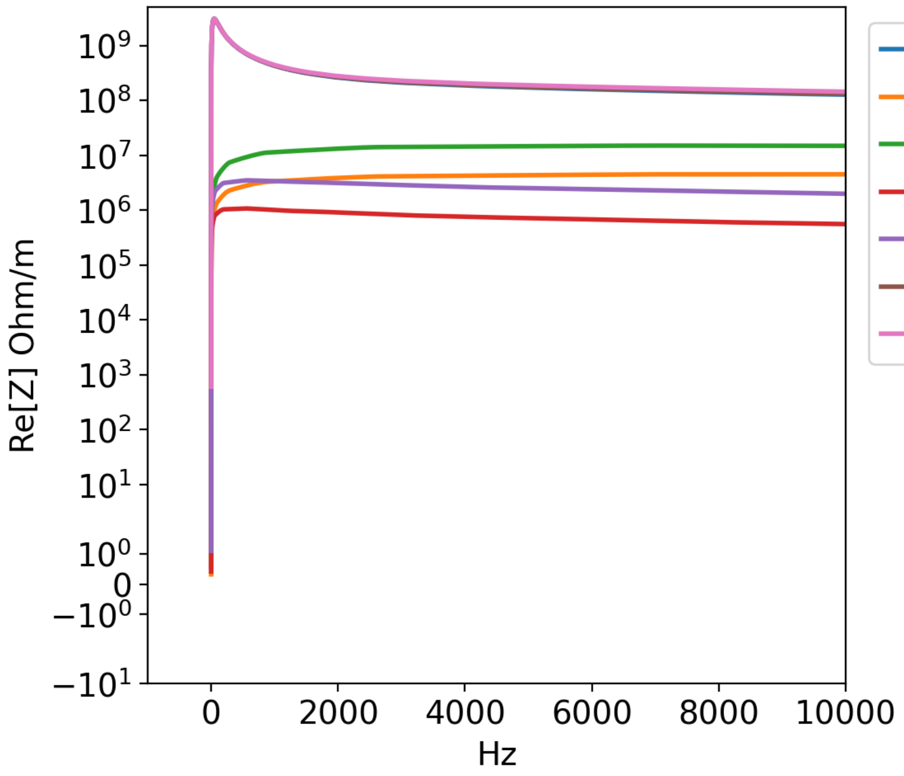




**Rise times:**

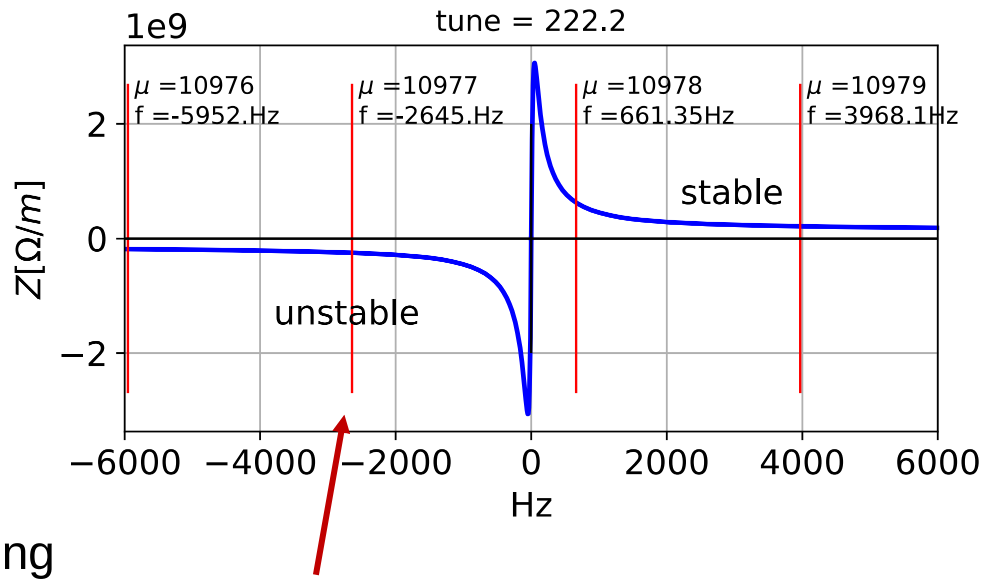
$N_p = 1.0 \times 10^{11}$ → **stable beam**

$N_p = 1.2 \times 10^{11} \rightarrow \simeq 17.6$ **ms**

# 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.

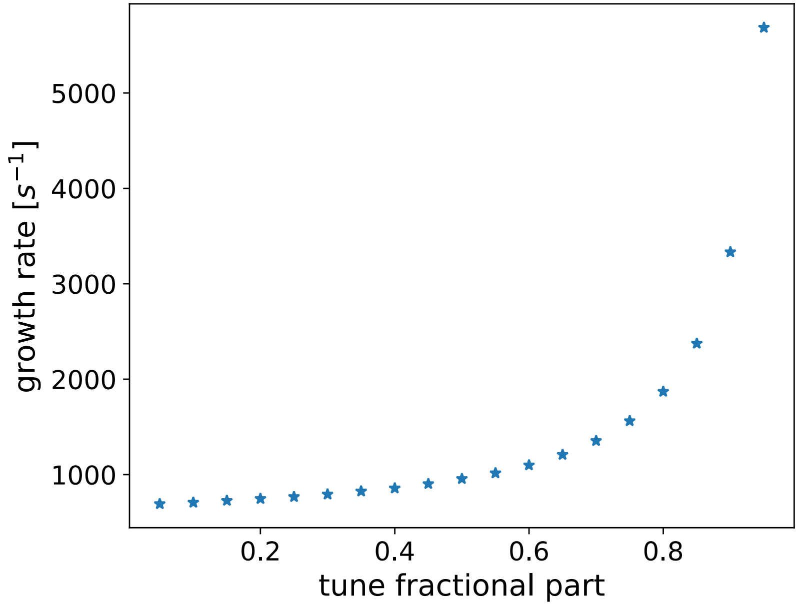


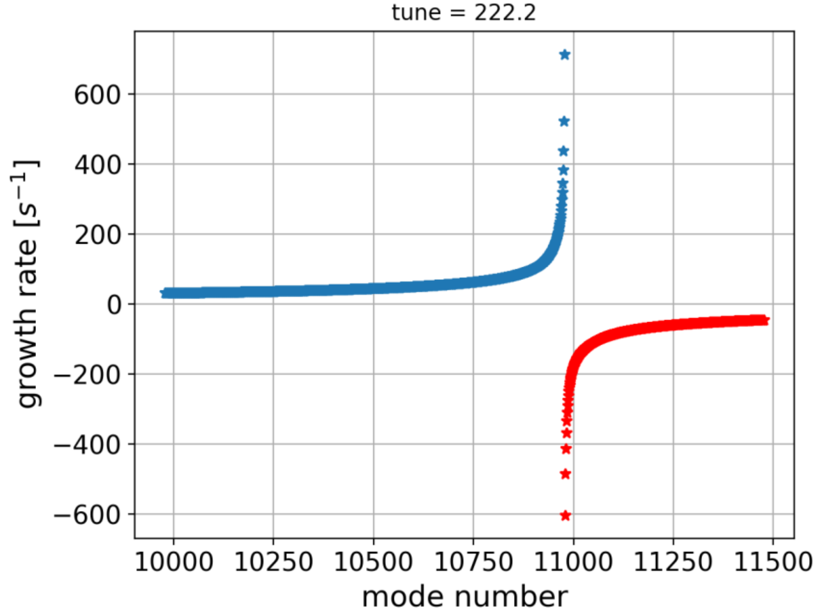

The most dangerous mode is that closest to the origin (with negative frequency)

*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

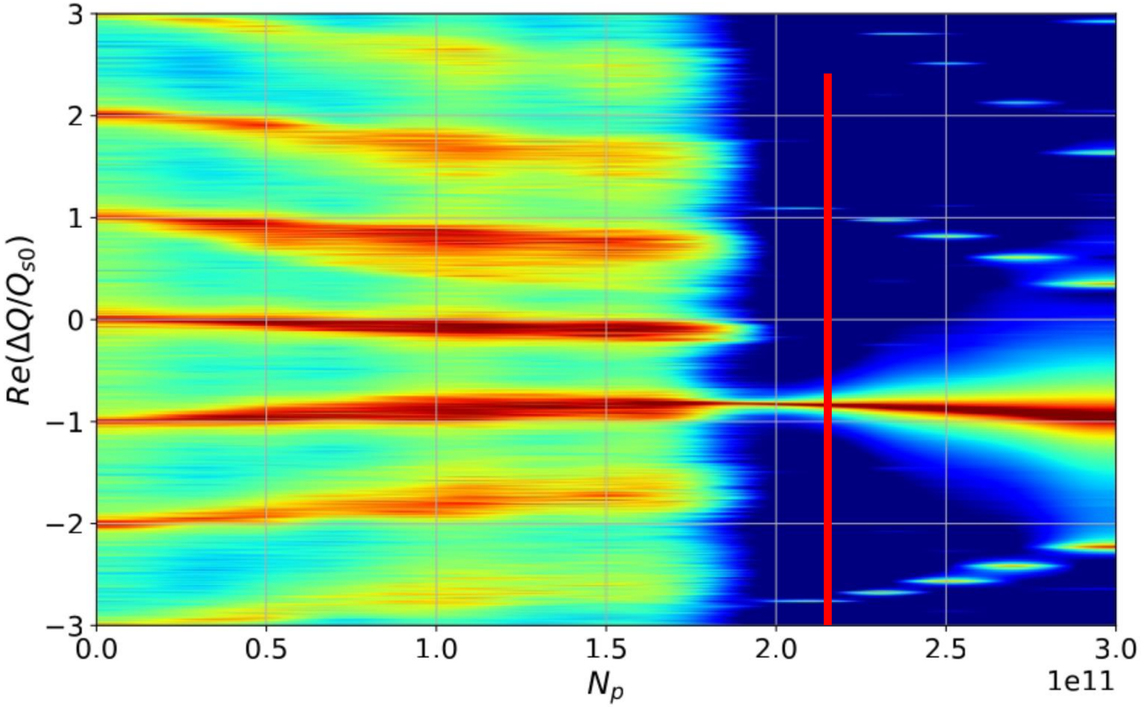
- The rise time of the most dangerous mode is about 1.3 ms (growth rate of about 750 $s^{-1}$).
- To suppress the TCBI, a bunch-by-bunch feedback system can be used.
- The damping time in the transverse plane should be 1 ms, similar to the damping time of the SuperKEKB feedback.
- However, 1 ms in FCC-ee 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.

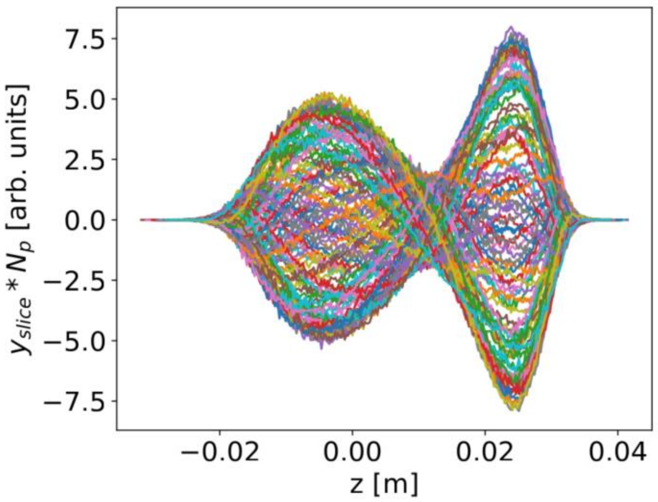


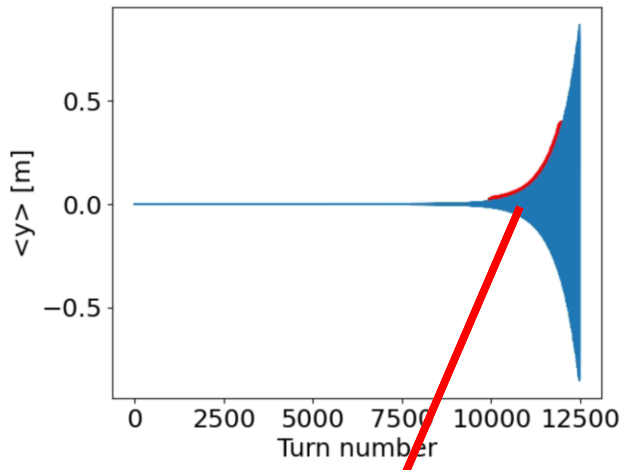



# Collective effects in transverse plane: TMCI

chromaticity = 0, feedback system on (4 turns)




The intra-bunch motion beyond the threshold shows an instability of the -1 mode. TMCI is suppressed: no shift of the 0 mode is observed with an (ideal) feedback system.

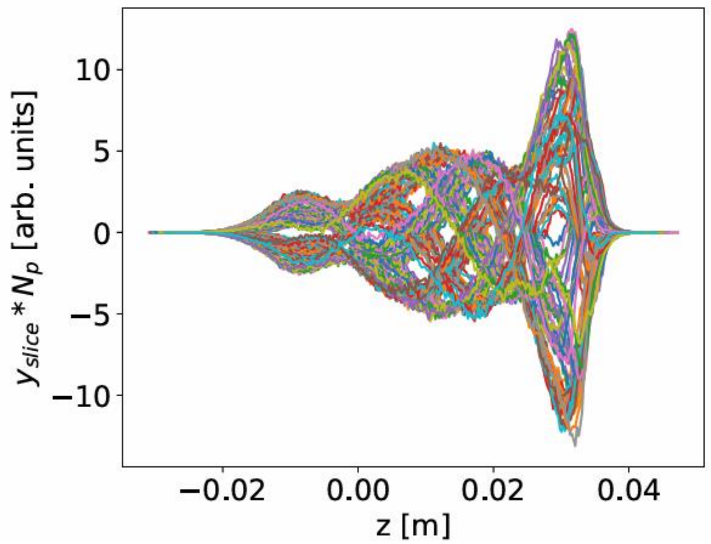
**Rise time:**

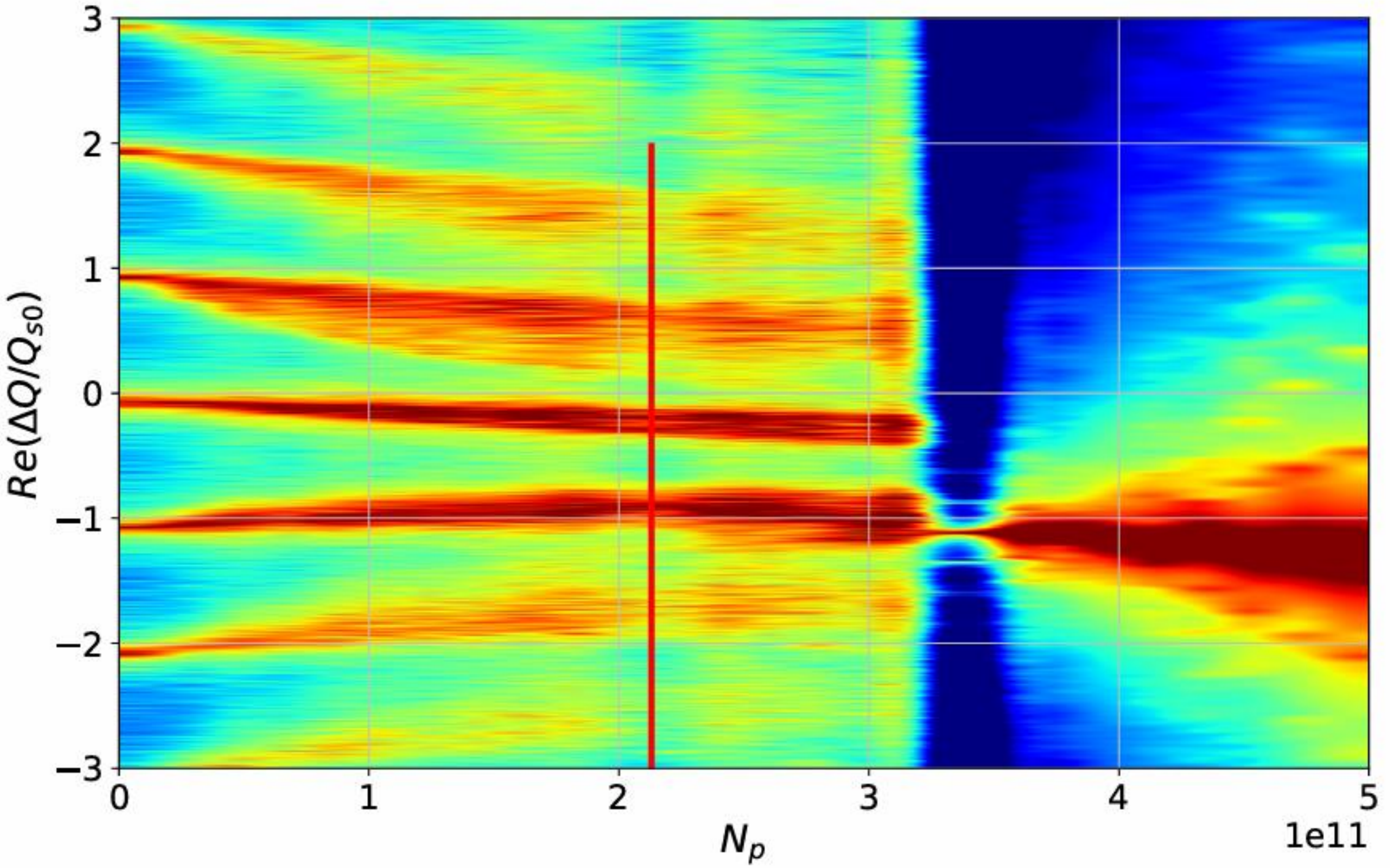
$N_p = 2.2 \times 10^{11} \rightarrow \simeq 187$ **ms**

# Collective effects in transverse plane: TMCI

chromaticity = 5
feedback system on (4 turns)

Intra-bunch motion at
$N_p = 3.4 \times 10^{11}$

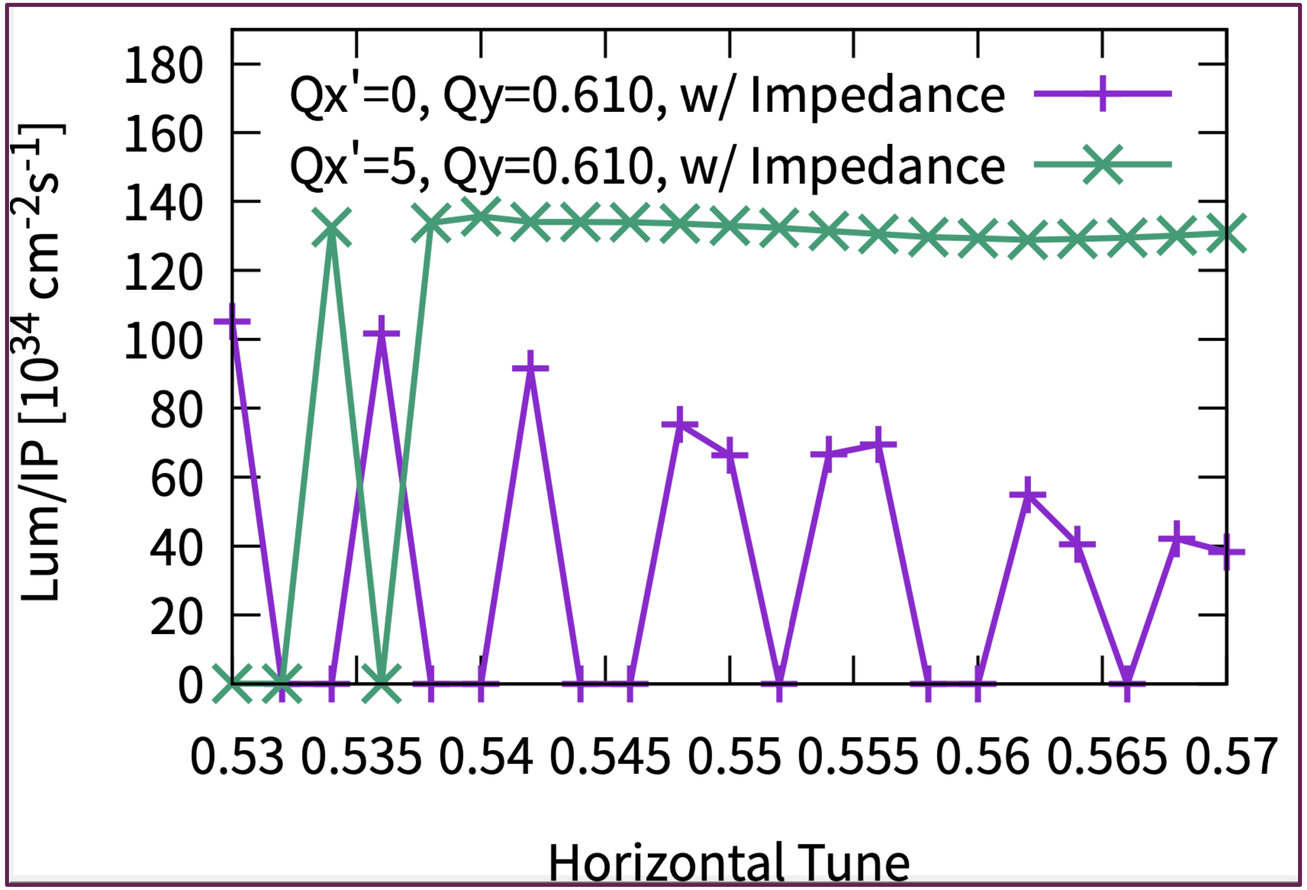


# Interplay between beam-beam and coupling impedance

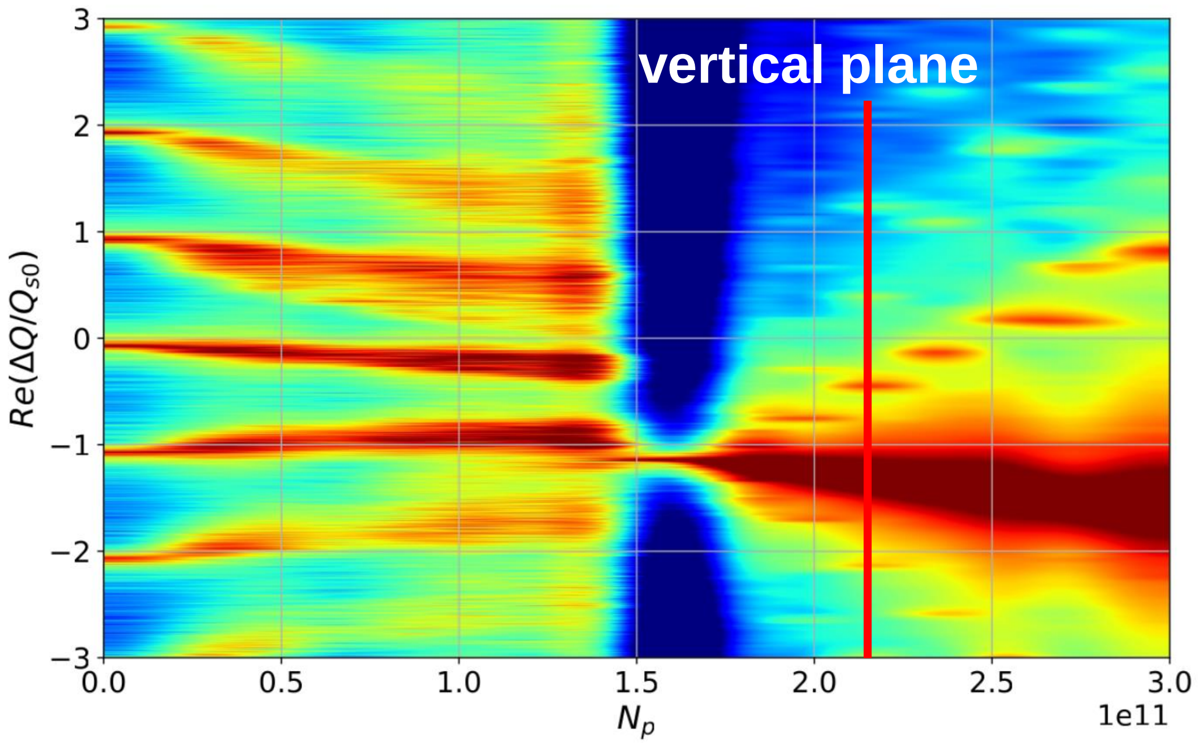
A positive chromaticity has a beneficial effect on the beam-beam. Self-consistent simulations show a luminosity per IP close to the nominal value of 141 x $10^{34}$ $cm^{-2}s^{-1}$ by properly choosing the collider working point.

Y. Zhang, IHEP, Beijing, China



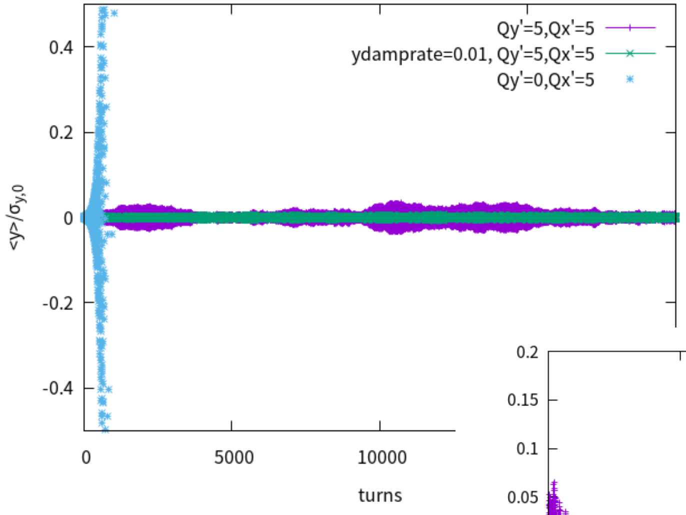
# Missing impedance and mitigation tools

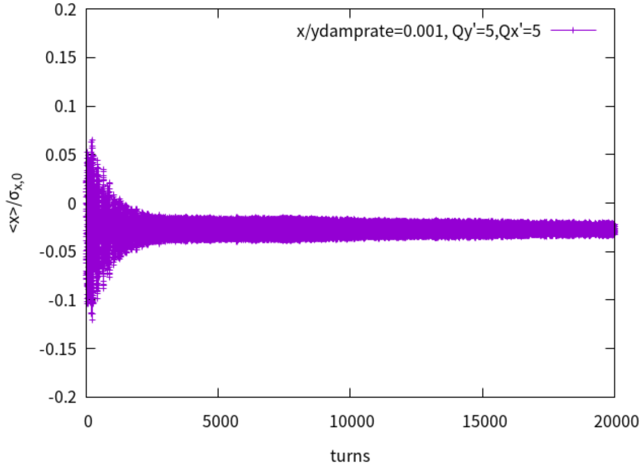
We still miss several impedance devices. Some of them could be important (as the geometric contribution of the collimators). If we double the total wake and impedance we have evaluated so far, despite feedback and chromaticity, the TMCI threshold will be below the nominal intensity.

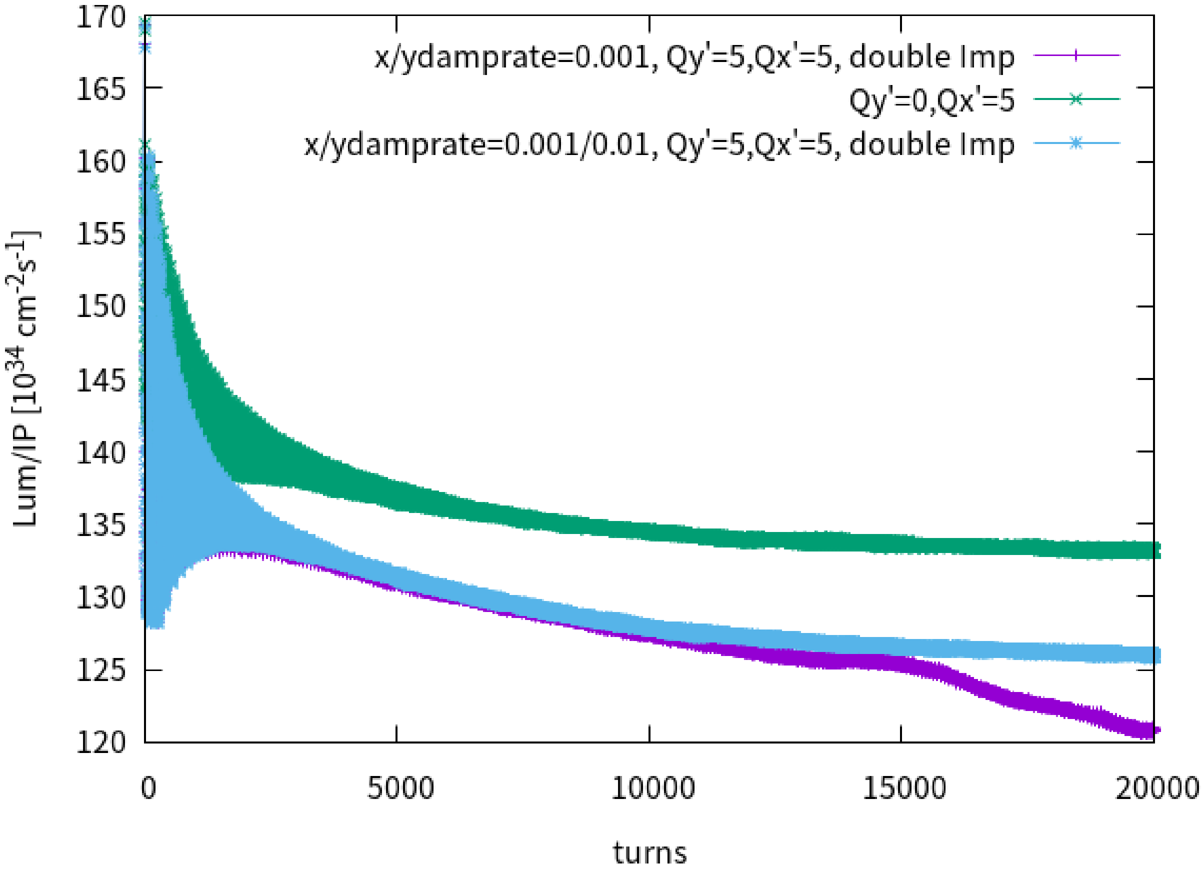


# Missing impedance and mitigation tools

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 …).

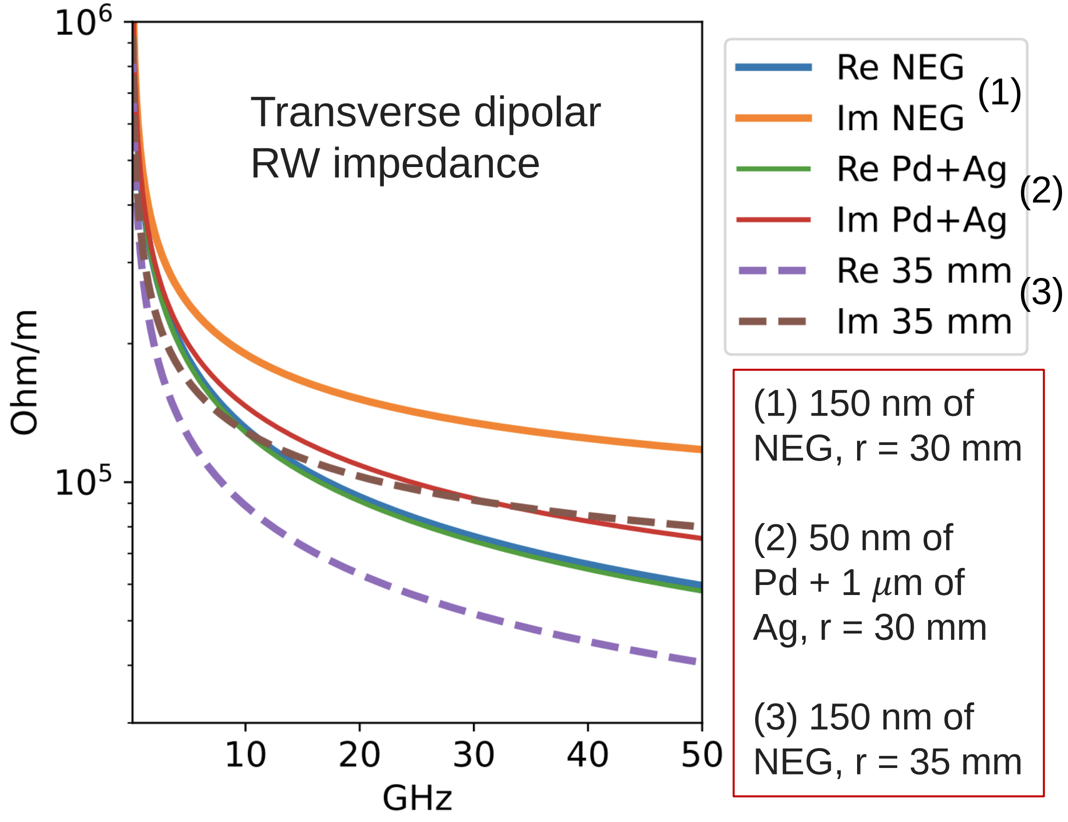


# Missing impedance and mitigation tools

A palladium (Pd) coating was recently studied at KEK. Compared with NEG coating, for example, it exhibited ultra-low photon stimulated desorption yields and a lower resistivity (https://doi.org/10.1016/j.vacuum.2023.112370)

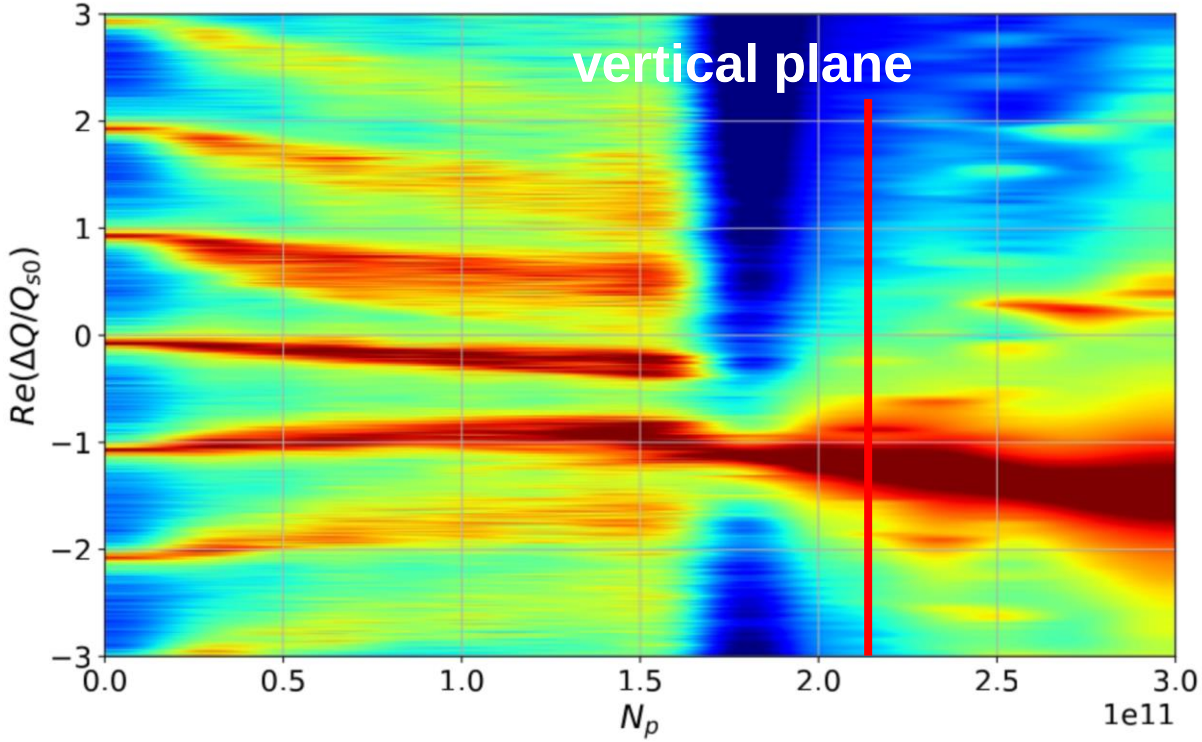



(1) 150 nm of NEG, r = 30 mm

(2) 50 nm of Pd + 1 $\mu$m of Ag, r = 30 mm

(3) 150 nm of NEG, r = 35 mm

In the worst scenario with twice the wake, feedback system on and chromaticity = 5, this coating helps a bit in mitigating the instability: the threshold is now at about $N_p = 1.8 \times 10^{11}$ instead of $1.6\times 10^{11}$.



# Missing impedance and mitigation tools

- In the previous cases with the feedback system turned on, we have always considered an ideal pure resistive feedback.

- What happens to the instability threshold if we also include a reactive term? … This is to be investigated

- With the bunch-by-bunch feedback system turned on, the instability is no longer of the TMCI type, but the '-1' mode instability appears.

- If we damp this '-1' mode instability, can we further increase the instability threshold?

- At SuperKEKB, by properly playing with the filter coefficients they managed to suppress the -1 mode instability (at least up to the nominal single bunch population).

- Are there other possibilities? Is it possible to develop a head-tail feedback system?

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*August 7-10, 2018, Nagaoka, Japan*

**PASJ2018 THP089**

# Missing impedance and mitigation tools

**CHALLENGE TO HEAD-TAIL FEEDBACK FOR MODE COUPLING INSTABILITY**

中村　剛#
Takeshi Nakamura#
Japan Synchrotron Radiation Research Institute

Paper in Japanese, abstract and figures in English

*Abstract*

Mode-coupling instability, or strong head-tail instability, is the single bunch instability that limits stored bunch current of electron storage rings. The instability is controlled by conventional transverse feedback that controls center-of-mass motion of bunches, and the bunch current reached by the feedback up to several times more. However, the increase of the gain of feedback leads to the instability of feedback itself and further increase of the bunch current is not easy. To overcome this situation, we propose the head-tail feedback that controls head-tail motion of bunches with a head-tail kicker that proposed by the author before, and a head-tail position detector that proposed in this report.

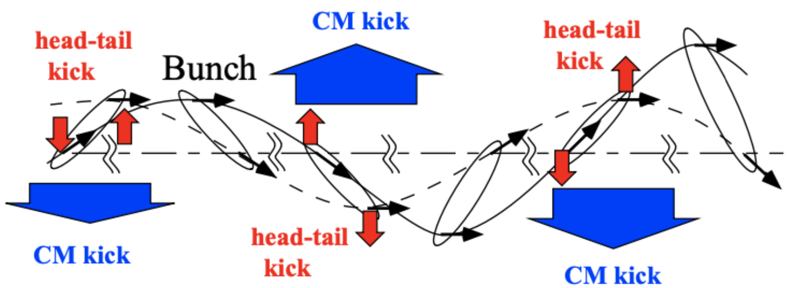


Figure 1: Head-tail motion, center of mass (CM) kick, and head-tail kick.

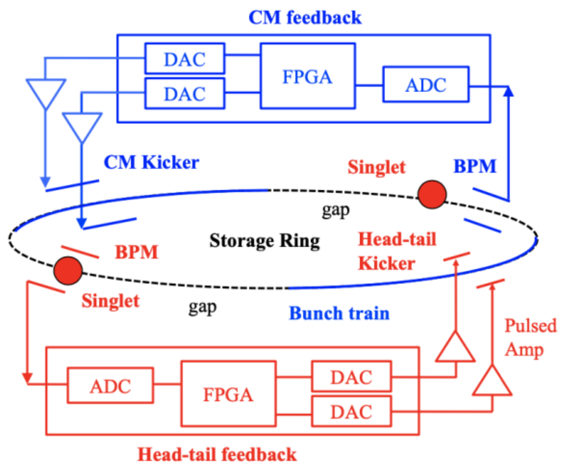


Figure 2: Center-of-mass (CM) feedback and head-tail feedback for hybrid filling.

See also
I.FAST Workshop 2024 on Bunch-by-Bunch Feedback Systems and Related Beam Dynamics

"Bunch Pitch/Yaw Monitor Development and Proposal of Pitch/Yaw Feedback"

Takeshi Nakamura (KEK)

https://indico.scc.kit.edu/event/3742/contributions/15197/

# Conclusions

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

- The collective effects play an important role in the machine’s stability, and their understanding necessitates ongoing reassessment.

- 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**