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Overview of collective effects for the main rings

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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 (Feasibility Study Report)
- Wakefields and coupling impedance $\rightarrow$ see also presentations of C. Zannini and D. Gibellieri for additional details
- Single bunch effect in longitudinal plane: PWD
- Transverse coupled bunch instability and feedback system
- Transverse single bunch instability (TMCI, …) under different scenarios

FCC-ee main parameters (from the Feasibility Study Report)

For the study of collective effects, we considered the Z-pole having the lower beam energy and the higher beam current than the other machine configurations

We focused our study on the single bunch beam dynamics

Single bunch population is $N_p = 2.18 \times 10^{11}$

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658509			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0387	0.369	1.86	9.93
SR power / beam	[MW]	50			
Beam current	[mA]	1292	135	26.8	5.0
Colliding bunches / beam		11200	1856	300	60
Colliding bunch population	[10^{11}]	2.18	1.38	1.69	1.58
Hor. emittance at collision ε_x	[nm]	0.71	2.16	0.66	1.65
Ver. emittance at collision ε_y	[pm]	2.1	2.0	1.0	1.32
Lattice v. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.87	1.20	0.57	0.82
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.52	28.67	7.52	7.57
Arc sext families		73		144	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		218.168 / 222.200	218.185 / 222.220	398.150 / 398.220	394.148 / 390.218
Chromaticities $Q'_{x/y}$		+5 / +5	0 / +5	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.115	0.069 / 0.105	0.102 / 0.176	0.152 / 0.186
Bunch length (SR/BS) σ_z	[mm]	5.15 / 15.2	3.46 / 5.28	3.26 / 5.59	1.91 / 2.34
RF voltage 400/800 MHz	[GV]	0.0885 / 0	1.00 / 0	2.09 / 0	2.10 / 9.20
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.788026			
Synchrotron tune Q_s		0.0310	0.0809	0.0334	0.0892
Long. damping time	[turns]	1179	218	65.4	19.4
RF acceptance	[%]	1.21	3.32	2.06	3.07
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.9	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	60	55	50	40
Beam-beam ξ_x/ξ_y [2]		0.0023 / 0.098	0.013 / 0.129	0.0108 / 0.130	0.066 / 0.144
Piwinski ang. $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		25.8	3.6	6.6	0.91
Lifetime (q + BS + lattice)	[sec]	5200	4500	6000	6300
Lifetime (lum) [3]	[sec]	1330	960	600	640
Luminosity / IP /10^{34}	[/cm^{2}s]	144	20	7.5	1.45

Wakefields and coupling impedance

For the impedance model, we have evaluated the contribution of:

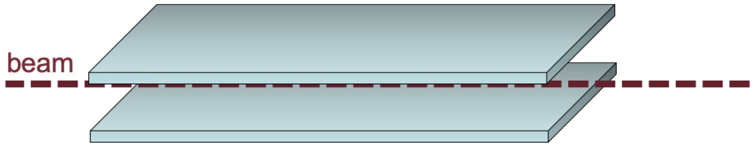
- RW (30 mm) plus NEG (150 nm)
- A new cavity system: 132 two-cell cavities instead of 56 single-cell cavities. We have also increased the number of tapers from the beam pipe to the cryomodule from 14 to 33 double tapers.
- New design (and number) of BPMs (10000 vs previous 7000).

Some comments:

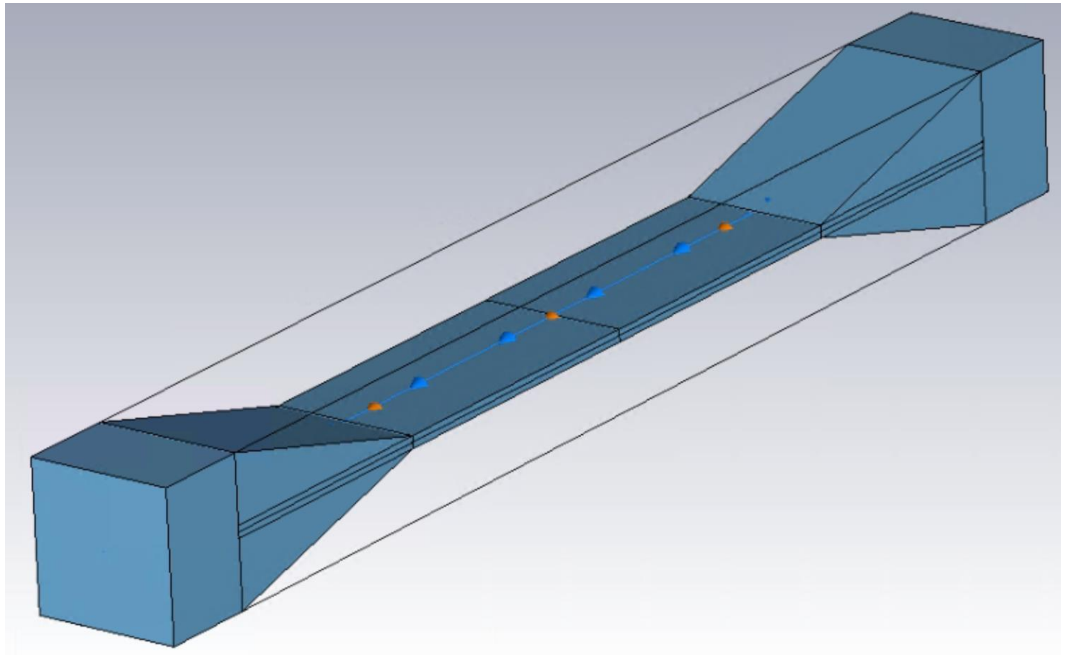
- RW of the beam pipe is the largest impedance source so far.
- The collimation system represents, in the transverse plane, the second largest impedance source. This is another great challenge for the collective effects, and the work is still in progress.

Wakefields and coupling impedance: collimation system

We have evaluated the RW contribution of the collimators, weighted by the local beta function, by considering parallel plates



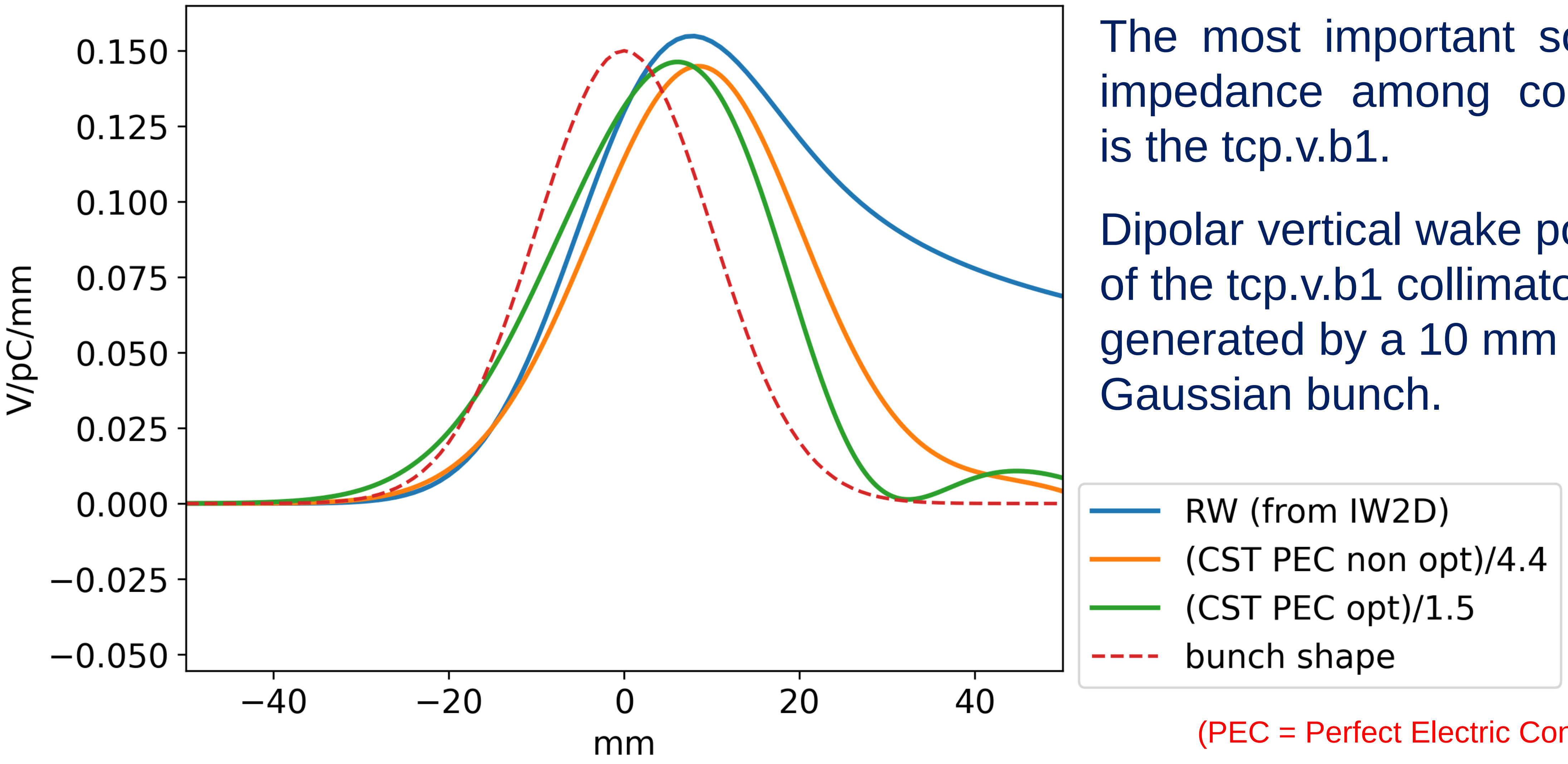
For the geometrical contribution, a first estimation considered a simplified model.



The length of the tapers is used as a parameter for the impedance optimization. Two angles were used: 15° (non-optimized angle) and 2.5° (optimized angle).

The current collimation model used for beam dynamics simulations uses the version: FCCee_z_v23_coll_table_TCTs (2023)

Wakefields and coupling impedance: collimation system



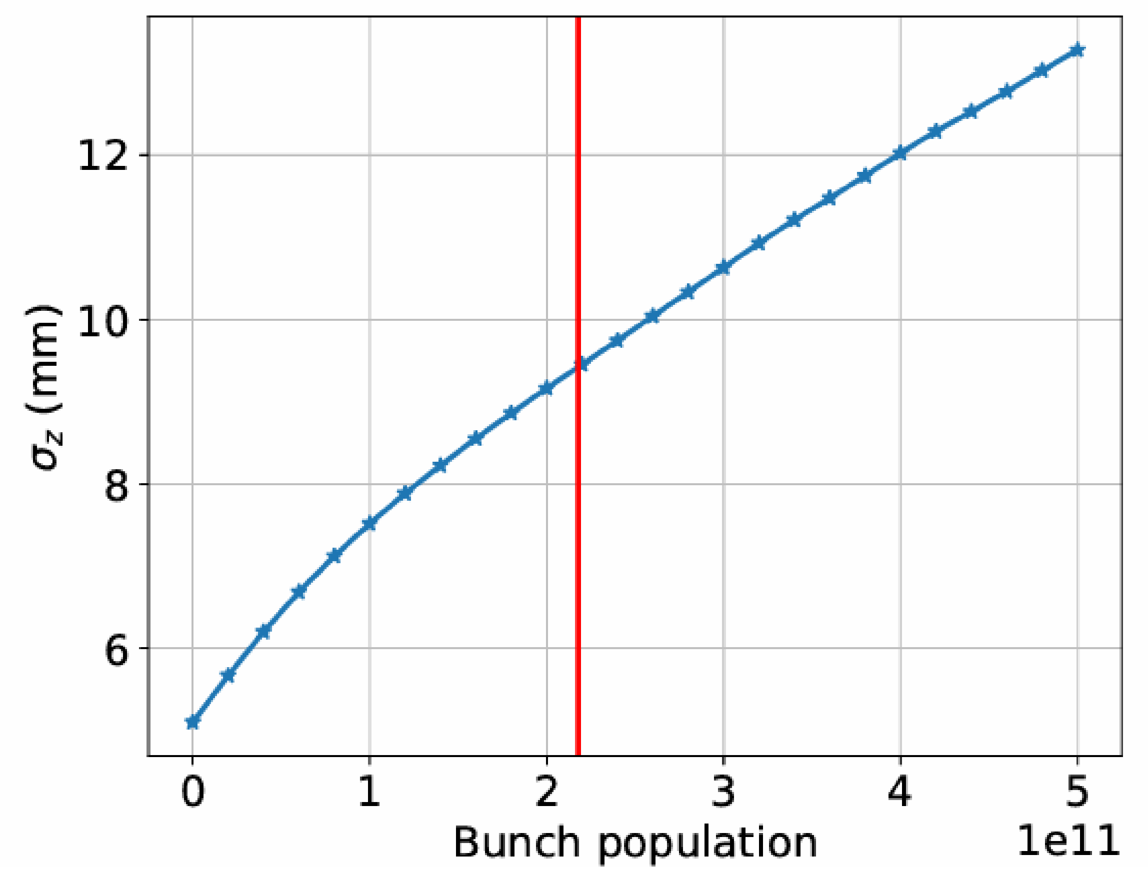
The most important source of impedance among collimators is the tcp.v.b1.

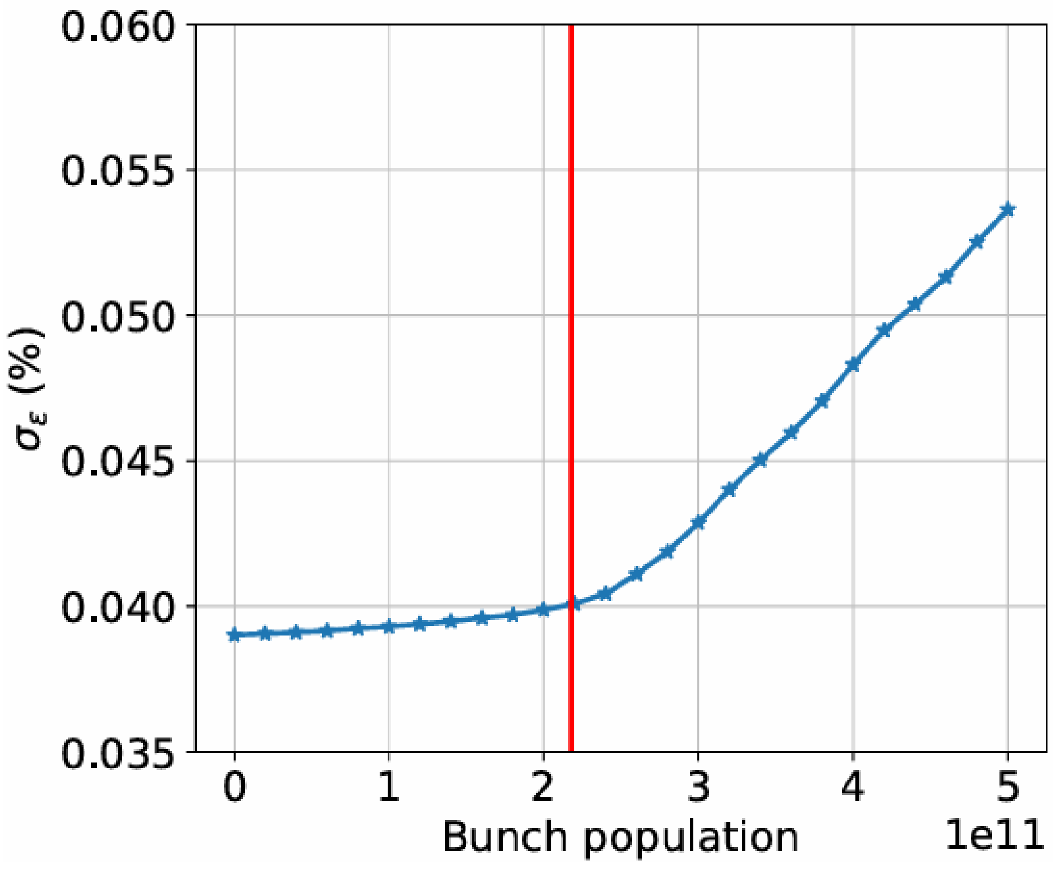
Dipolar vertical wake potential of the tcp.v.b1 collimator generated by a 10 mm Gaussian bunch.

(PEC = Perfect Electric Conductor)

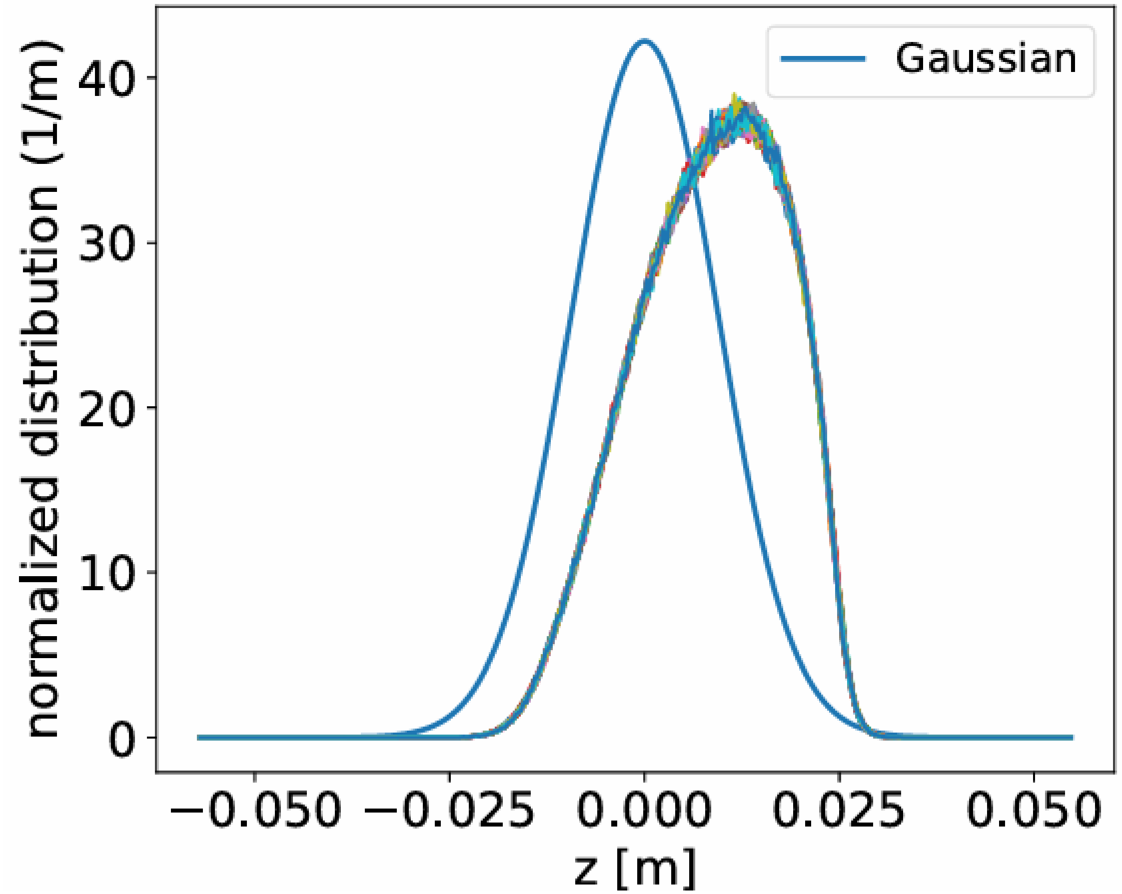
PWD in the longitudinal plane

For beam dynamics studies and collective effects evaluations, we have used the wake potential of a 0.4 mm Gaussian bunch as a pseudo-Green function.





PWD in the longitudinal plane

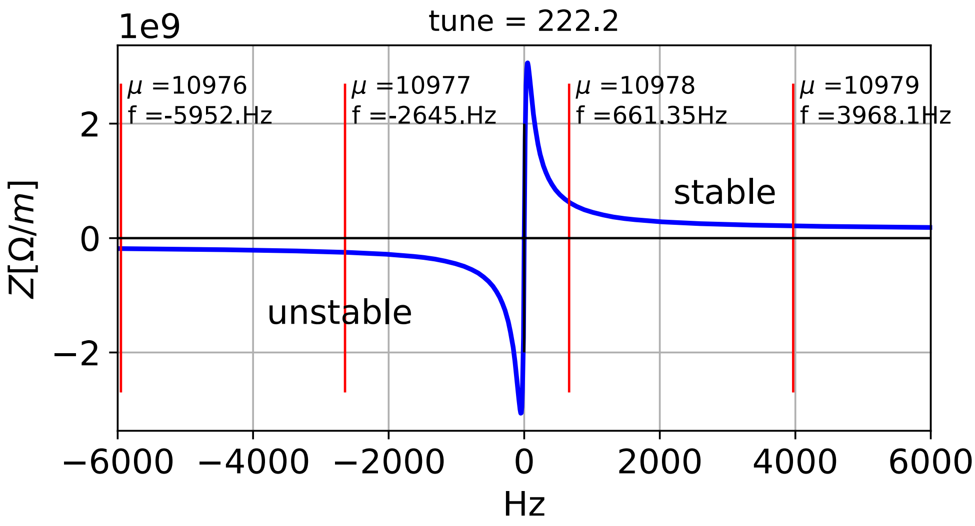


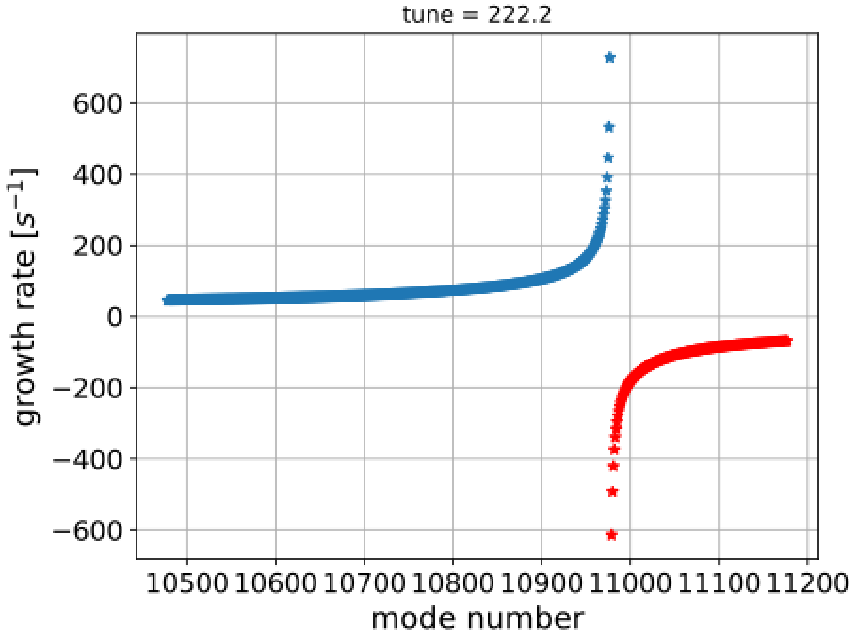
Bunch shape due to the potential well distortion at the nominal intensity of 2.18e11 ppb

Transverse coupled bunch instability and feedback system

The TCBI is evaluated by considering 11200 Gaussian bunches with rigid dipolar oscillations, and the real part of the dipolar impedance (RW) at the lowest frequencies.

The growth rate of the instability depends on the fractional part of the tune. For $Q_y = 222.2$ the rise time of the most dangerous mode is about 1.3 ms, corresponding to about 4 turns.





Observe that many coupled bunch modes are excited.

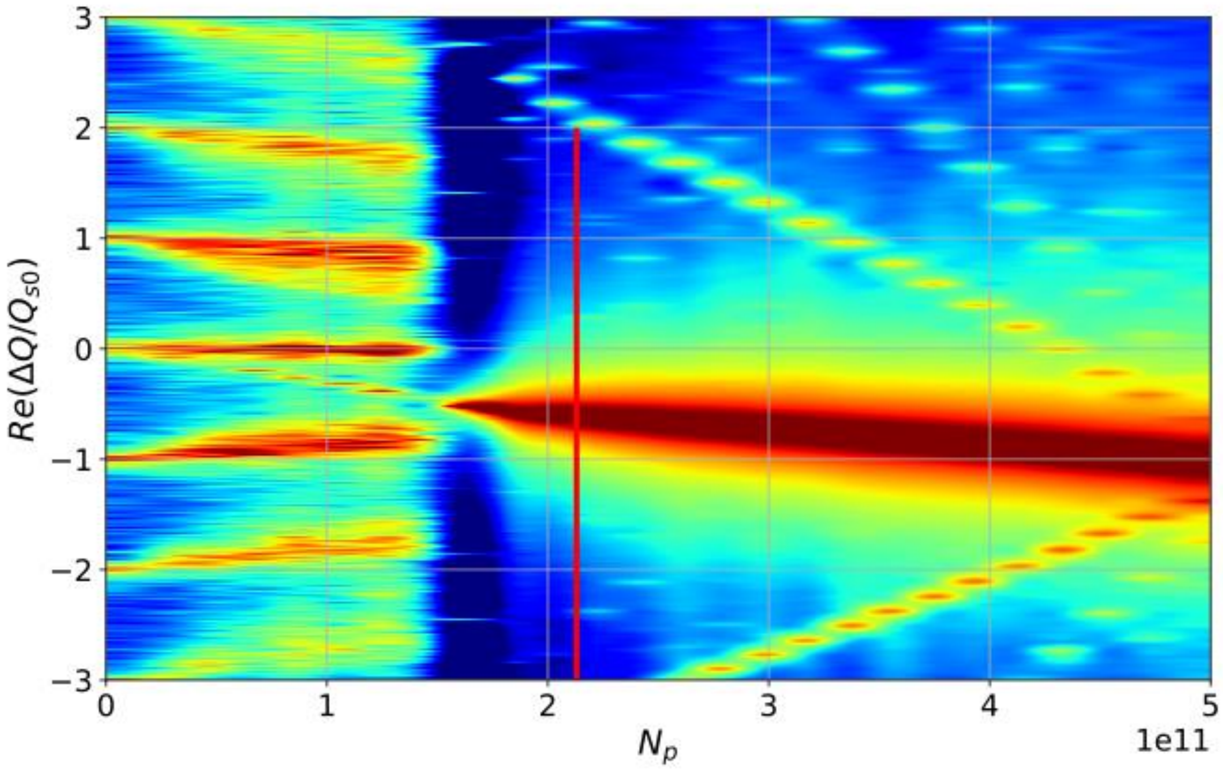
A feedback system is necessary to suppress the TCBI.

The damping time of the feedback system in the transverse plane should be about 1 ms.

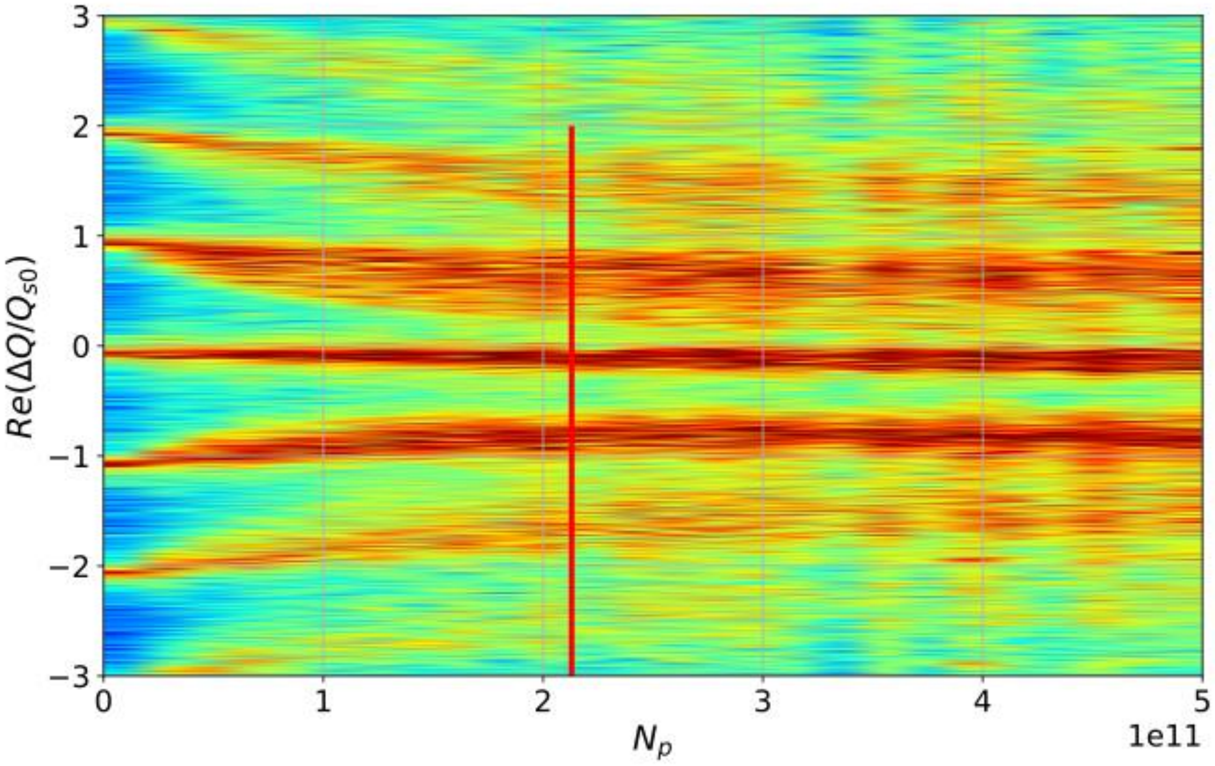
Transverse single bunch instability under different scenarios

Wake without collimators

no chromaticity, no feedback system



chromaticity = 5 - feedback system on (4 turns)

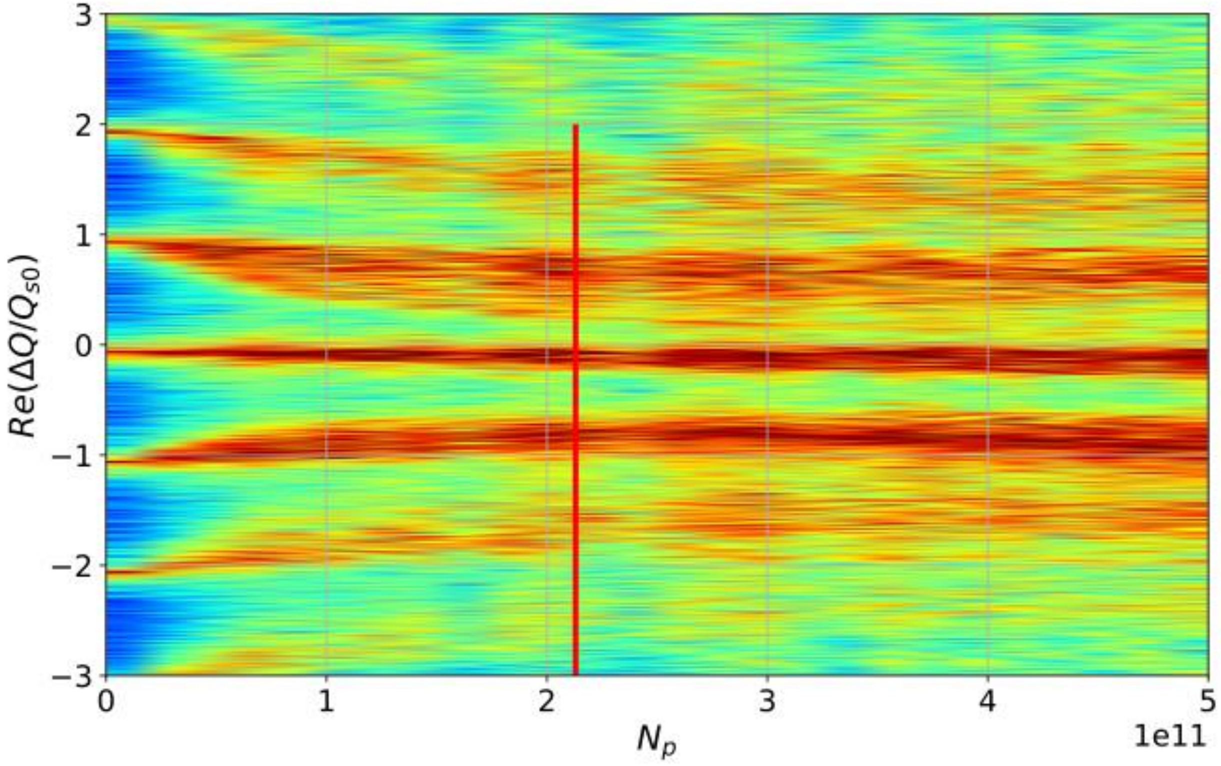


Transverse single bunch instability under different scenarios

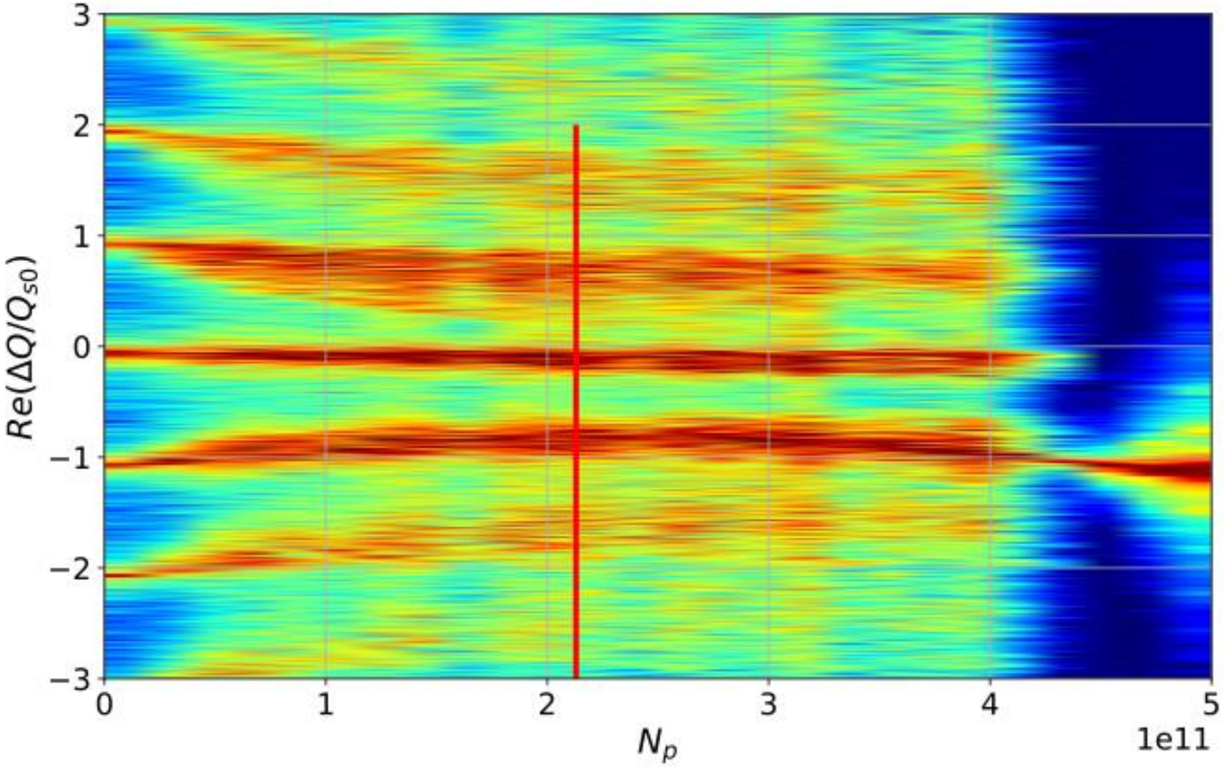
Wake without collimators' geometric contribution (only RW)

chromaticity = 5 - feedback system on (4 turns)

x-plane



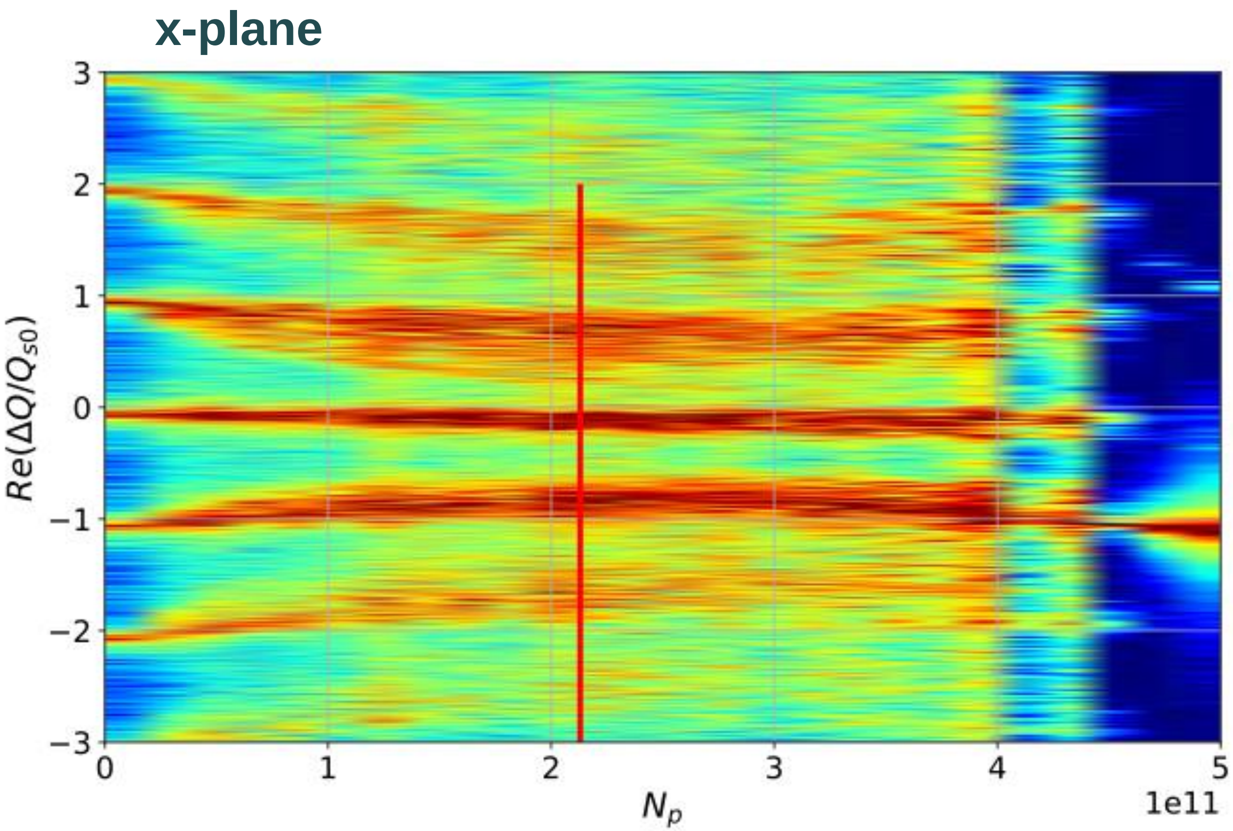
y-plane

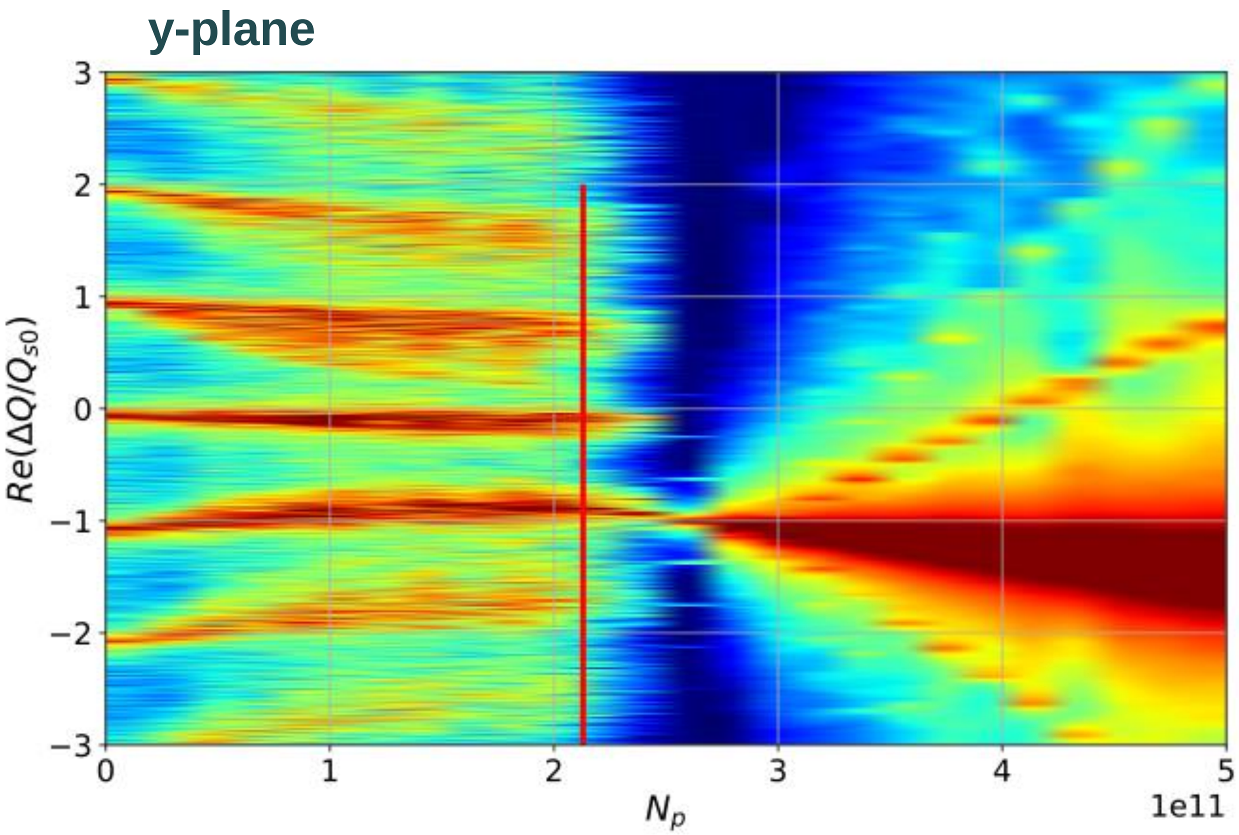


Transverse single bunch instability under different scenarios

Wake with optimised collimators' geometry (geometric part = 1.5*RW part)

chromaticity = 5 - feedback system on (4 turns)





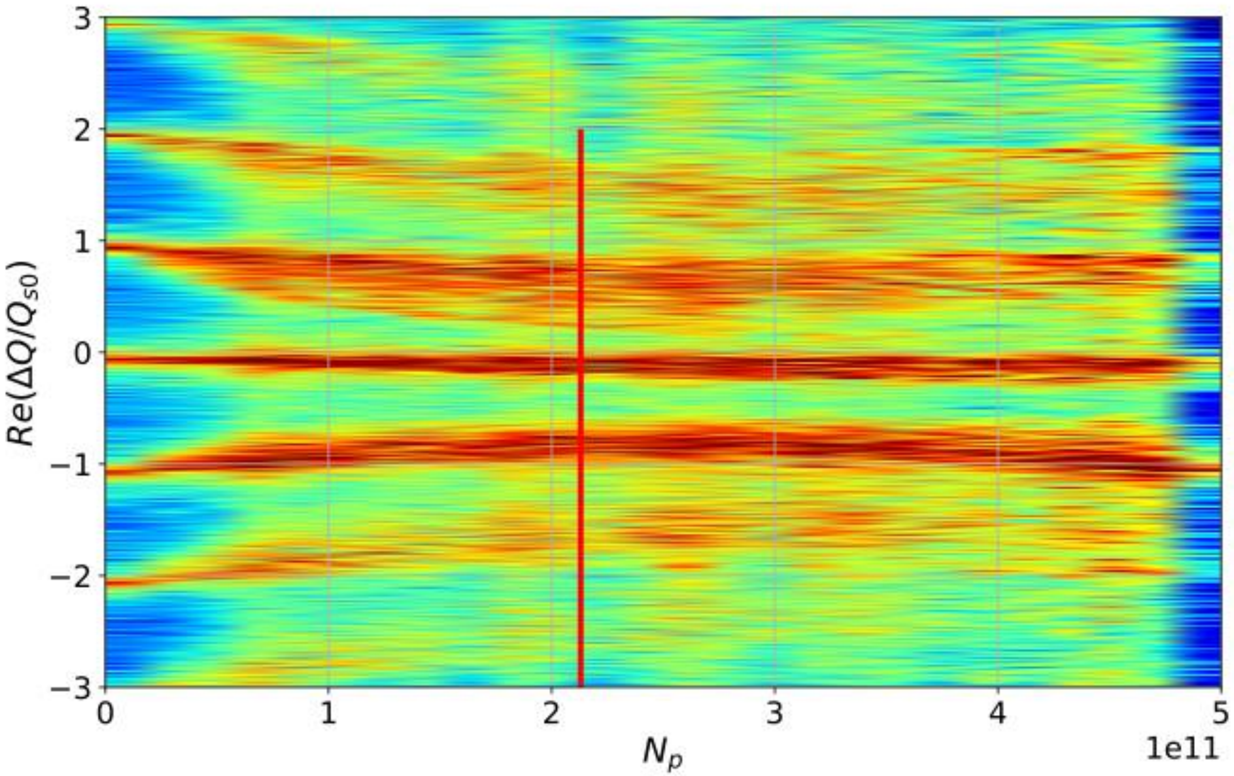
Transverse single bunch instability under different scenarios

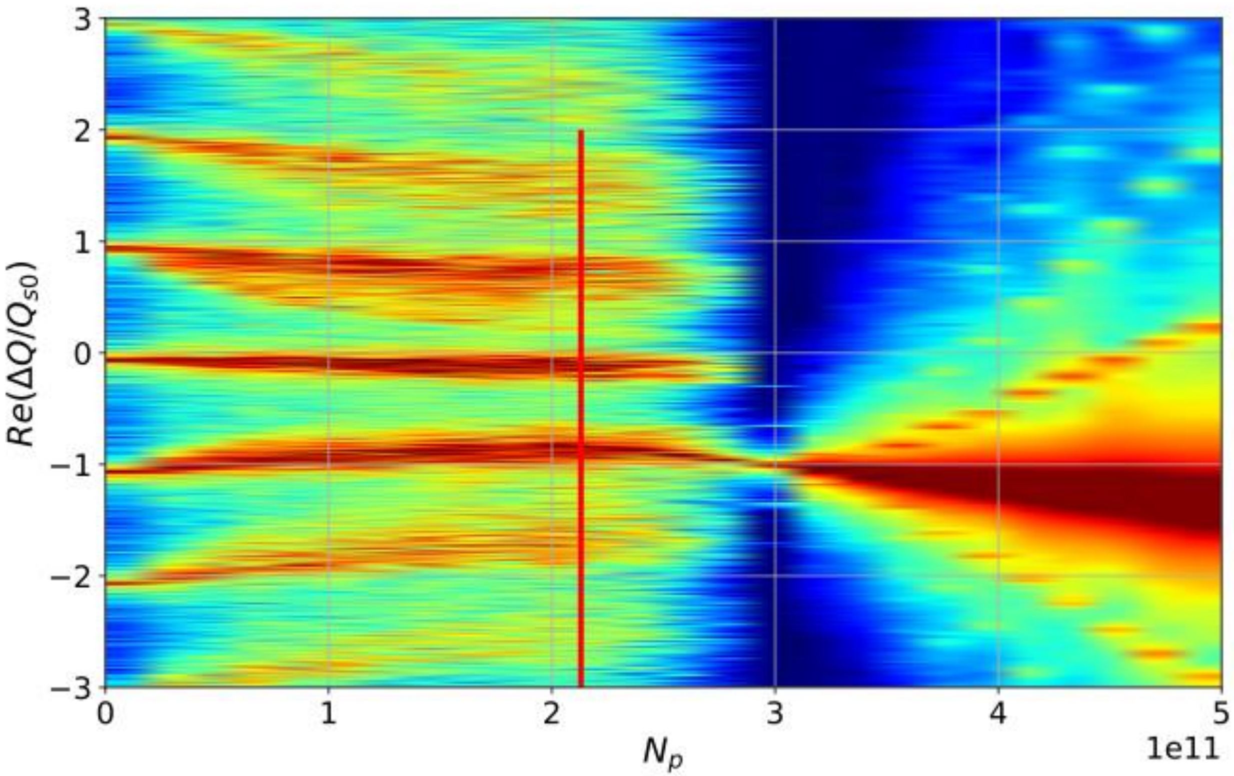
Wake with reduced collimators' geometric contribution (geometric part = RW part)

chromaticity = 5 - feedback system on (4 turns)

x-plane

y-plane



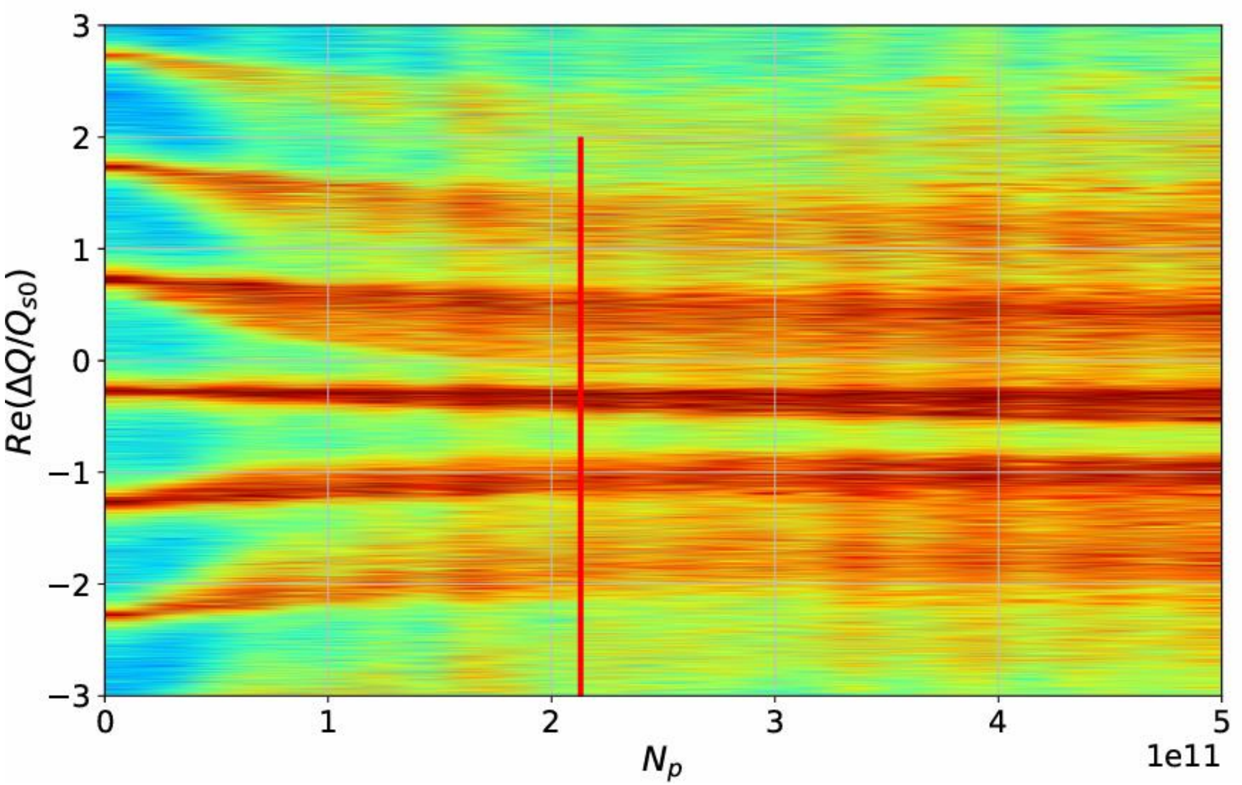


Transverse single bunch instability under different scenarios

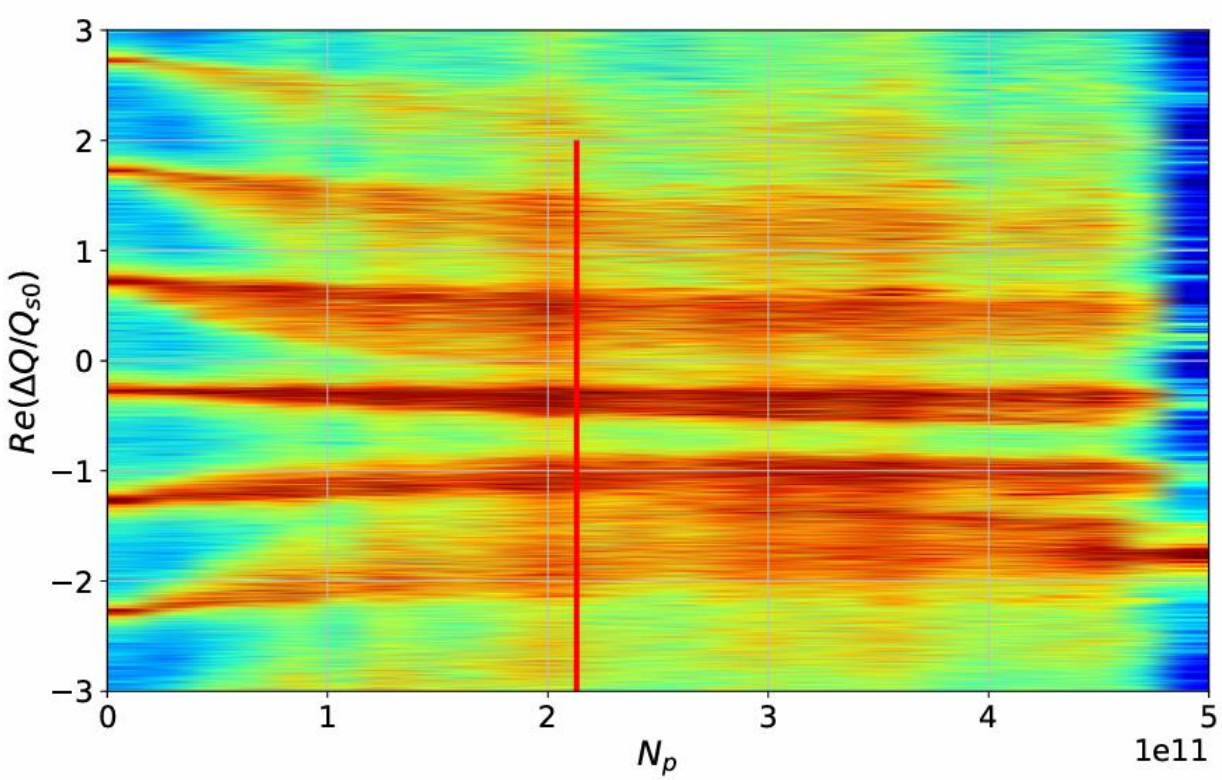
Wake with reduced collimators' geometric contribution (geometric part = RW part)

chromaticity = 20 - feedback system on (4 turns)

x-plane



y-plane

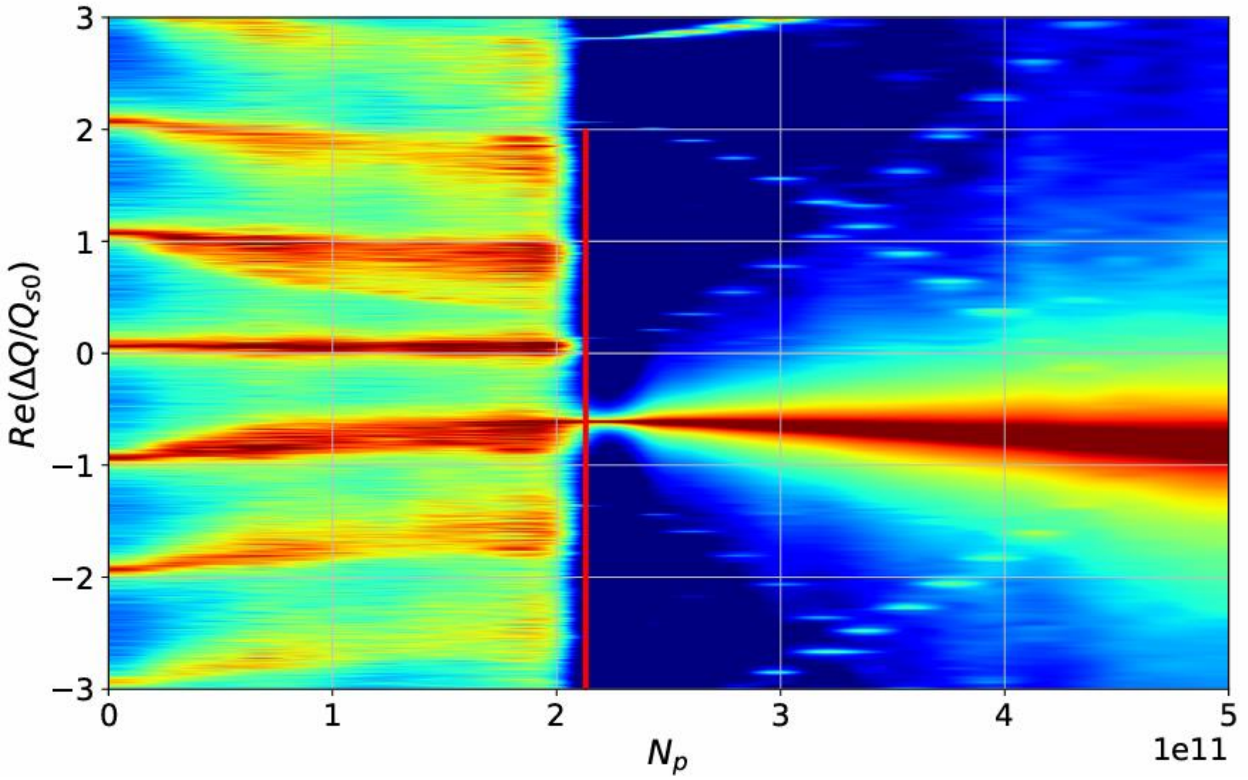


Transverse single bunch instability under different scenarios

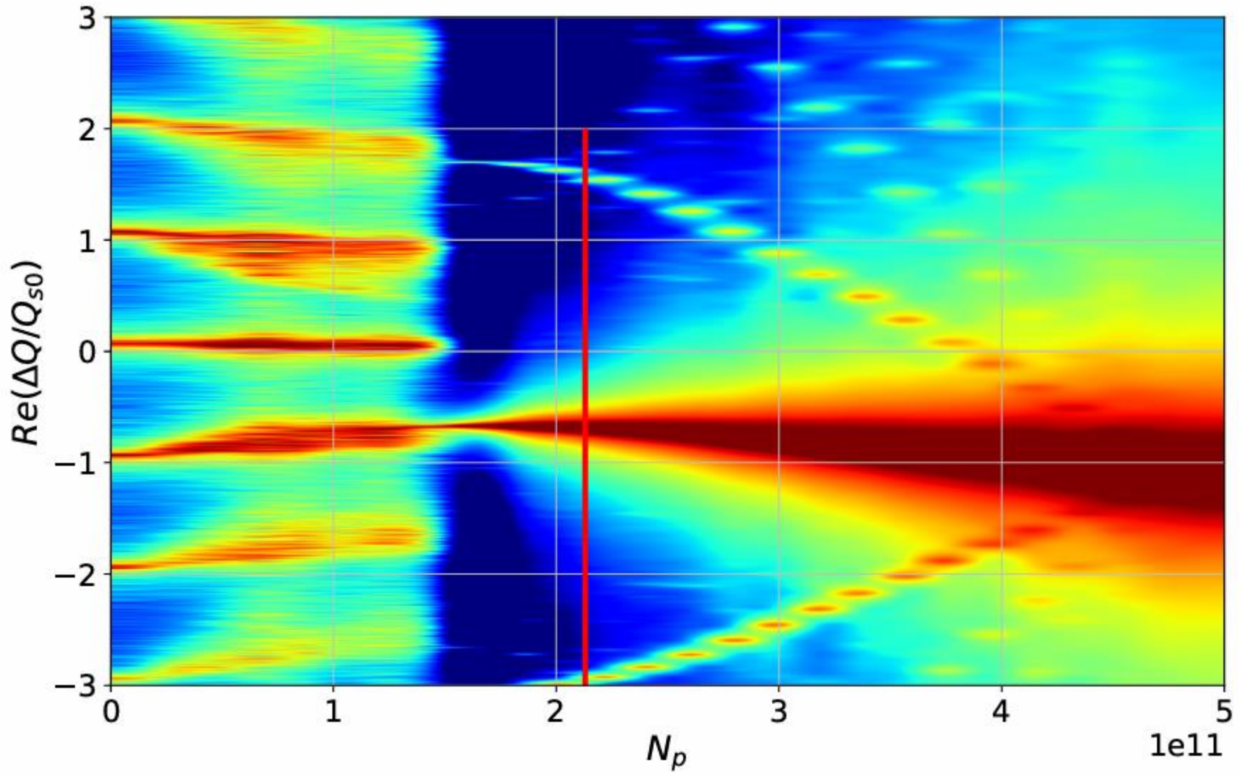
Wake with reduced collimators' geometric contribution (geometric part = RW part)

chromaticity = -5 - feedback system on (4 turns)

x-plane



y-plane

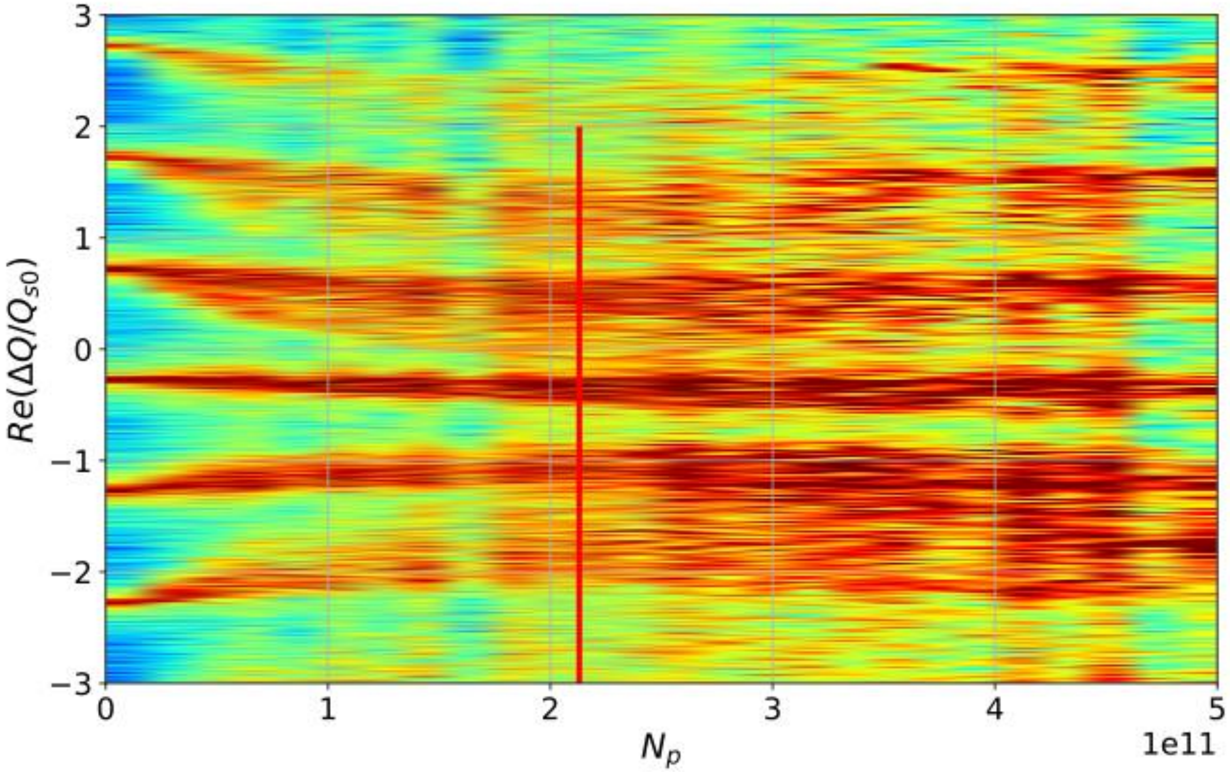


Transverse single bunch instability under different scenarios

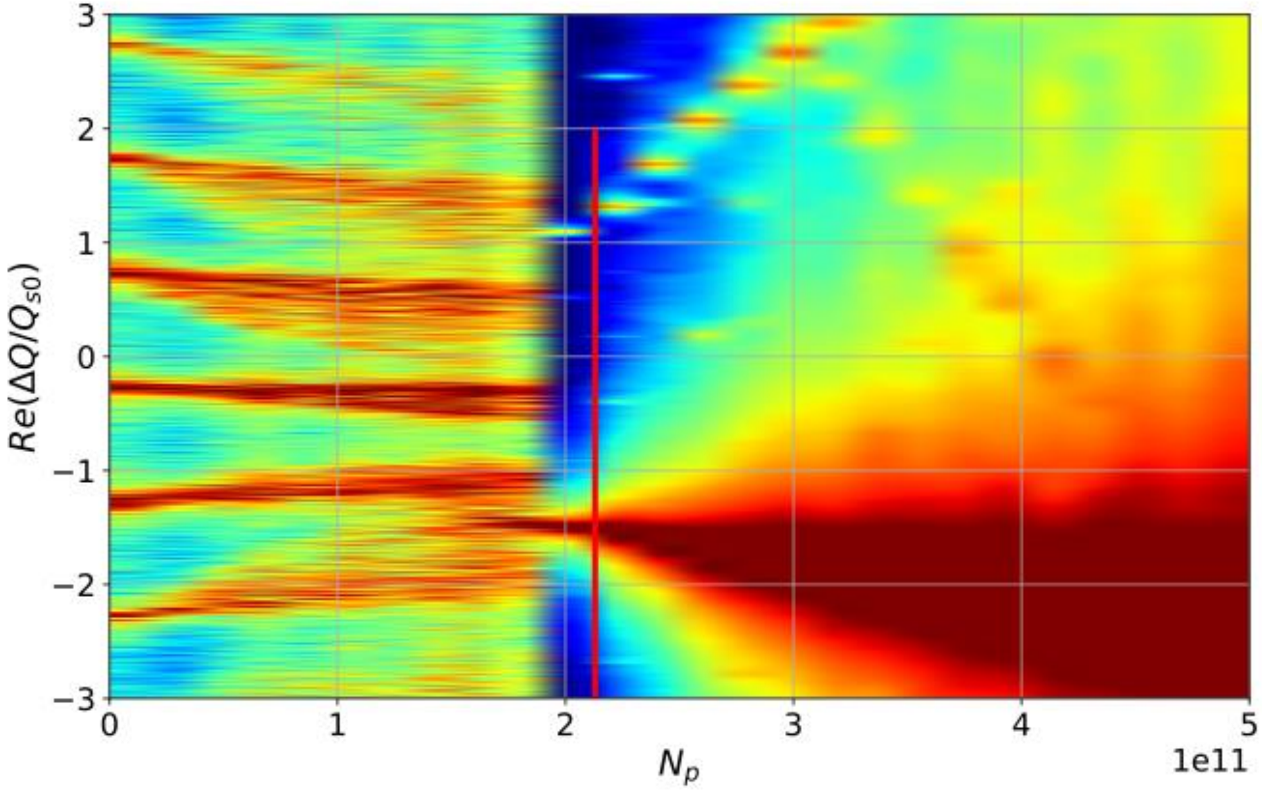
Wake with non-optimised collimators' geometry (geometric part = 4.4*RW part)

chromaticity = 20 - feedback system on (4 turns)

x-plane



y-plane



Conclusions

- Transverse single-bunch instability is the most challenging collective effect in the single-beam regime. The feedback system seems able to suppress TMCI, but the ‘-1 mode’ instability appears. An investigation with a more realistic feedback system is necessary.
- Different scenarios have been presented. With the current impedance model, the vertical plane shows an instability threshold close to the nominal intensity.
- Feedback system and chromaticity help, but vertical instability remains critical.
- We are still missing several impedance sources (e.g. stripline kickers, vacuum flanges, 200 nm NEG thickness instead of 150, …). Additionally, other impedance devices need to be updated (such as bellows that, so far, were evaluated using a 35 mm beam pipe radius).
- A common question from different groups is whether a device's design can be ‘accepted’ from the impedance point of view. We cannot answer such a question. An effective strategy to mitigate collective effects should include the optimized design of all devices contributing to the overall impedance.
- Additionally, interplay with beam-beam and beamstrahlung must be taken into account.

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Thank you for your attention