FCC-ee Collective Effects

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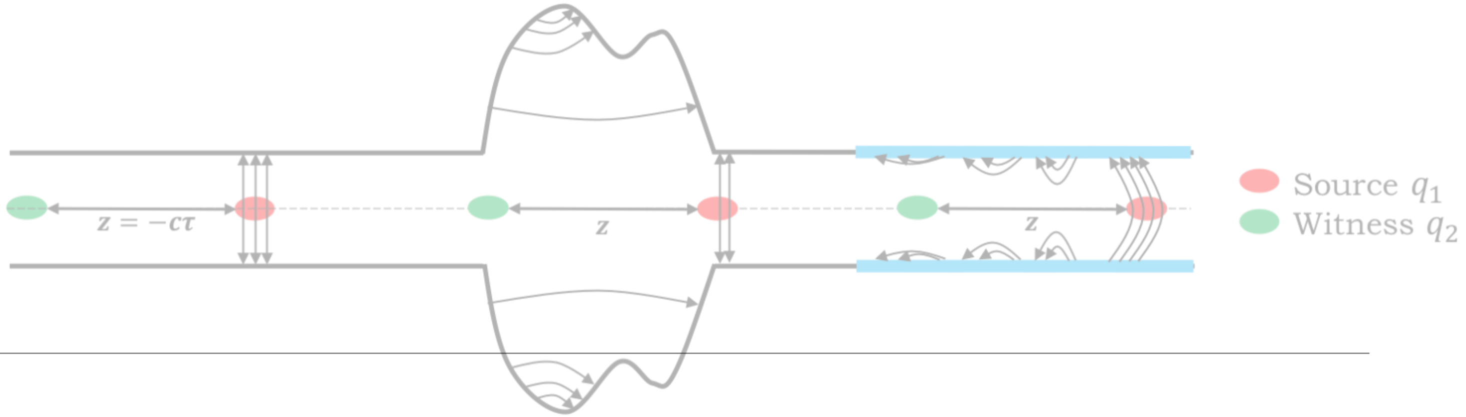
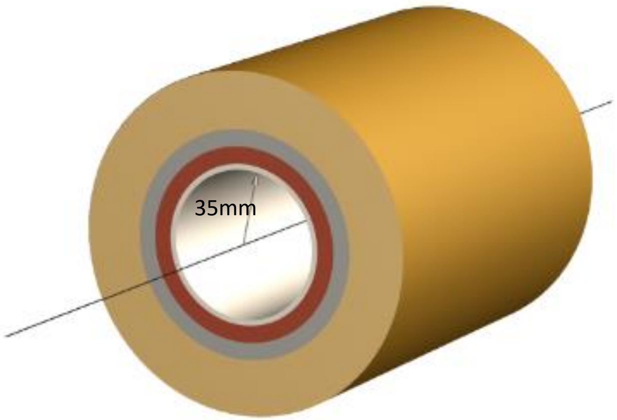
FCC-ee main parameters

Layout	PA31-1.0			
	Z	WW	ZH	$t\hat{t}$
Circumference (km)	91.174117 km			
Beam energy (GeV)	45.6	80	120	182.5
Bunch population (10^{11})	2.53	2.91	2.04	2.64
Bunches per beam	9600	880	248	36
RF frequency (MHz)	400			400/800
RF Voltage (GV)	0.12	1.0	2.08	4.0/7.25
Energy loss per turn (GeV)	0.0391	.37	1.869	10.0
Longitudinal damping time (turns)	1167	217	64.5	18.5
Momentum compaction factor 10^{-6}	28.5		7.33	
Horizontal tune/IP	55.563		100.565	
Vertical tune/IP	55.600		98.595	
Synchrotron tune	0.0370	0.0801	0.0328	0.0826
Horizontal emittance (nm)	0.71	2.17	0.64	1.49
Verical emittance (pm)	1.42	4.34	1.29	2.98
IP number	4			
Nominal bunch length (mm) (SR/BS)*	4.37/14.5	3.55/8.01	3.34/6.0	2.02/2.95
Nominal energy spread (%) (SR/BS)*	0.039/0.130	0.069/0.154	0.103/0.185	0.157/0.229
Piwinski angle (SR/BS)*	6.35/21.1	2.56/5.78	3.62/6.50	0.79/1.15
ξ_x/ξ_y	0.004/0.152	0.011/0.125	0.014/0.131	0.096/0.151
Horizontal β^* (m)	0.15	0.2	0.3	1.0
Vertical β^* (mm)	0.8	1.0	1.0	1.6
Luminosity/IP ($10^{34}/cm^2 s$)	181	17.4	7.8	1.25

*SR: syncrotron radiation, BS: beamstrahlung

Resistive wall





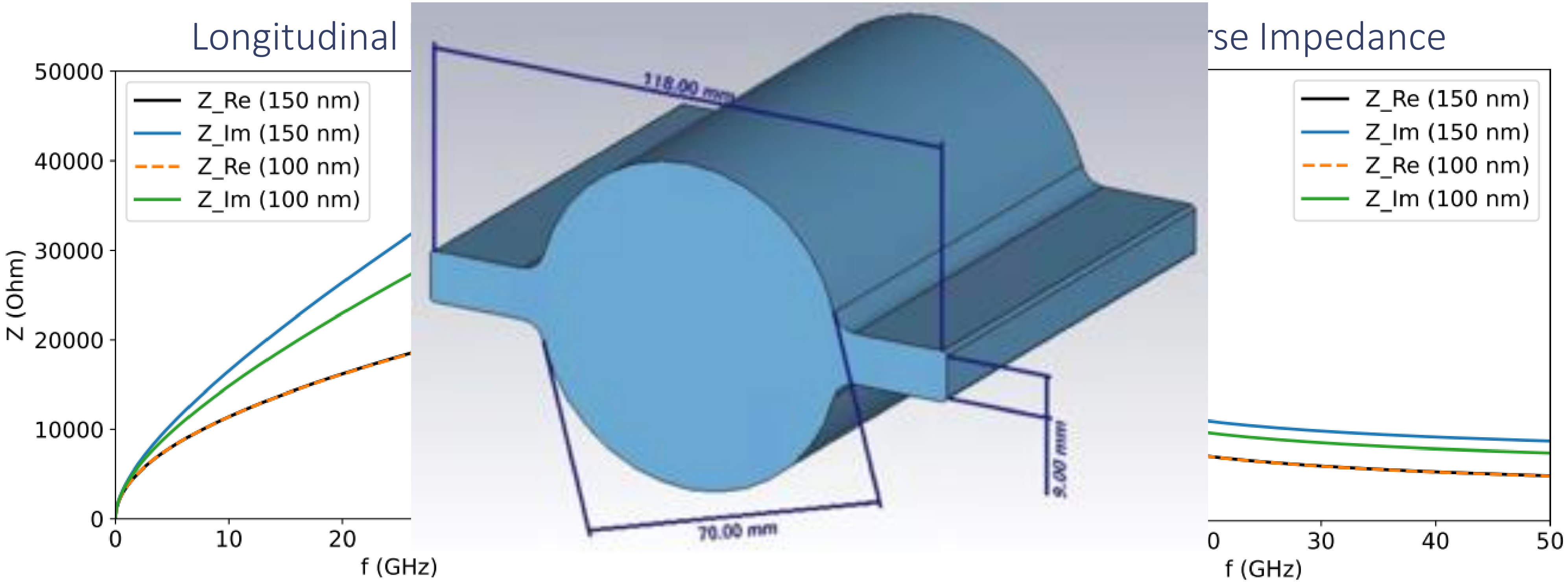
IRON	$\Delta = \infty$	$\rho = 6.89 \cdot 10^{-7} \Omega m$
DIELECTRIC	$\Delta = 6\, mm$	$\rho = 10^{-15} \Omega m$
COPPER	$\Delta = 2\, mm$	$\rho = 1.66 \cdot 10^{-8} \Omega m$
NEG	$\Delta = 150\, nm$	$\rho = 10^{-6} \Omega m$

- The interaction of the beam with the environment can produce **wakefields** (**impedances** in the frequency domain) that induce **instabilities**
  - The resistive wall impedance is produced by the finite conductivity of the pipe walls. The presence of the coating affects the RW impedance, increasing its imaginary part.
  - Since the resistive wall impedance is proportional to C, its contribution to the total machine impedance increases linearly with the machine length.
  - The main difference between FCC-ee and other colliders is its large circumference ≈ 91.17 km
  - By increasing the machine length the contribution of the RW impedance assumes more and more importance with respect to other elements

In FCC-ee, RW represents the main source of wakefields

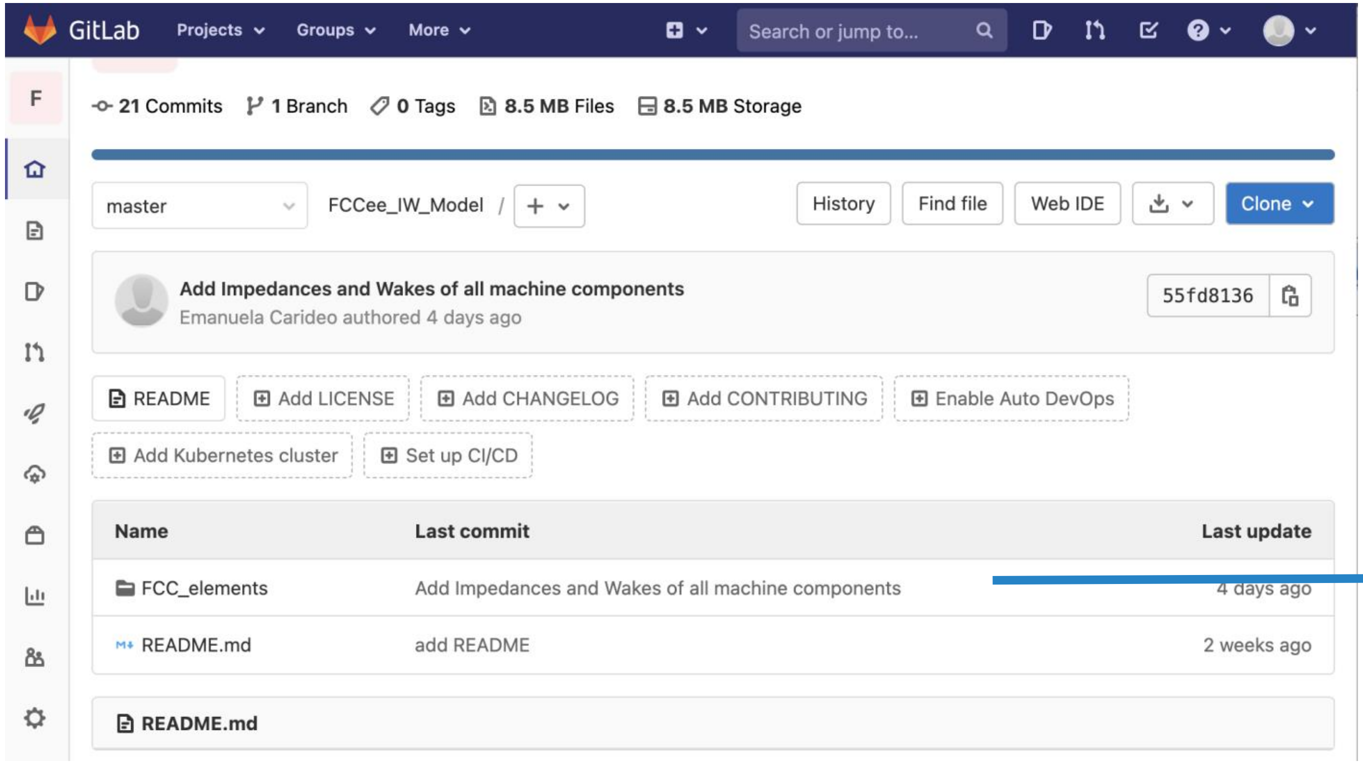
NEG coating is needed to mitigate the electron cloud build-up in the positron machine and for pumping reasons in both rings.

IW2D results for a circular pipe. We estimated a factor 1.1 for winglets contribution



Wake and impedance repository for FCC-ee: https://gitlab.cern.ch/ecarideo/FCCee_IW_Model

A repository, or Git project, encompasses the entire collection of files and folders associated with a project. Working in repositories keeps development projects organized and organized and protected.



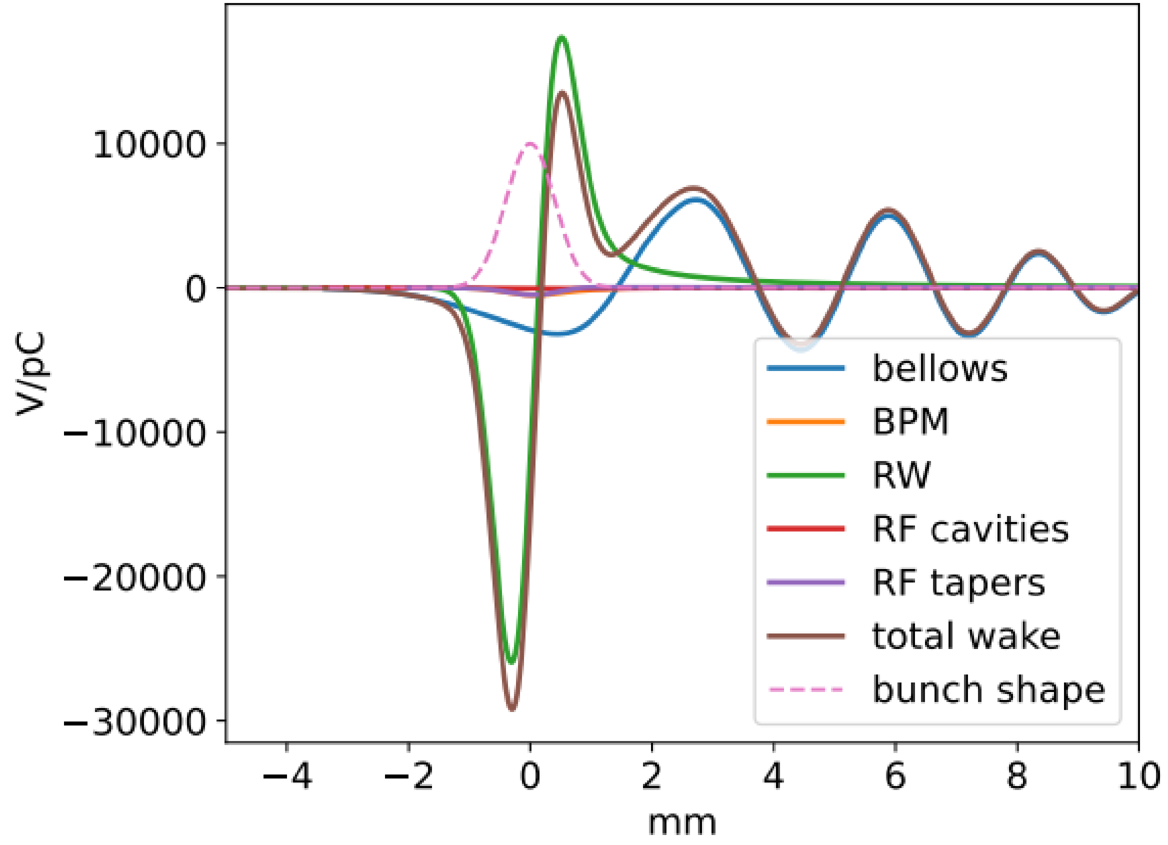
The Repository also provides more opportunities for project transparency and collaboration, working together to build the best possible final product.

How is it developed?

In this folder there are some of FCC-ee components and for each machine components the calculated impedance and wake

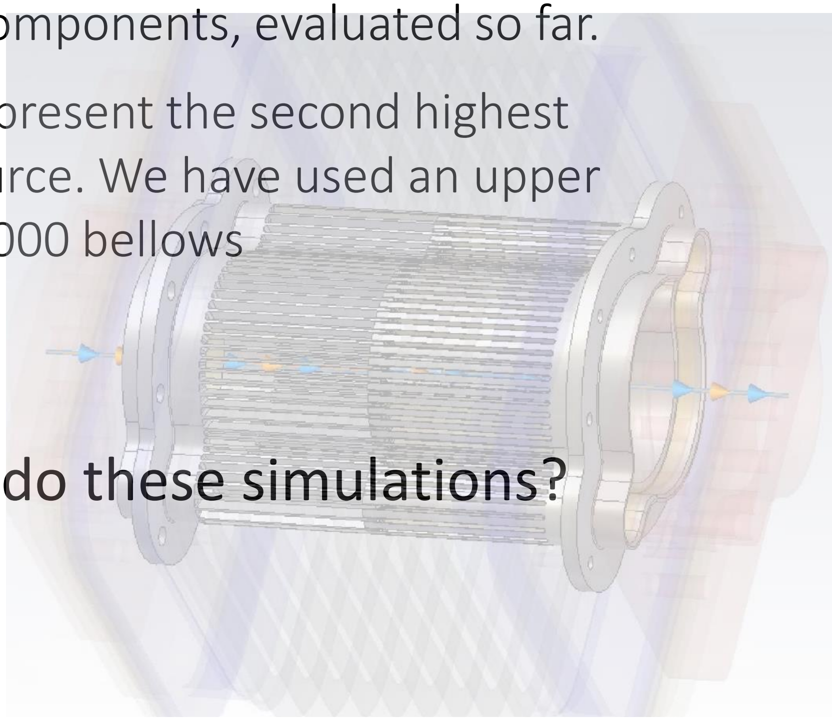
FUTURE CIRCULAR COLLIDER

Impedance Sources: CST and IW2D simulations



Longitudinal wake potentials for a Gaussian bunch with nominal bunch length, 4.37 mm, due to the main FCC-ee components, evaluated so far.

The bellows represent the second highest impedance source. We have used an upper estimate of 20000 bellows

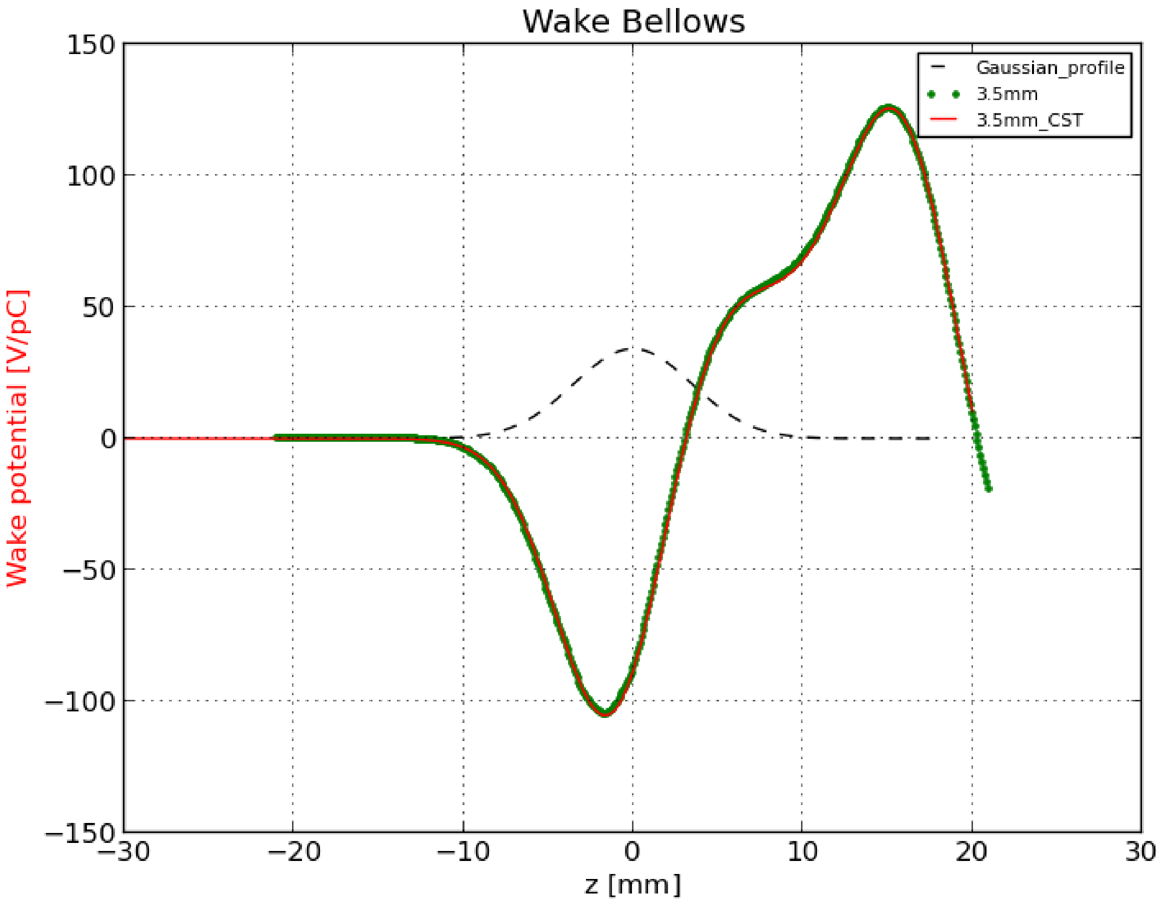


How did we do these simulations?

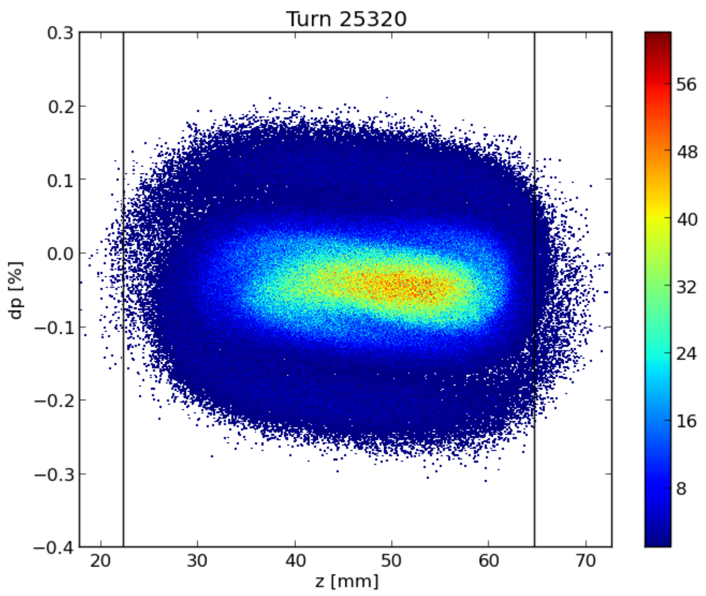
Method to calculate the Wake Potential by software simulation

Comparison of the wake potential of 3.5 mm bunch length between PyHT and CST: Bellows

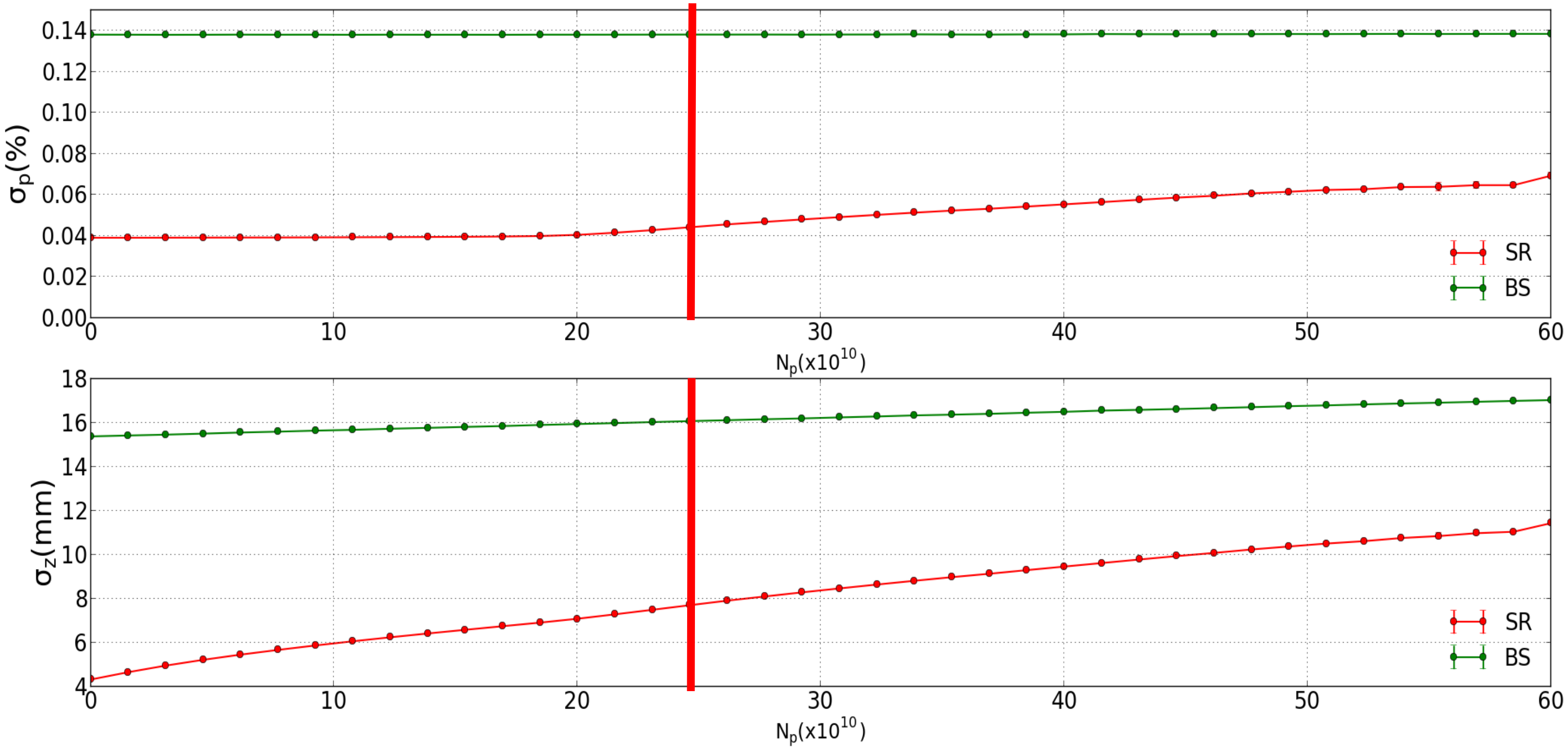
Wake potential for a Bellow of a 3.5 mm Gaussian bunch obtained directly by CST (red curve) and with the convolution by using the wake potential of 0.4 mm Gaussian bunch (green dots).



LONGITUDINAL DYNAMICS



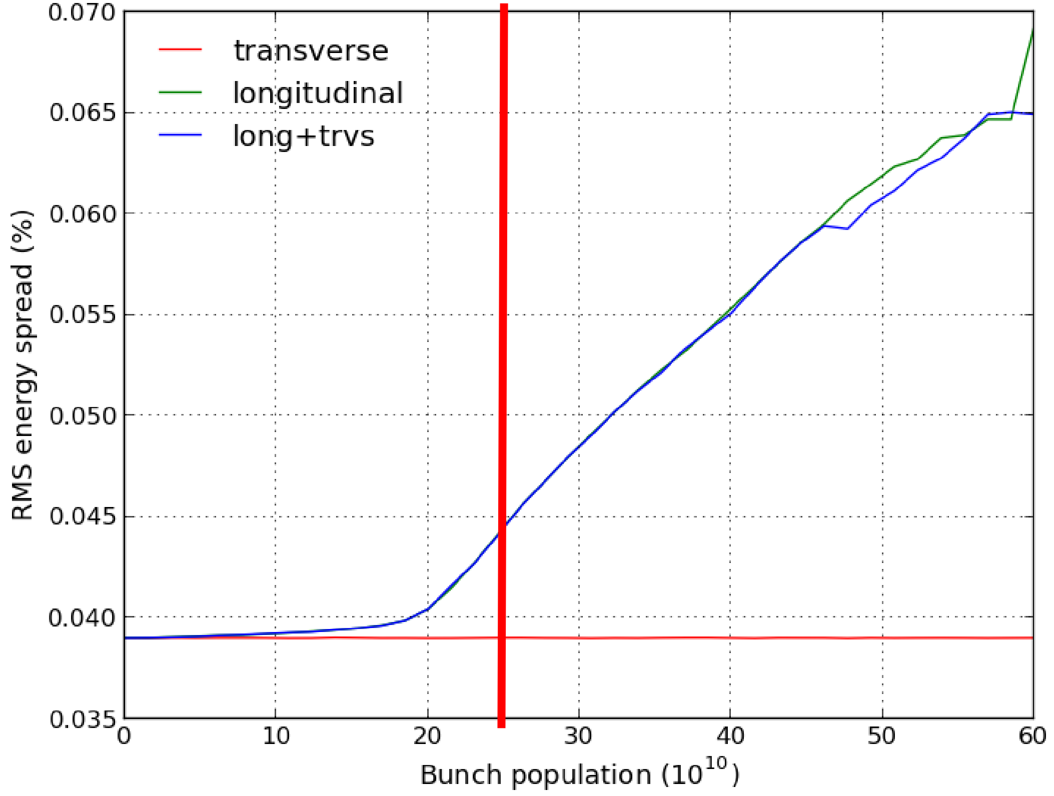
Longitudinal phase space

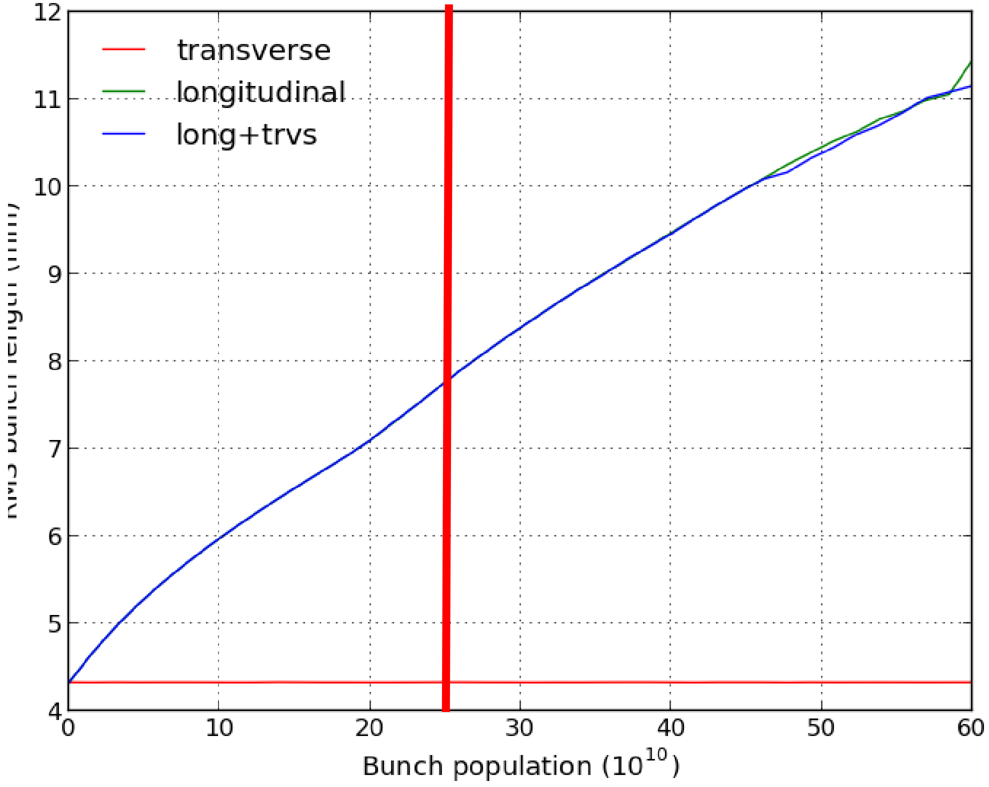


Bunch length (bottom) and RMS energy spread (top) as a function of bunch population in the case with (BS) and without (SR) beamstrahlung, which is considered here independent of the longitudinal impedance.

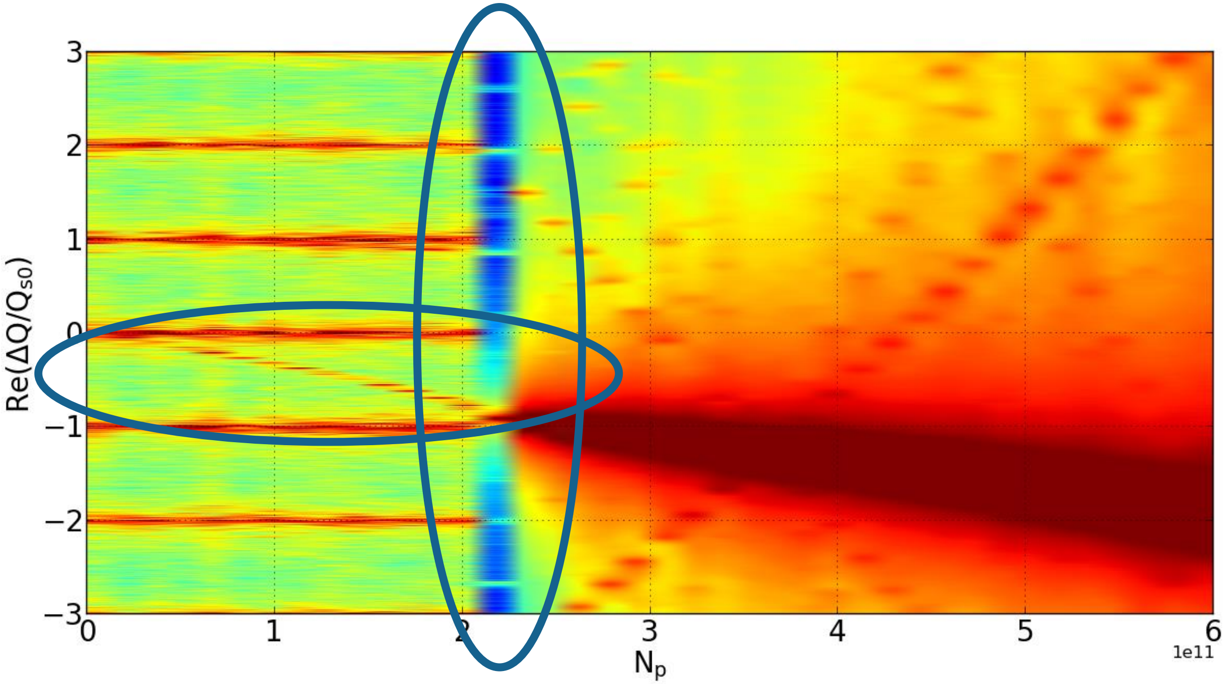
Bunch length and energy spread for considered cases

- The transverse impedance almost does not affect the longitudinal dynamics





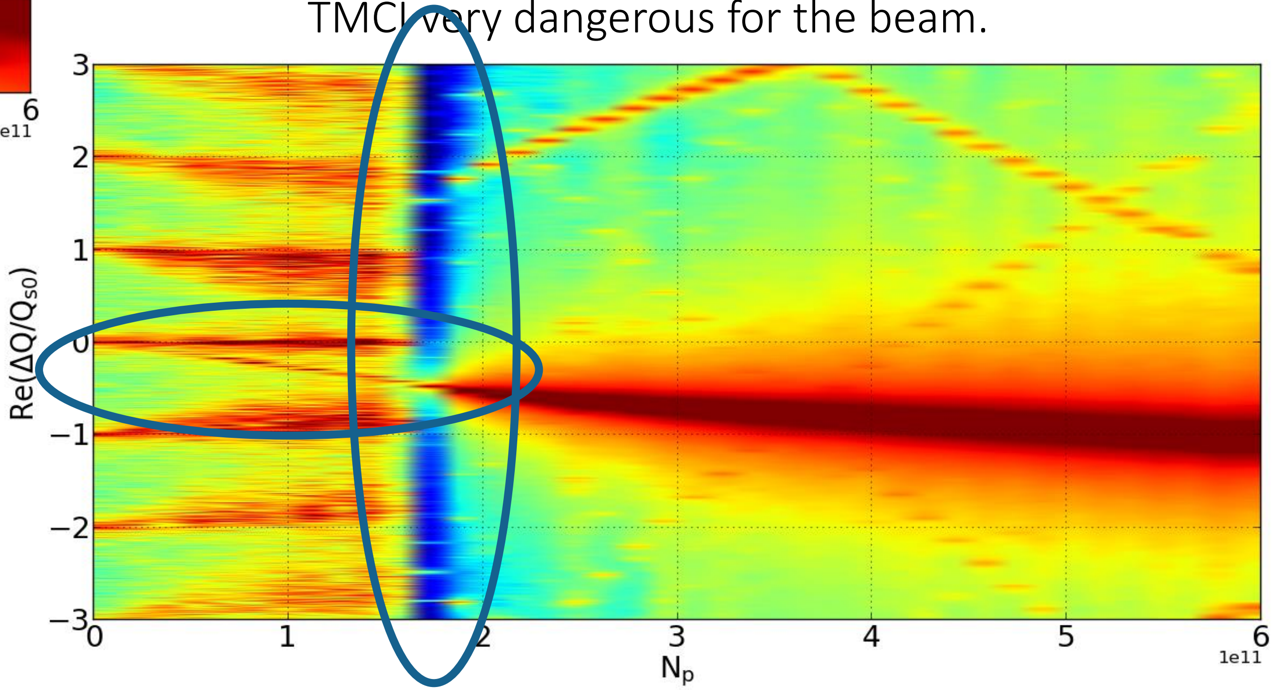
Transverse Dynamics



SR: Bunch length of 4.37 mm

The TMCI, **Transverse Mode Coupling Instability,** occurs when the frequencies of two neighboring coherent oscillation modes merge together. Above the transverse instability threshold the bunch is lost and this makes the TMCI very dangerous for the beam.

On the top, real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without beamstrahlung, by considering only the transverse wakefield.



On the right, real part of the coherent tune shift as a function of intensity considering both longitudinal and transverse wakefield, by using PyHEADTAIL.

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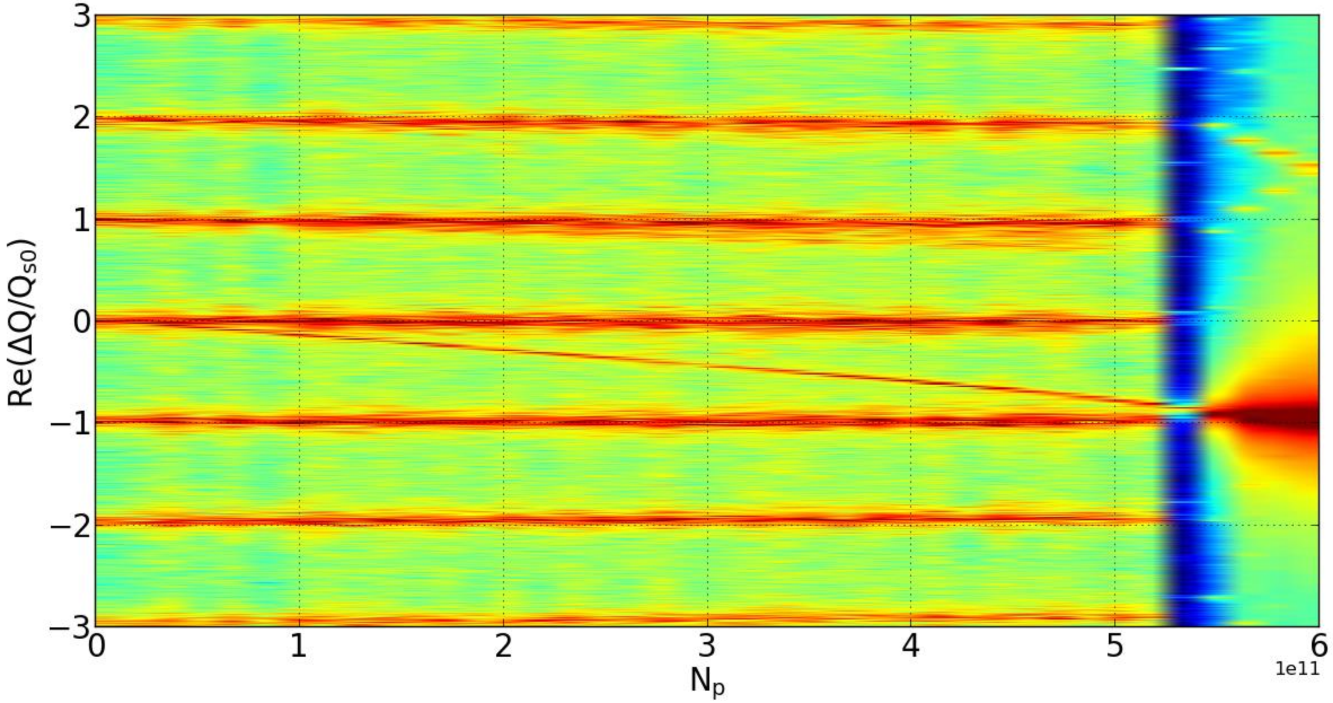
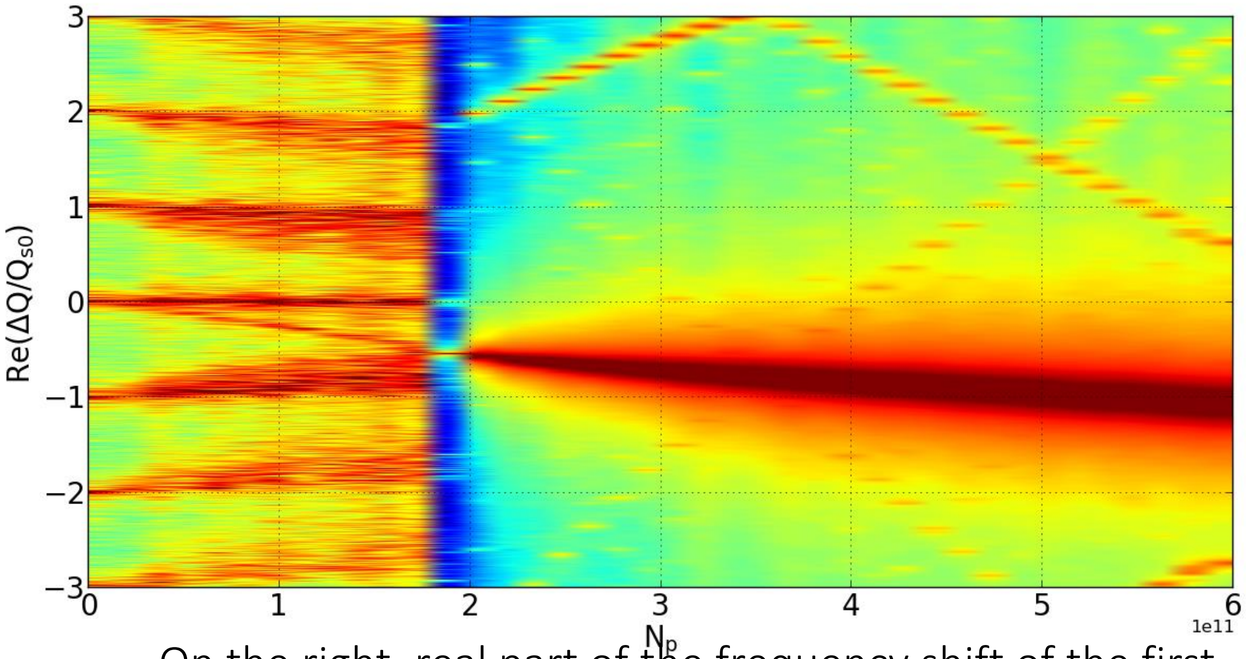
TMCI: longitudinal and transverse wake with a bunch length of 14.5 mm (BS)



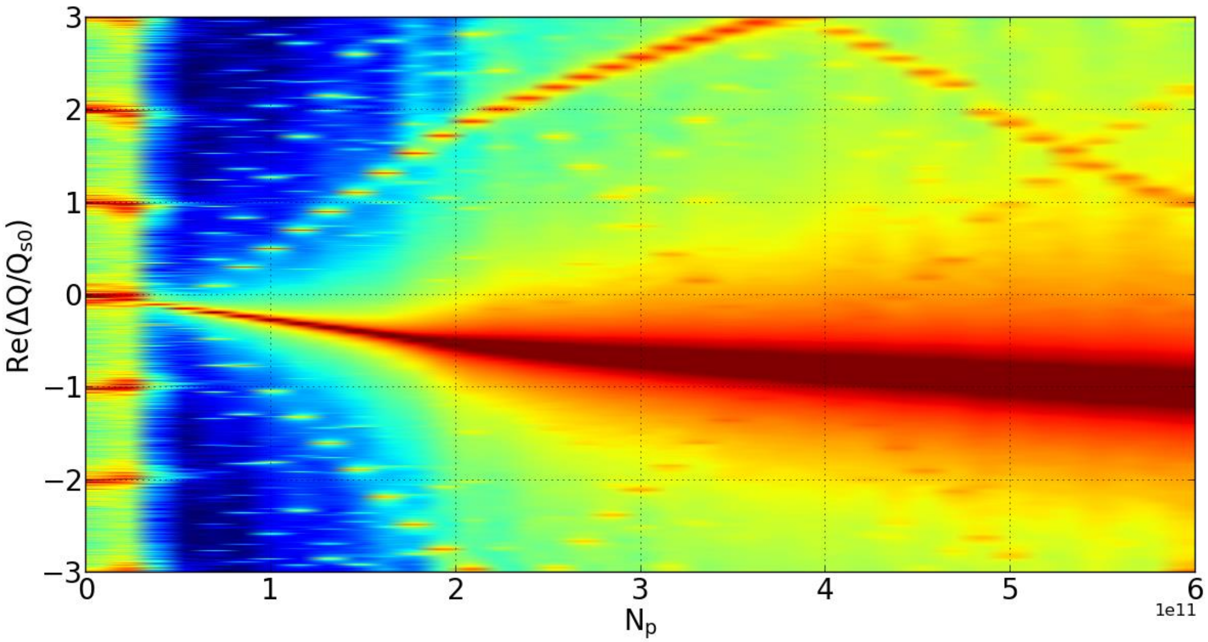
Variable Chromaticity:

Dependence of the TMCI from the Chromaticity



On the left, real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without beamstrahlung, so considering a bunch length of 4.37mm and a value of Chromaticity of +5

On the right, real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without beamstrahlung, so considering a bunch length of 4.37mm and a value of Chromaticity of -5: the 0-mode is unstable and a feedback system is necessary



FUTURE CIRCULAR COLLIDER

TCBI and feedback system

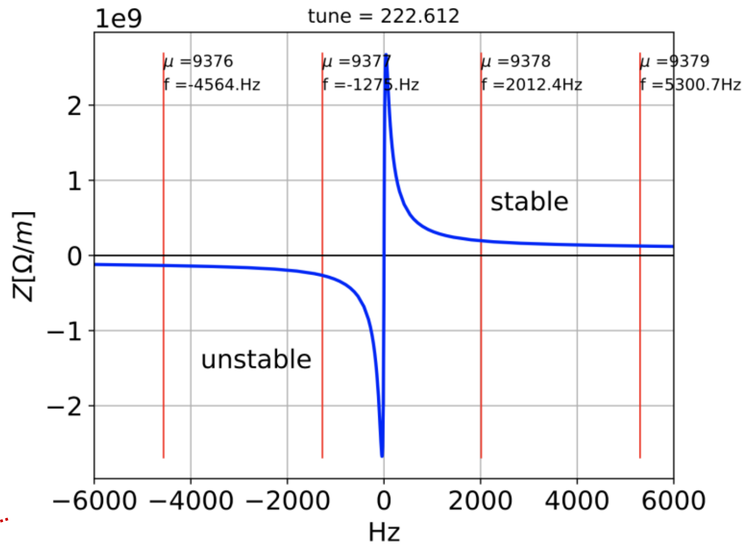
Transverse Coupled Bunch Instability (TCBI)

$$\frac{1}{\tau_{\mu,\perp}} = -\frac{ecI}{4\pi E Q_\beta}\sum_q Re[Z_\perp(\omega_q)]G_\perp\left(\frac{\sigma_z}{c}\omega'_q\right)$$

where $$Re[Z_\perp(\omega_q)] = \mathrm{sgn}(\omega)\frac{C}{2\pi b^3}\sqrt{\frac{2Z_0 c}{\sigma_c|\omega|}}$$

$$\omega_q = (qM + \mu + Q_\beta)\omega_0$$

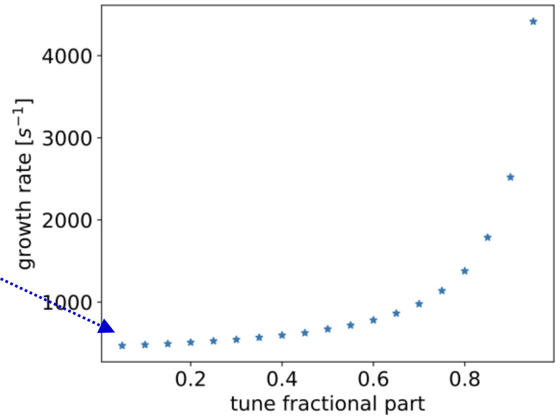
$$\omega'_q = \omega_q + \xi\frac{\omega_\beta}{\eta}$$



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

Rise time of about 6 revolution turns

A robust feedback is required for the instability suppression!



TMCI and feedback system

- In SuperKEKB the transverse feedback was one important source of the '-1' mode instability which limited the machine to reach the nominal intensity. Its damping time is around 100 turns, that is about 1000 1/s.

- What is the effect of feedback in FCC-ee that needs about the same damping time, but this corresponds to only few turns?

A robust feedback is required for the instability suppression!

- Is the TMCI perturbed by the feedback? And what about the longitudinal effect of the wake?

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 041003 (2021)

Imaginary tune split and repulsion single-bunch instability mechanism in the presence of a resistive transverse damper and its mitigation

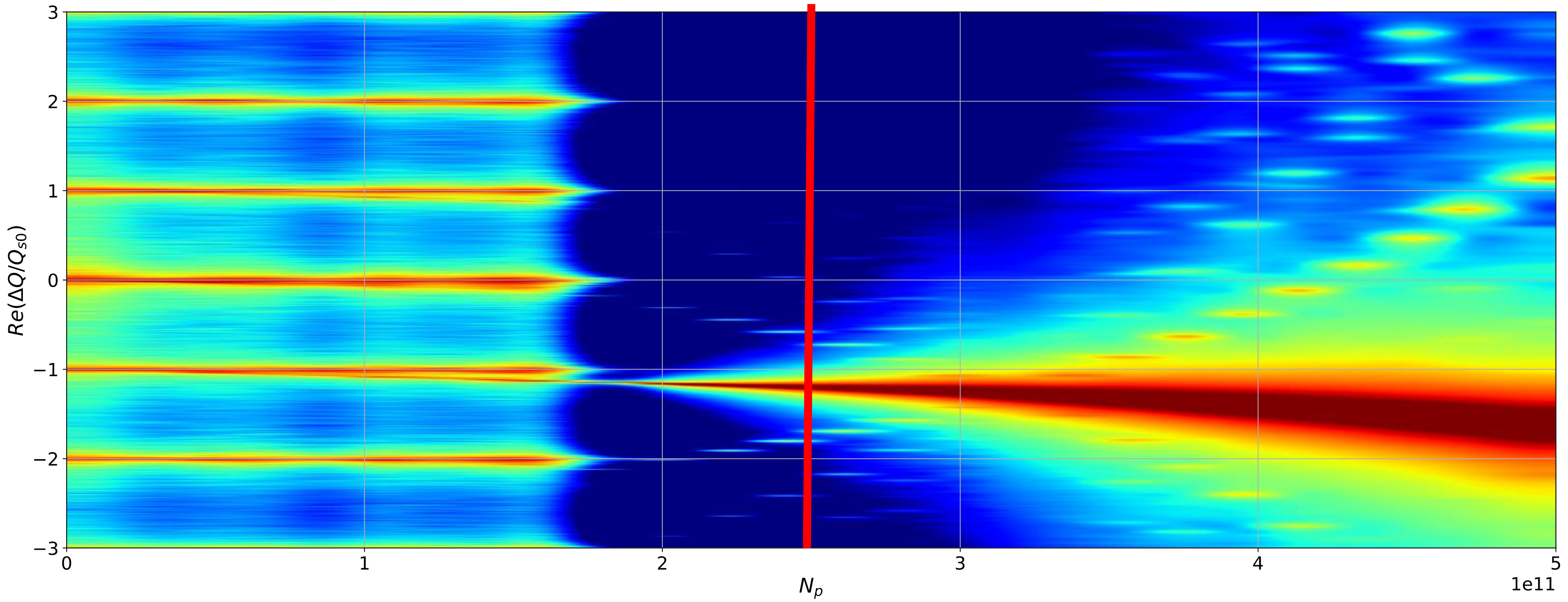
E. Métral

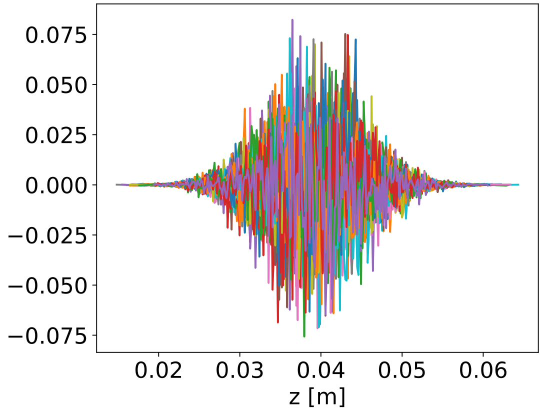
Introduction

[…] However, a resistive transverse damper also destabilizes the single-bunch motion below the transverse mode coupling instability intensity threshold (for zero chromaticity), introducing a new kind of instability, which has been called ITSR instability (for imaginary tune split and repulsion). […]

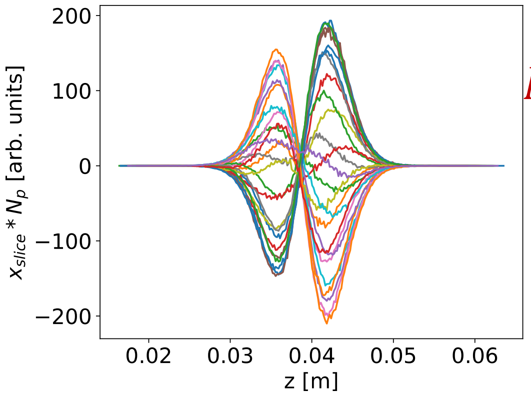
ITSR instability: Imaginary Tune Split and Repulsion

Only Transverse wakefield, resistive feedback, 10 turns damping time





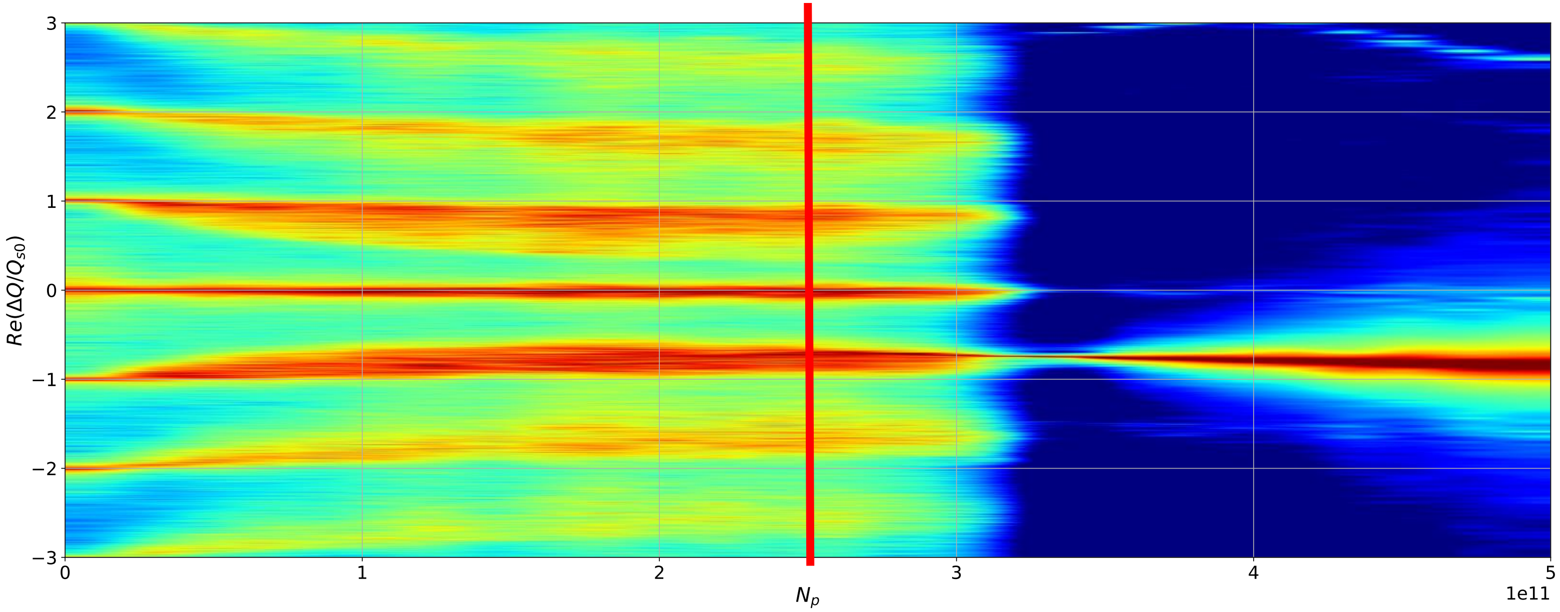
$N_p = 16 \times 10^{10}$

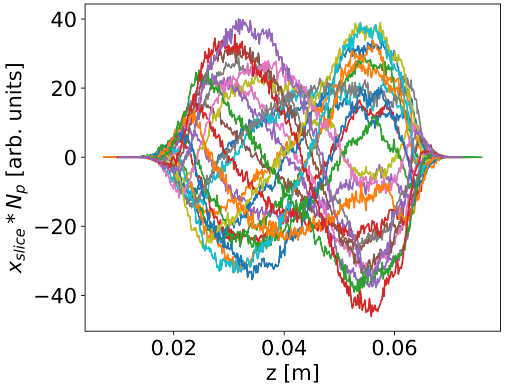


$N_p = 18 \times 10^{10}$

ITSR instability: Imaginary Tune Split and Repulsion

Long. + Transverse wakefield, resistive feedback, 10 turns damping time



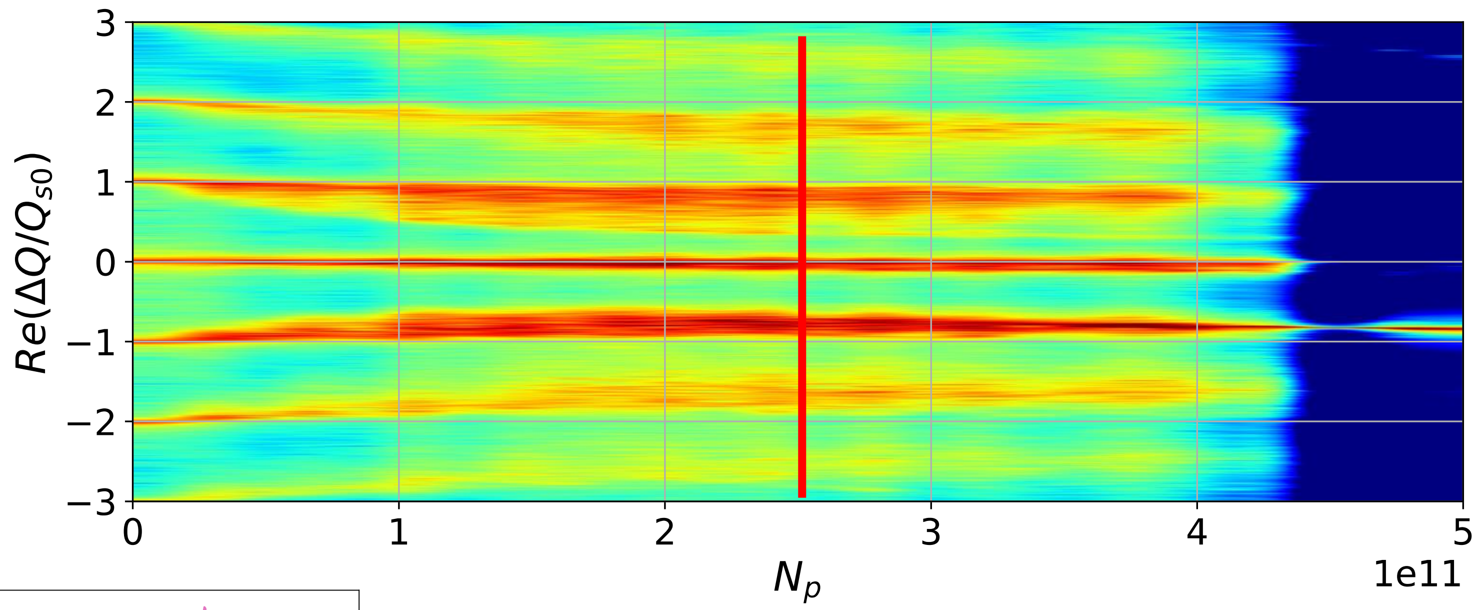


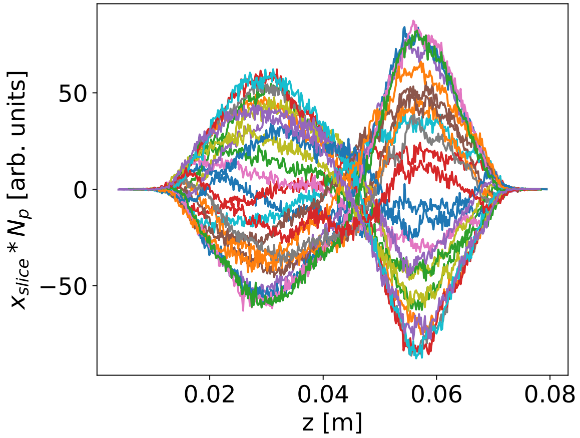
$N_p = 34 \times 10^{10}$

The spread in the synchrotron tune due to the longitudinal wakefield helps to mitigate the ITSR instability

ITSR instability: Imaginary Tune Split and Repulsion

Long. + Transverse wakefield, resistive feedback, 4 turns damping time





$N_p = 46 \times 10^{10}$

Beamstrahlung reduces the effect of the longitudinal wakefield which, on its turn, has a beneficial effect on the TMCI with a resistive transverse damper. What happens if both effects are present?

Challenges and Future Plan

Continue the work for the evaluation, reduction and optimization of the impedances of the main machine elements (e. g. collimators system), and also for implementing the FCC-ee repository.

Continue to investigate on the beam-beam effect, longitudinal and transverse coupling impedance

Continue to investigate diversified mitigation techniques: feedback system (resistive + reactive), chromaticity, …

Split the machine into segments, each one having its own longitudinal wake, transverse wake weighted by the local beta function, RF system (which is not evenly distributed along the machine), …

Study the effects of possible transverse localized impedances (in particular for the collimation system)

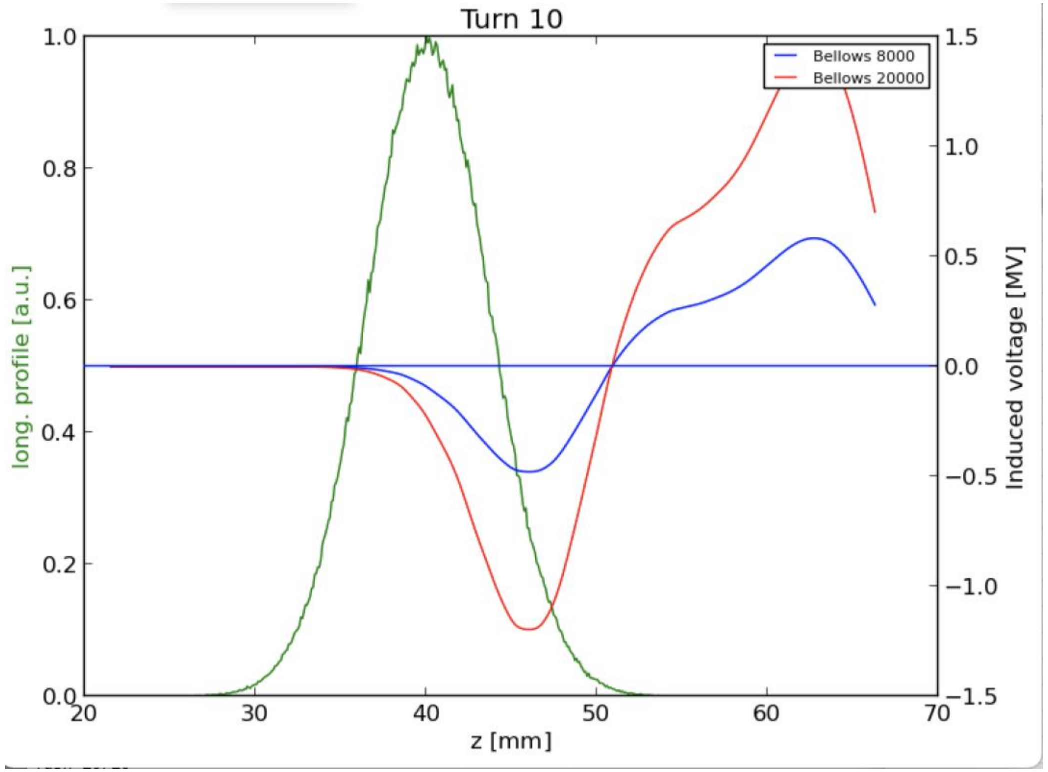
Use a more realistic transverse lattice

Other effects: electron could, (also multi-bunch), ion instabilities …

Thanks for your attention!

Back-up Slides

Updated FCC-ee impedance model: 20000 Bellows



We initially considered a number of 8000 Bellows

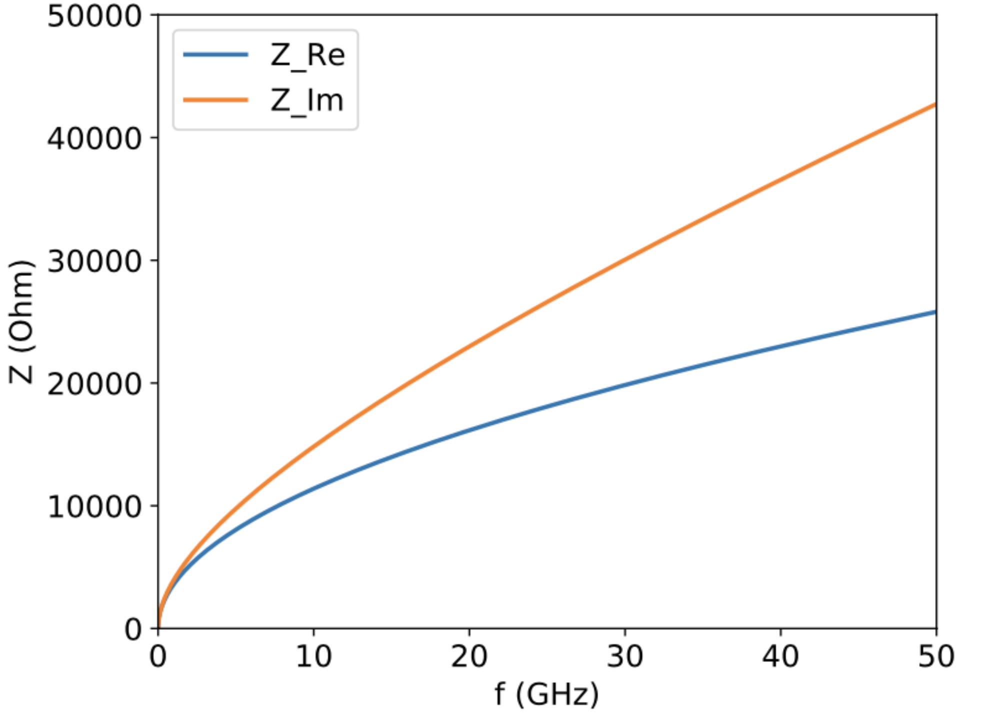
BUT

85% of arcs (~ 79 km)

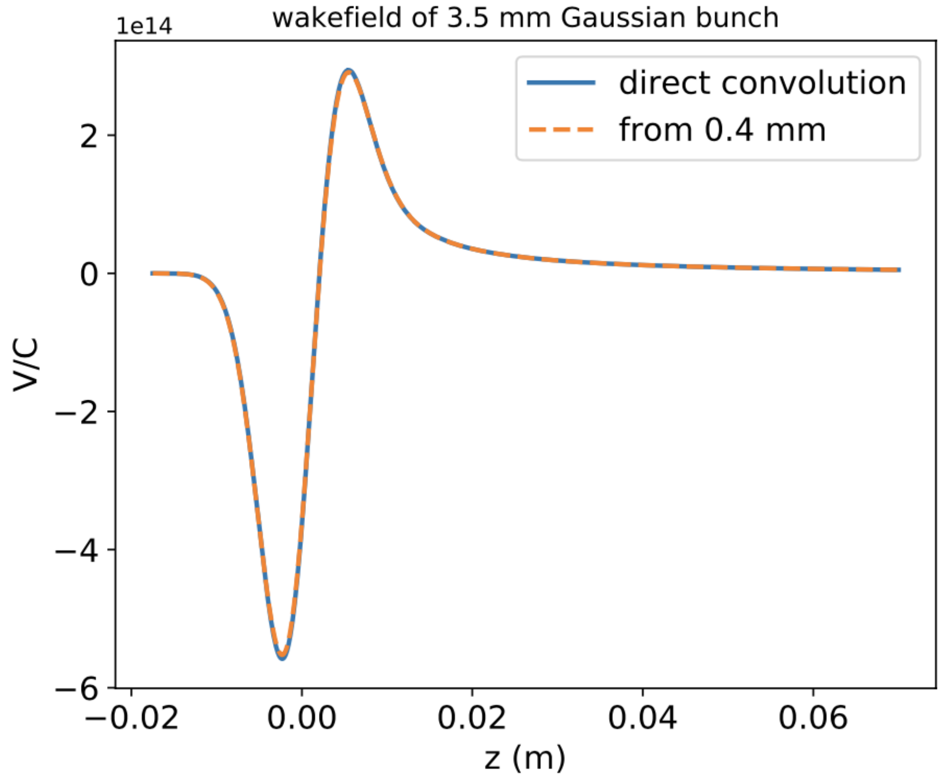
Every arc is 8m long
X2 because we have another bellow before any quadrupole

12000-13000 but to be sure we are performing our calculations considering up to 20000 bellows

Method to calculate the Wake Potential by software simulation: Resistive Wall

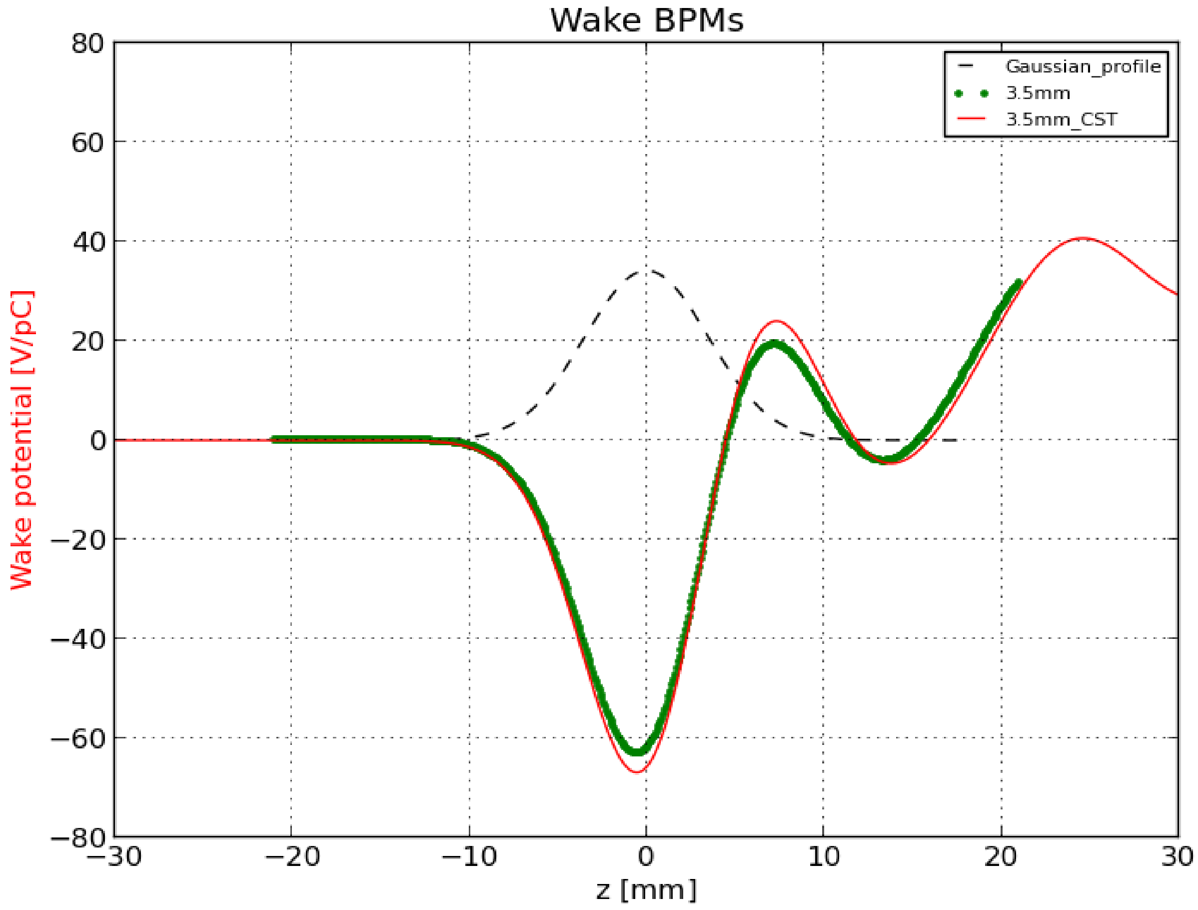


Real and imaginary part of the resistive wall impedance calculated by using the code ***IW2D***

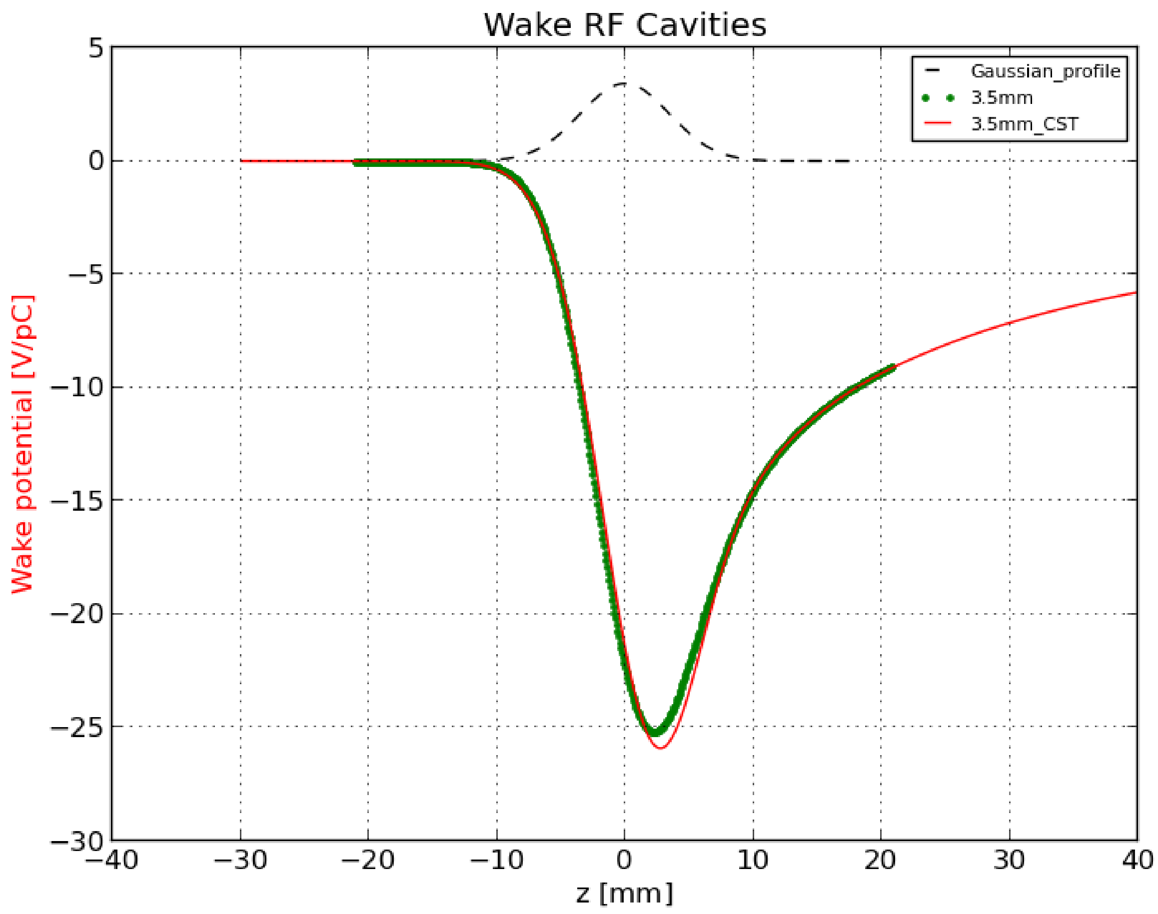


Wake potential of a 0.4 mm Gaussian bunch convoluted with the nominal bunch length and compared with the wake potential obtained directly from the convolution of the wakefield with the 3.5 mm Gaussian bunch.

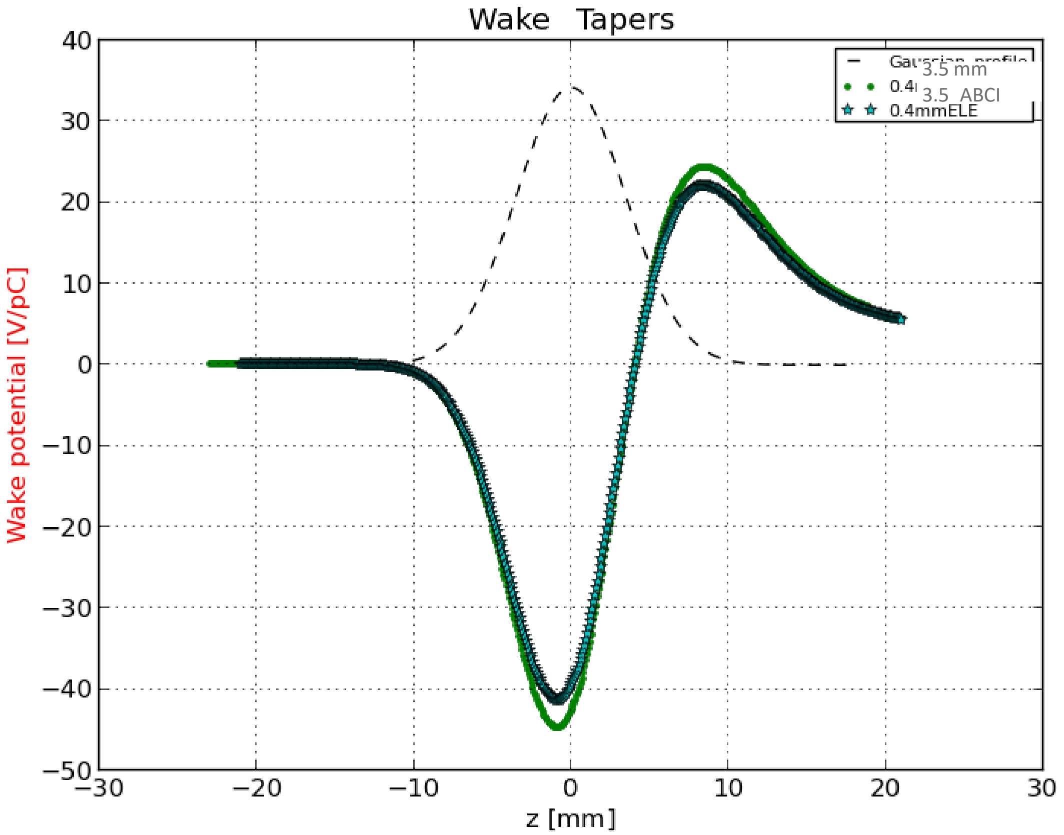
Comparison of the wake potential of 3.5 mm bunch length between PyHT and CST: BPMs



Comparison of the wake potential of 3.5 mm bunch length between PyHT and CST: RF Cavities

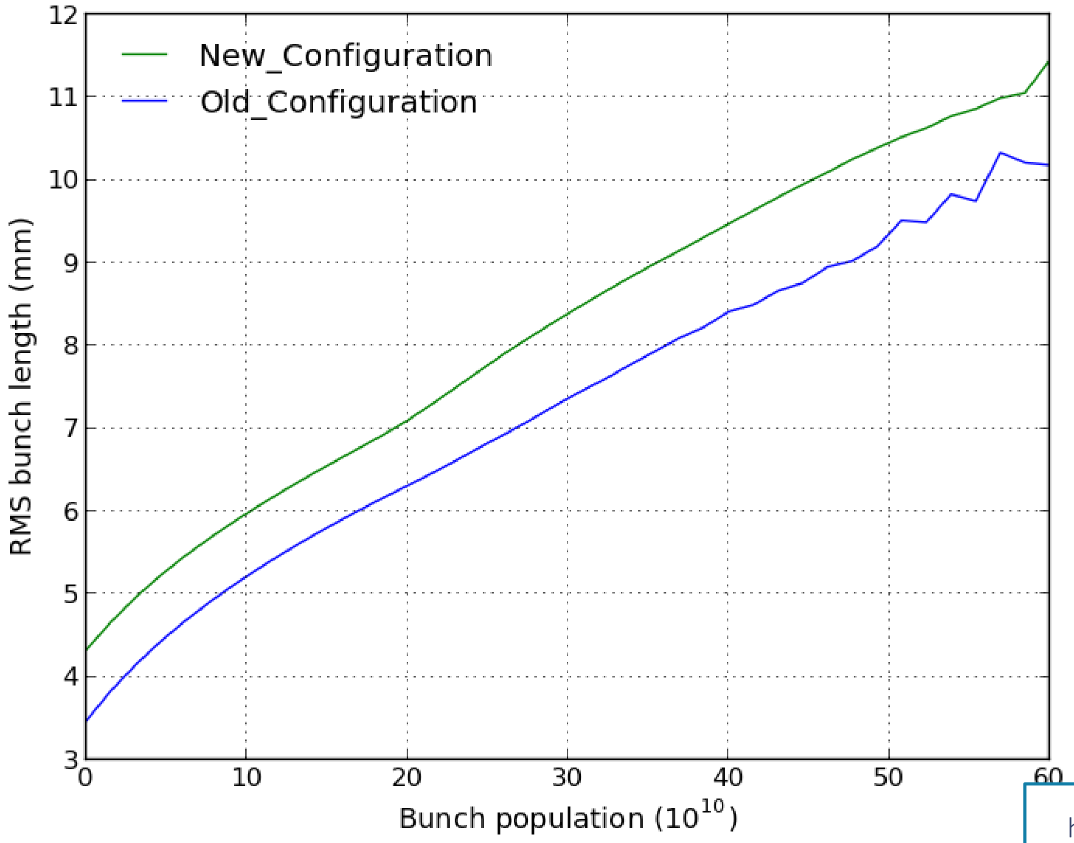


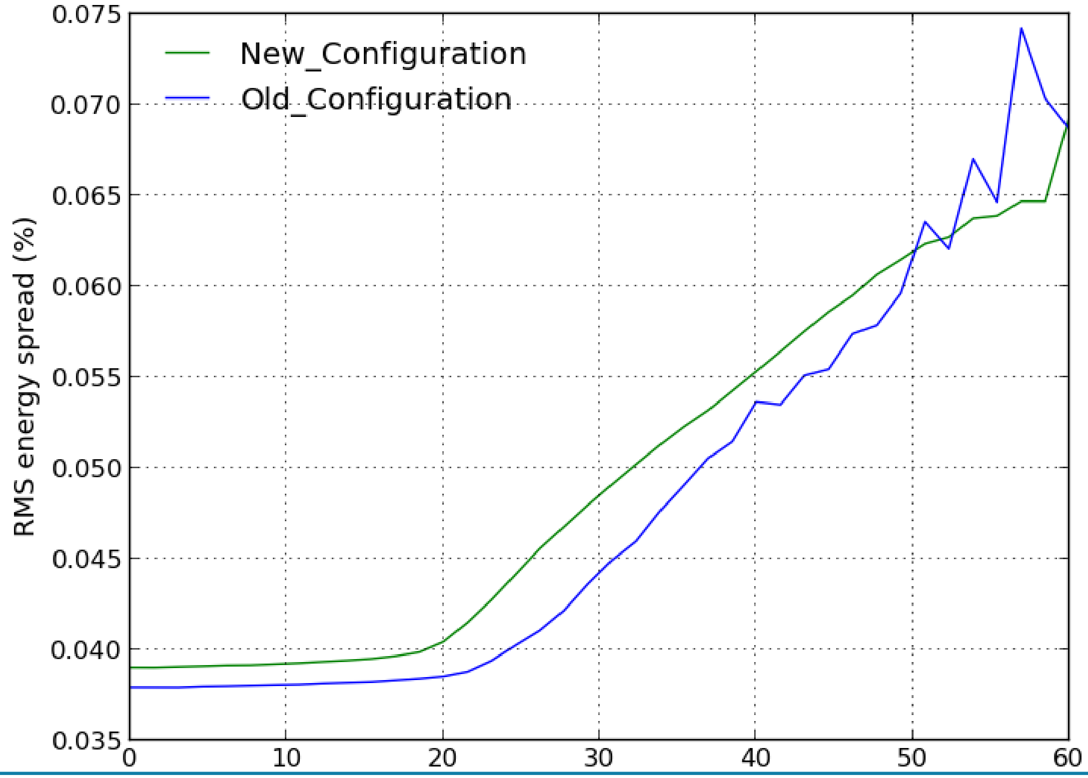
Comparison of the wake potential of 3.5 mm bunch length between PyHT and CST: RF double tapers



New Wakes with new machine parameters :

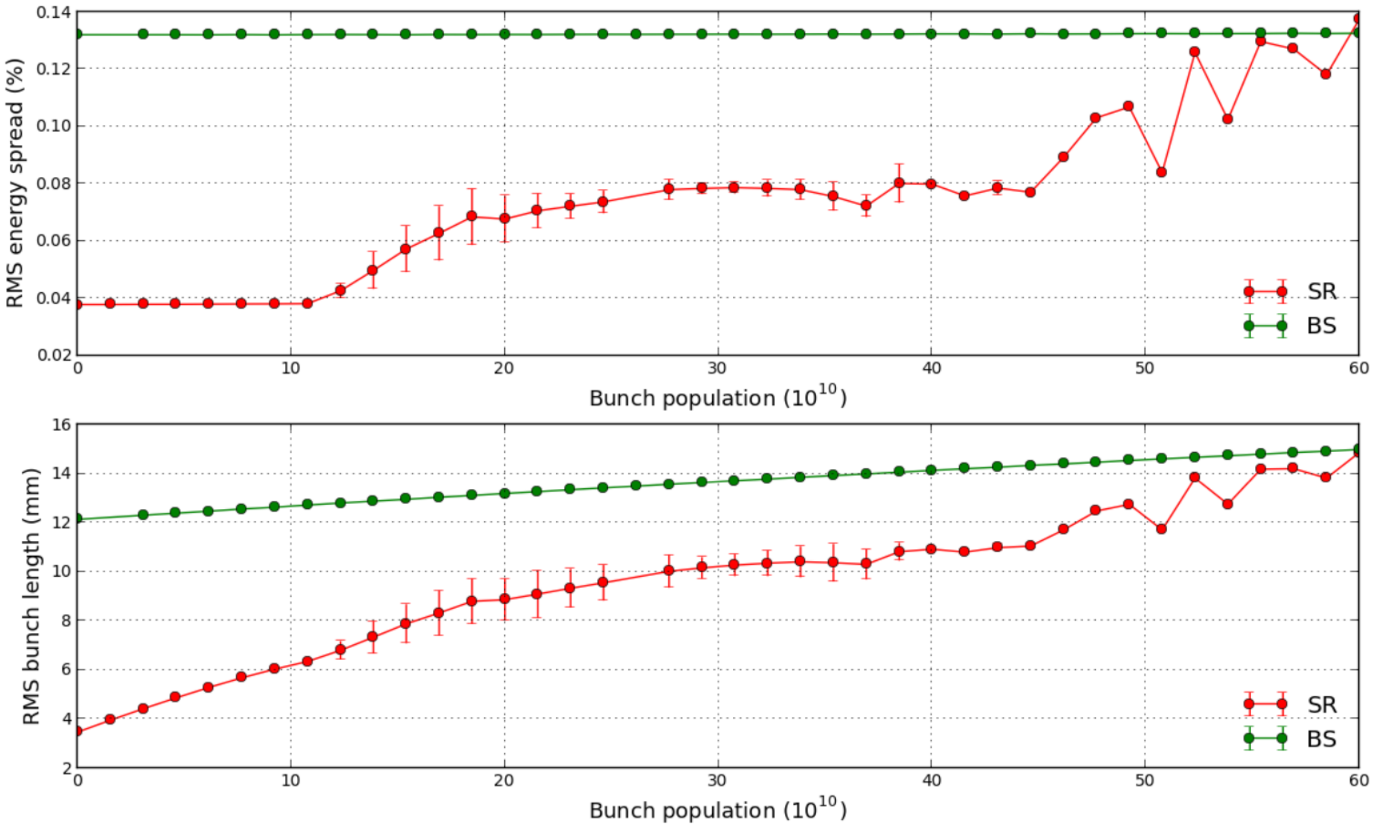
Longitudinal RW with 150nm of coating plus the Bellows without neglected the perturbation introduced by the lateral winglets used to place synchrotron radiation absorbers





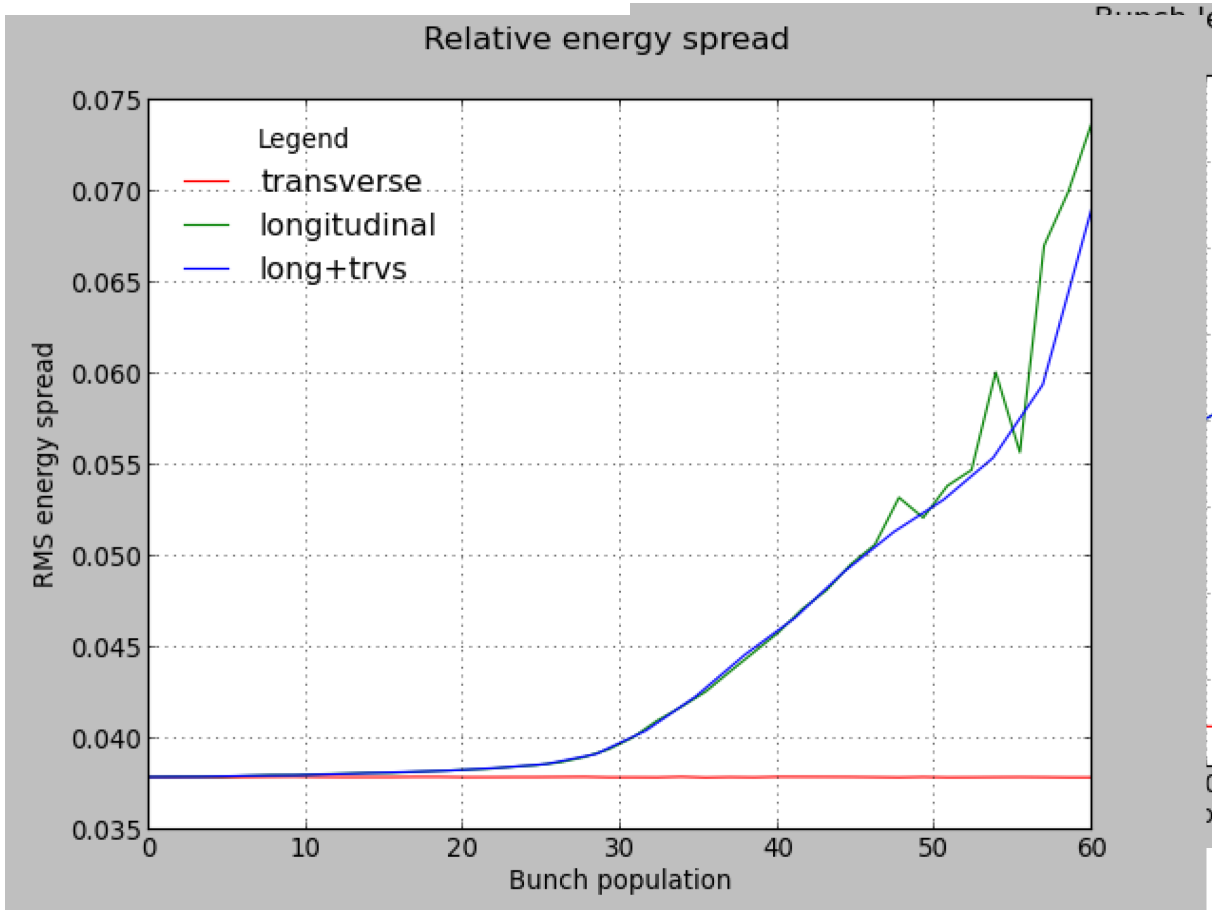
https://indico.cern.ch/event/995850/contributions/4401571/attachments/2275135/3864813/FCCweek.pdf

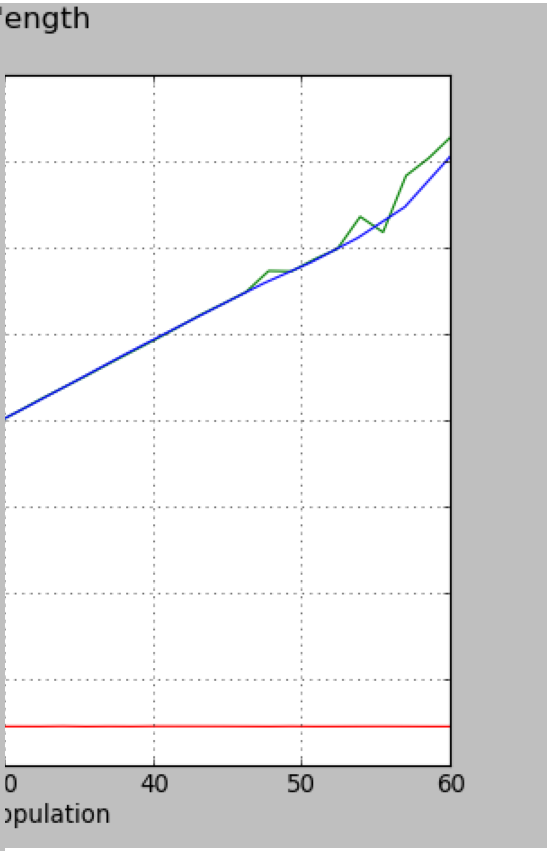
LONGITUDINAL DYNAMICS: OLD MACHINE PARAMETERS

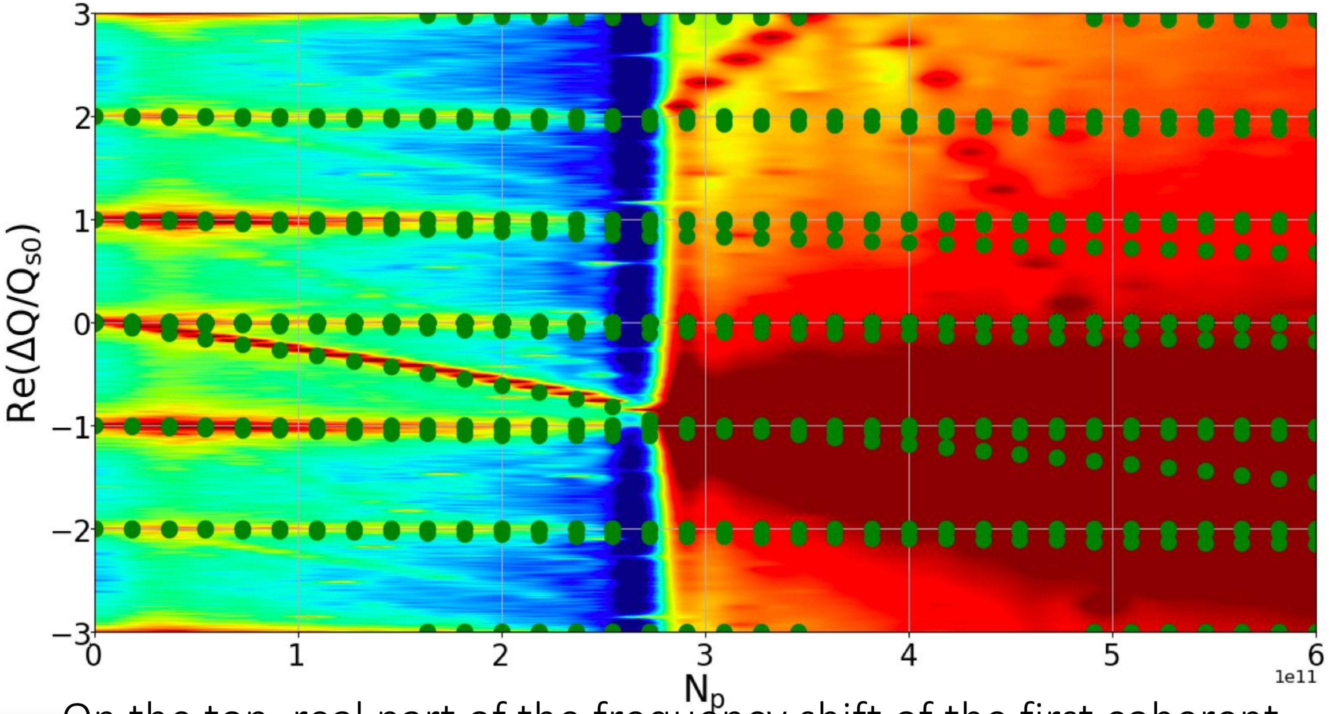


Bunch length (bottom) and RMS energy spread (top) as a function of bunch population in the case with (BS) and without (SR) beamstrahlung, which is considered here independent of the longitudinal impedance.

Bunch length and energy spread (old machine parameters)





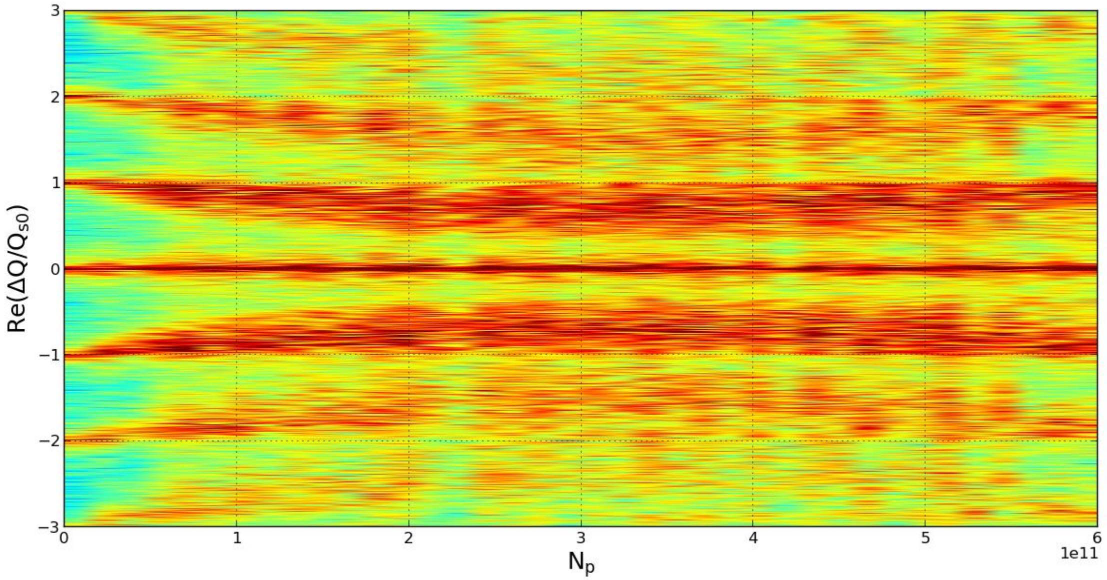


Transverse Dynamics

The TMCI occurs when the frequencies of two neighbouring coherent oscillation modes merge together. Above the transverse instability threshold the bunch is lost and this makes the TMCI very dangerous for the beam.

In addition to simulations with the tracking code, the TMCI threshold has been also evaluated with the analytic Vlasov solver DELPHI

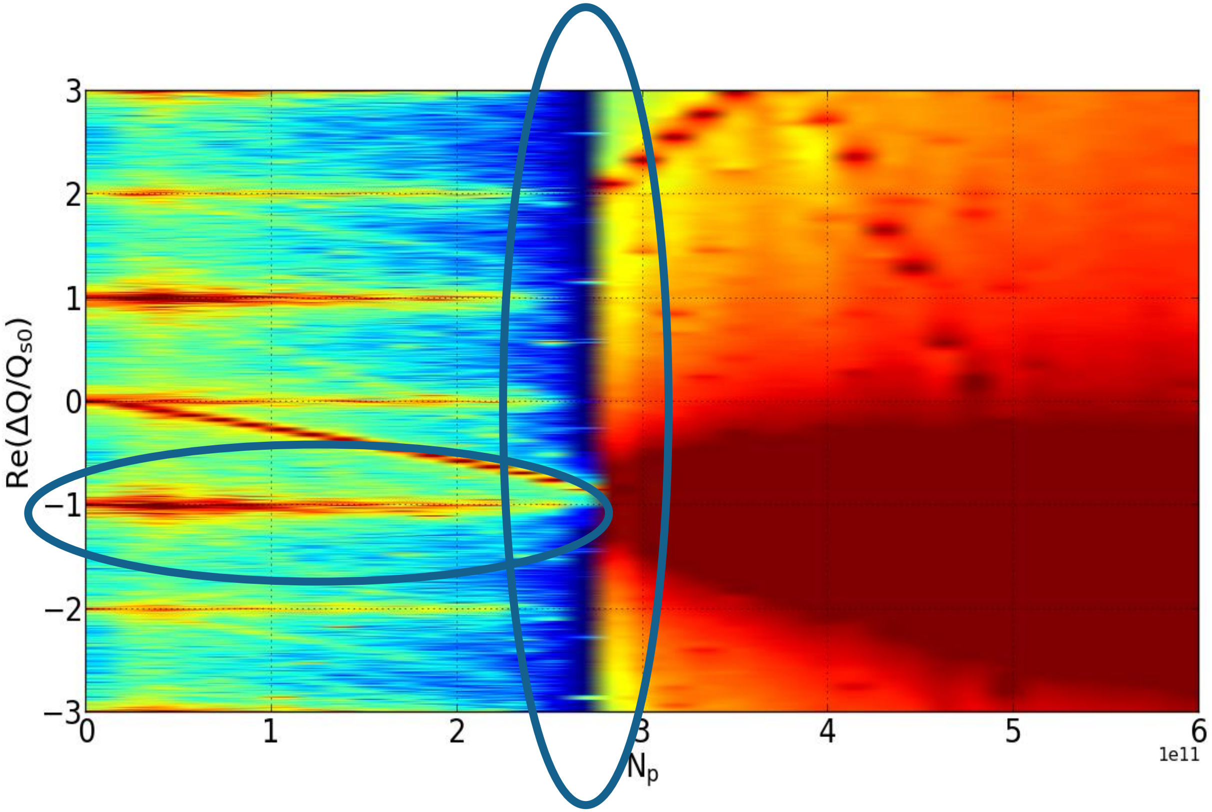
On the top, real part of the frequency shift of the first coherent oscillation modes as a function of the bunch population without beamstrahlung, by considering only the RW impedance produced by a NEG film with 150 nm thickness given by IW2D.



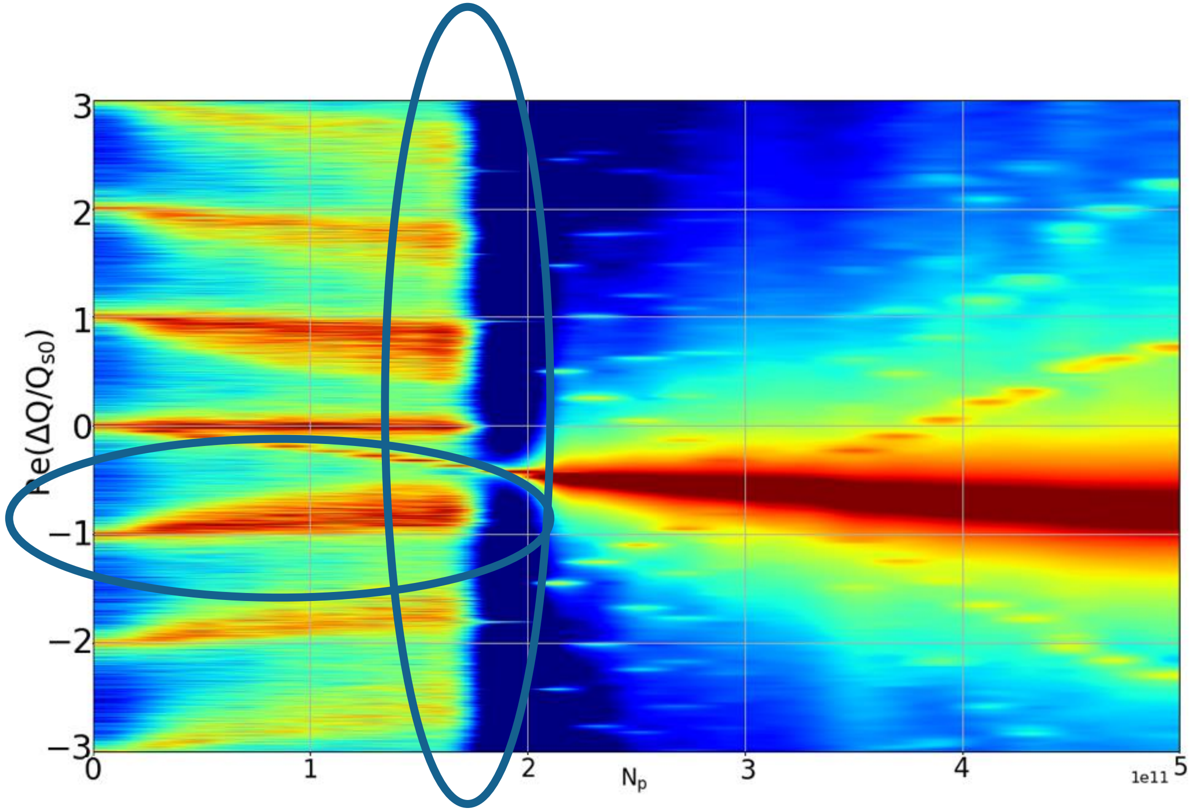
On the right, real part of the coherent tune shift as a function of intensity considering the longitudinal resistive wall wakefield, by using PyHEADTAIL.

TMCI

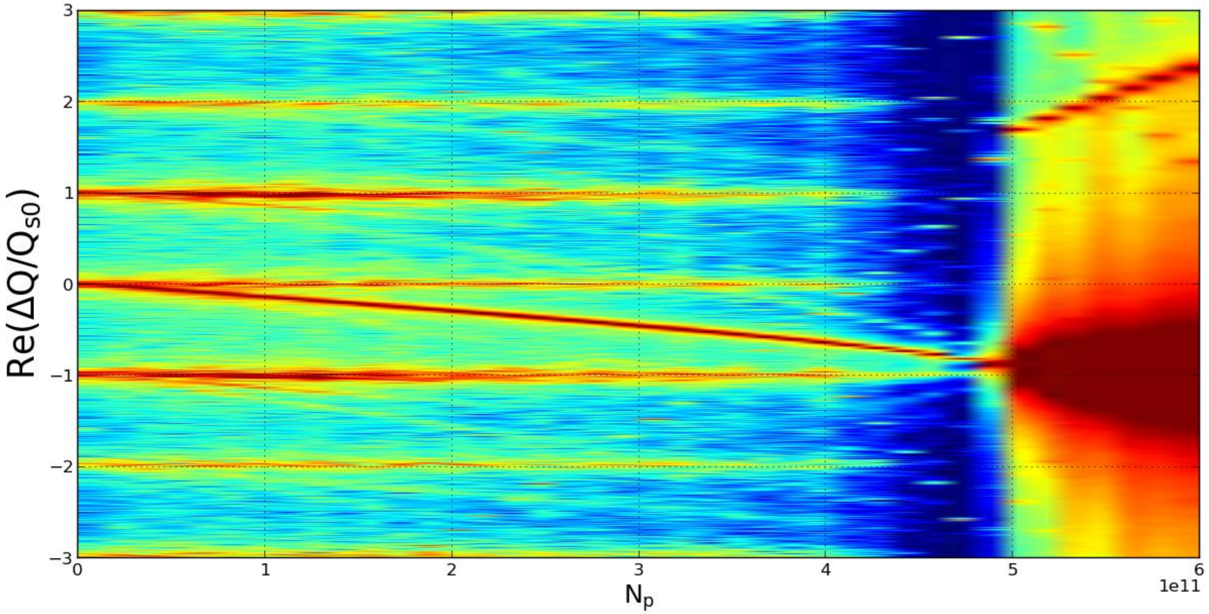
Without longitudinal resistive wall wakefield



Considering the longitudinal resistive wall wakefield



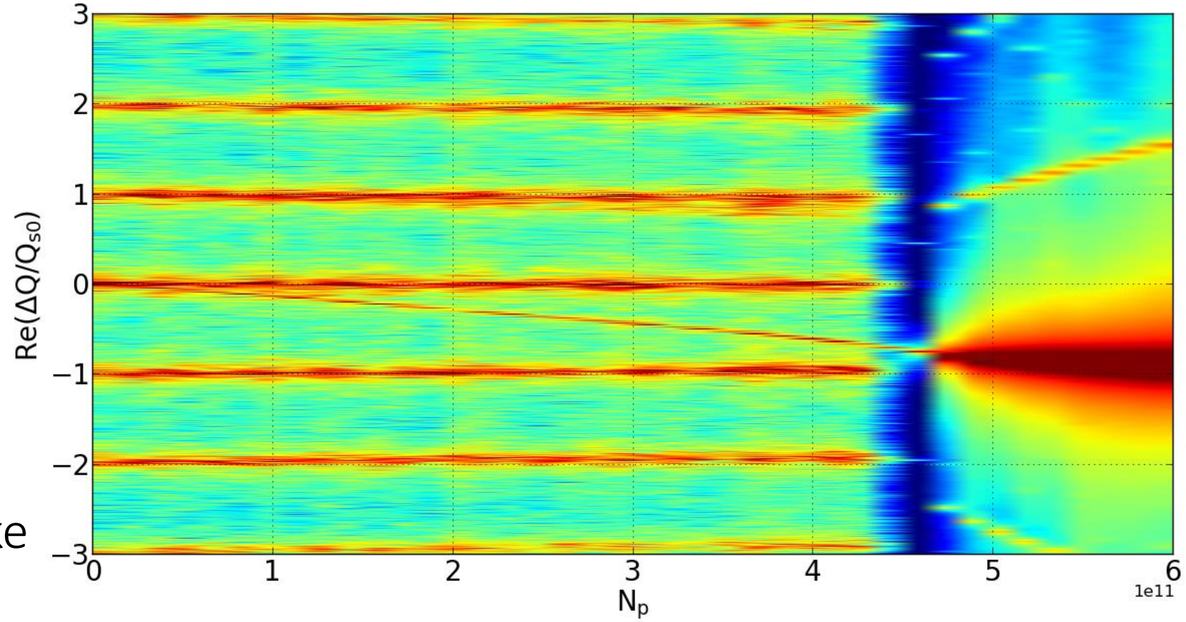
Transverse RW for a beam length of 12.1mm: TMCI analysis



Without longitudinal wakefield

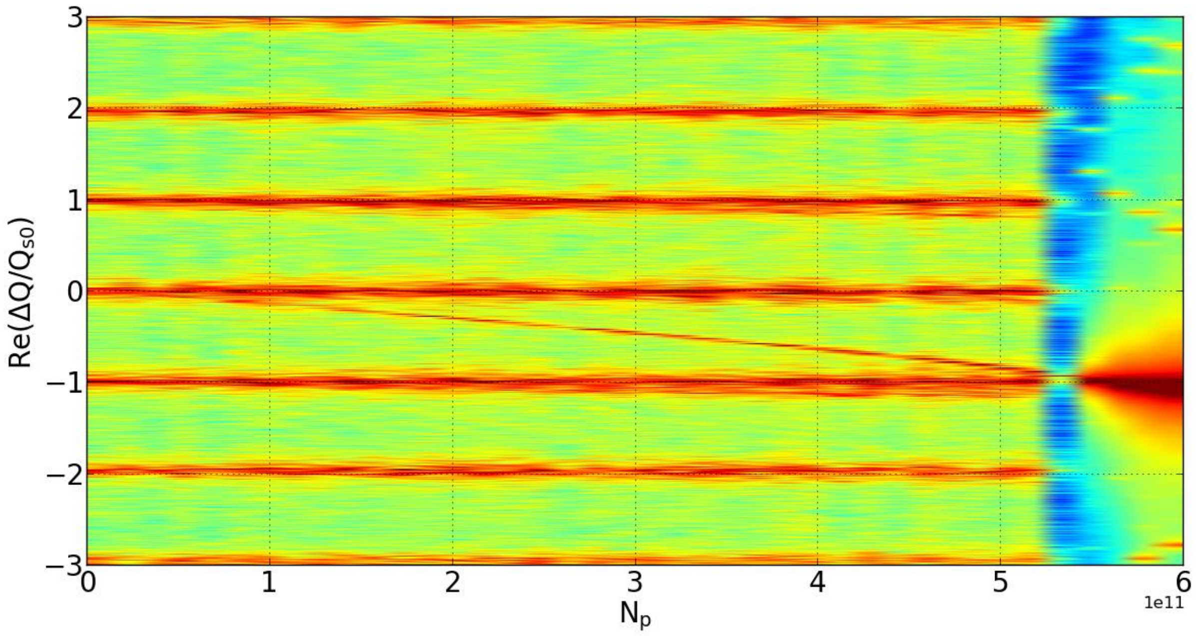
Transverse wake: PyHT vs Delphi

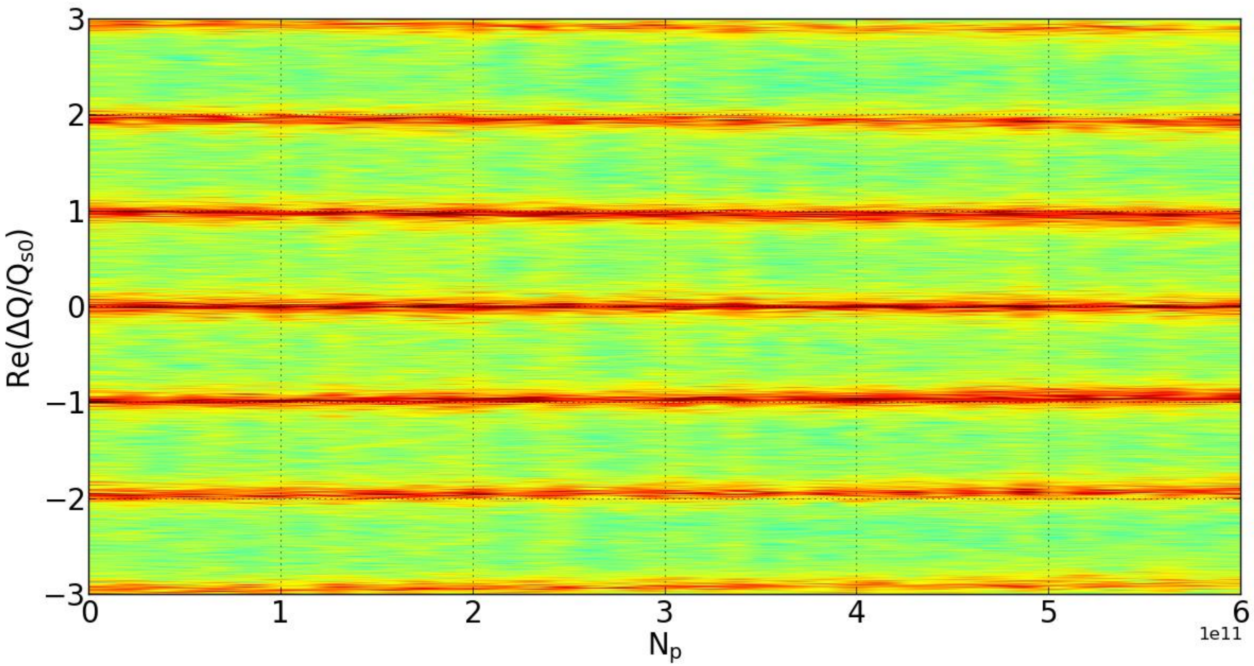
Considering the longitudinal wakefield



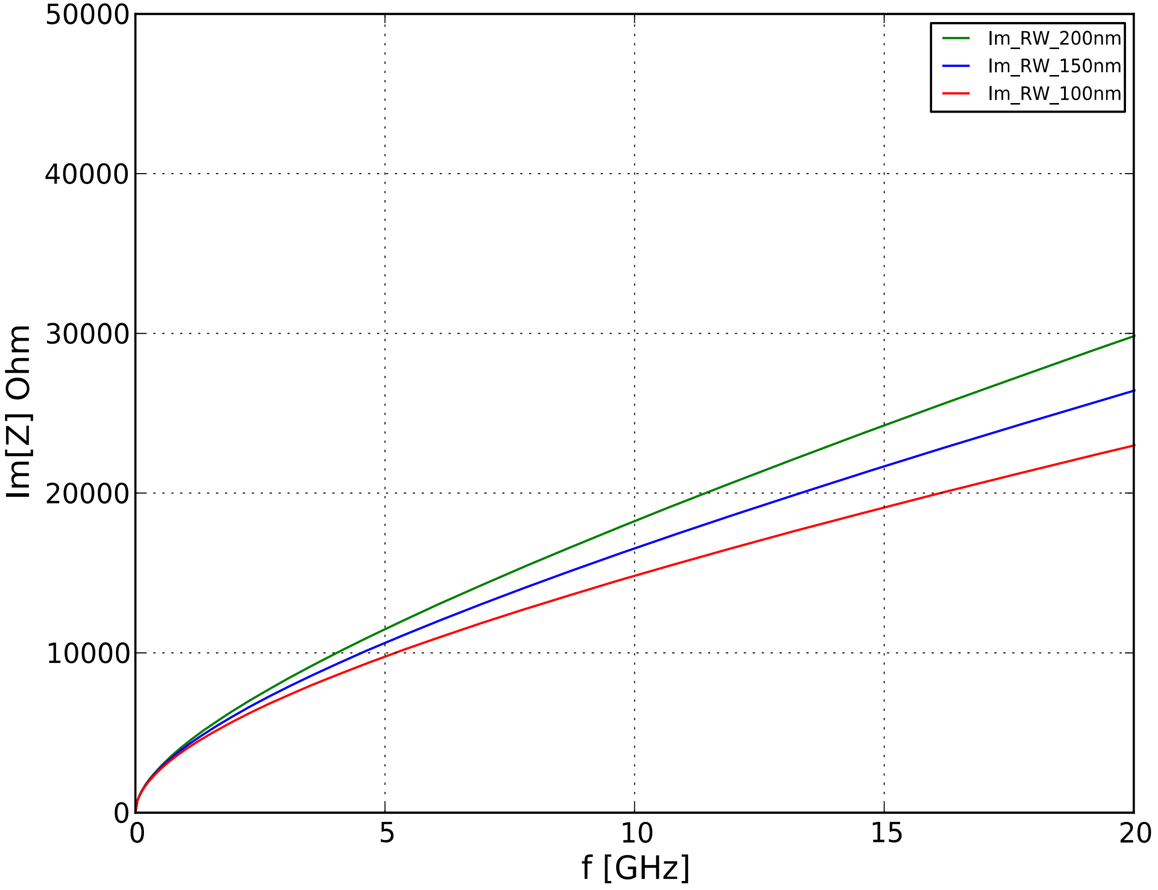
Longitudinal wake

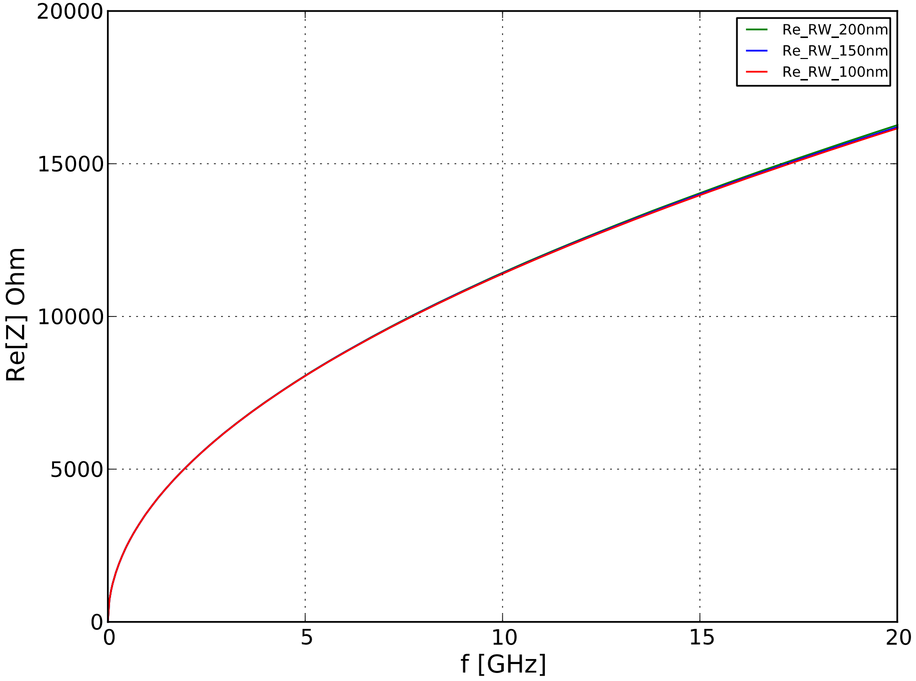
TMCI: longitudinal wake (on the right) and transverse wake (on the left) with a bunch length of 14.5 mm



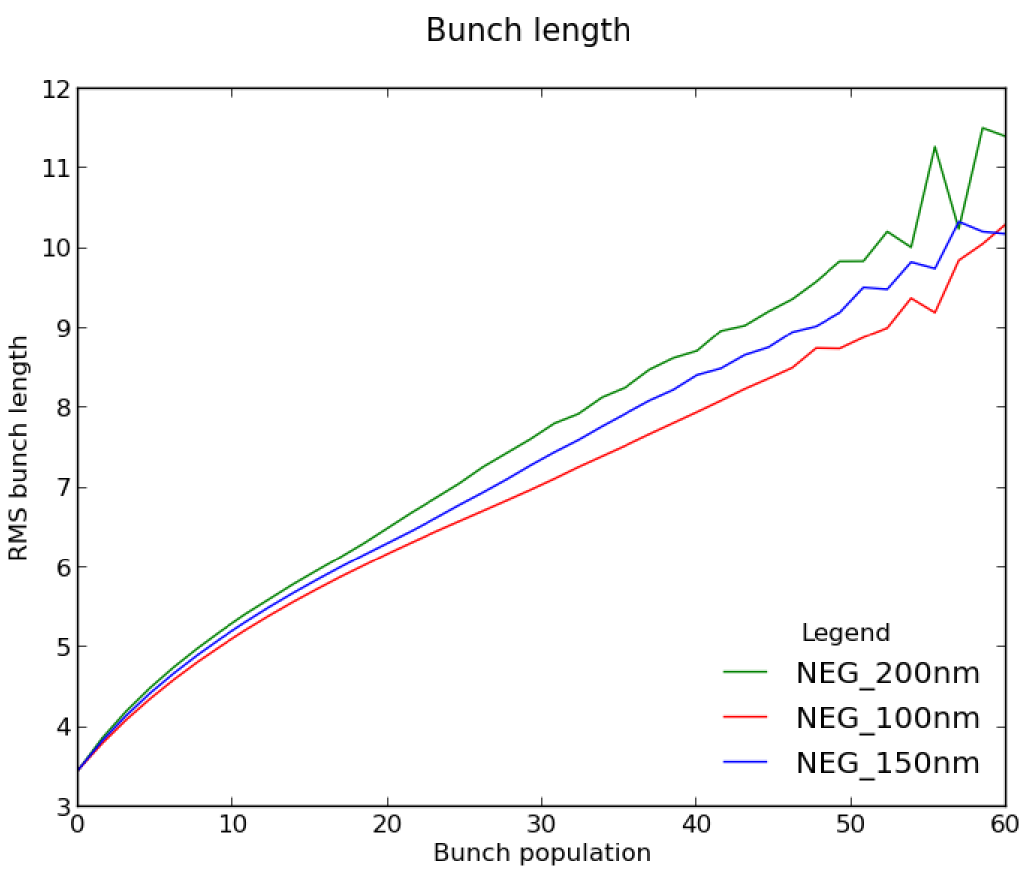


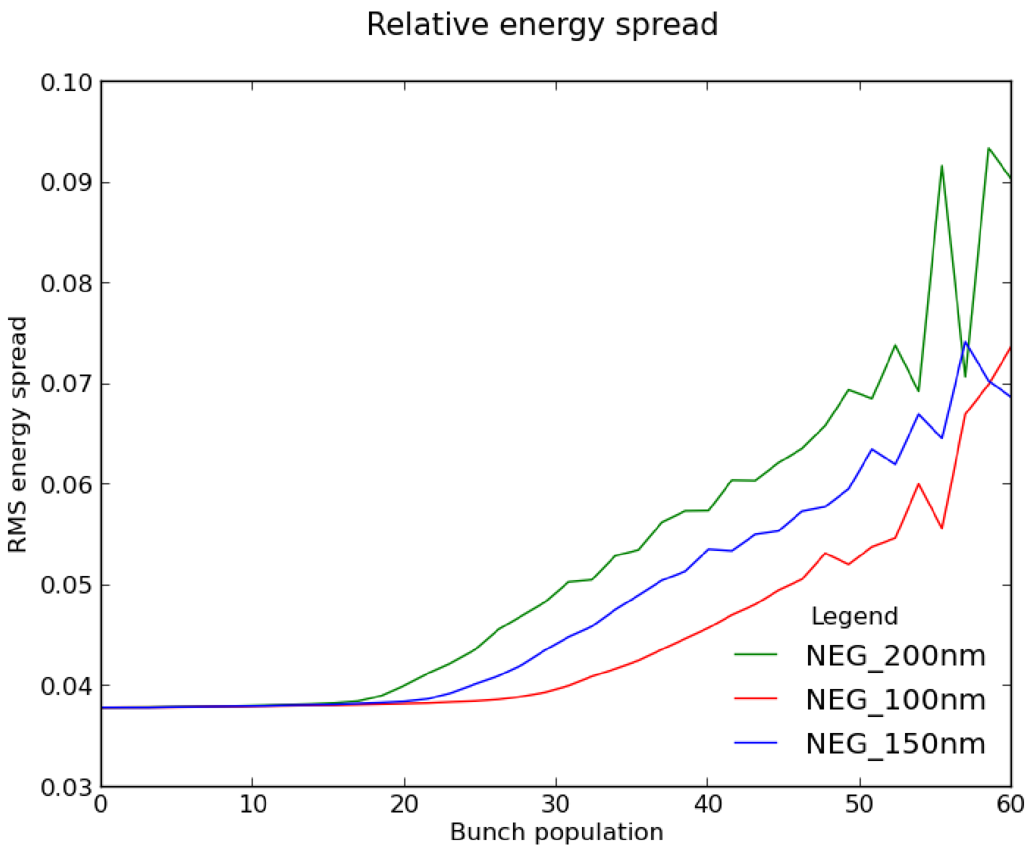
New evaluation of the impedances using different NEG coating : 100 nm 150 nm and 200 nm



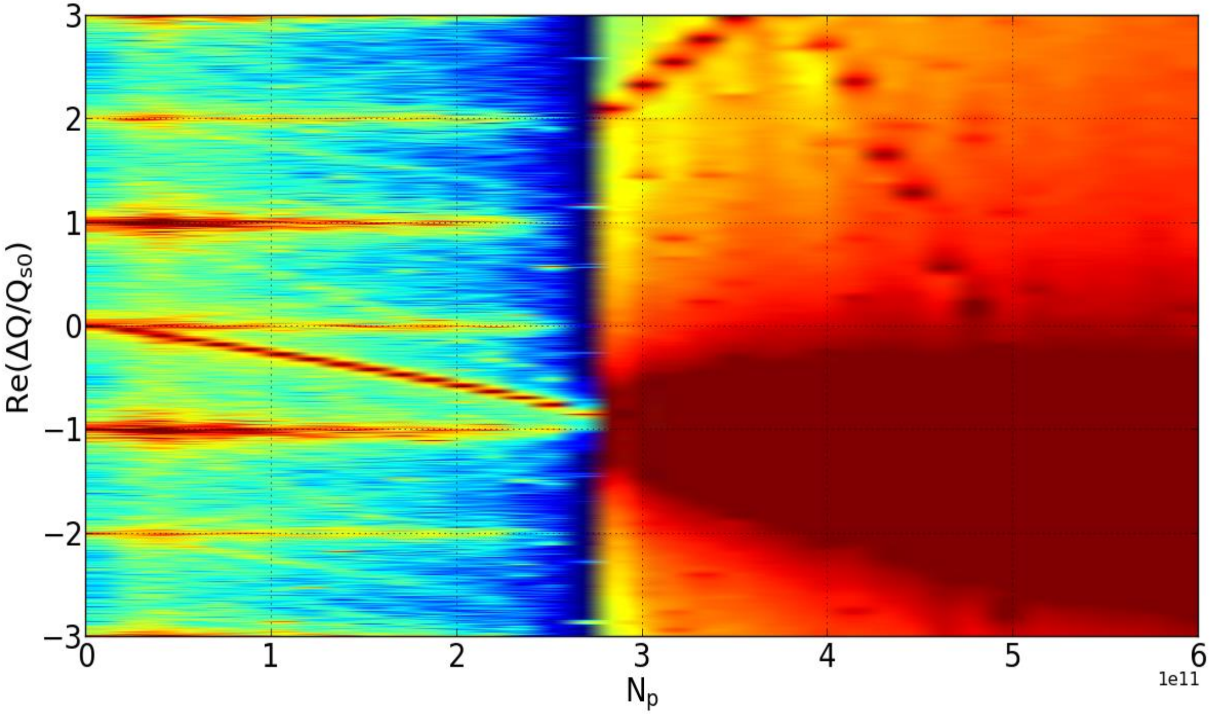


LONGITUDINAL DYNAMICS

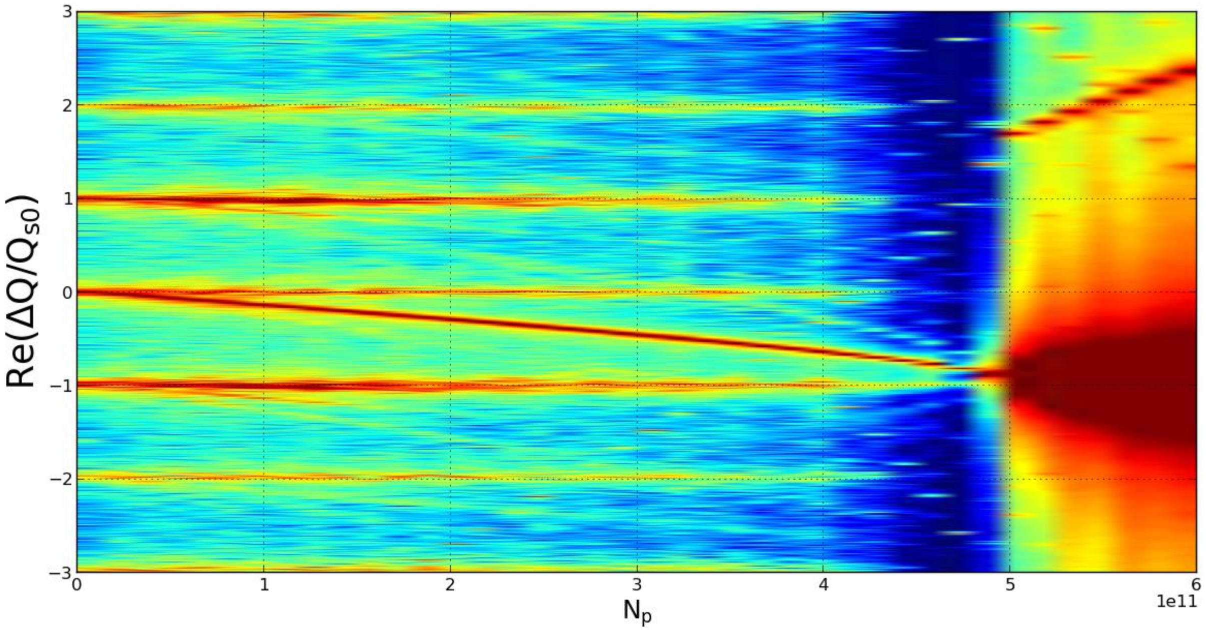




TMCI analyzes using wake with different NEGs : **100nm,** 150 nm and 200 nm

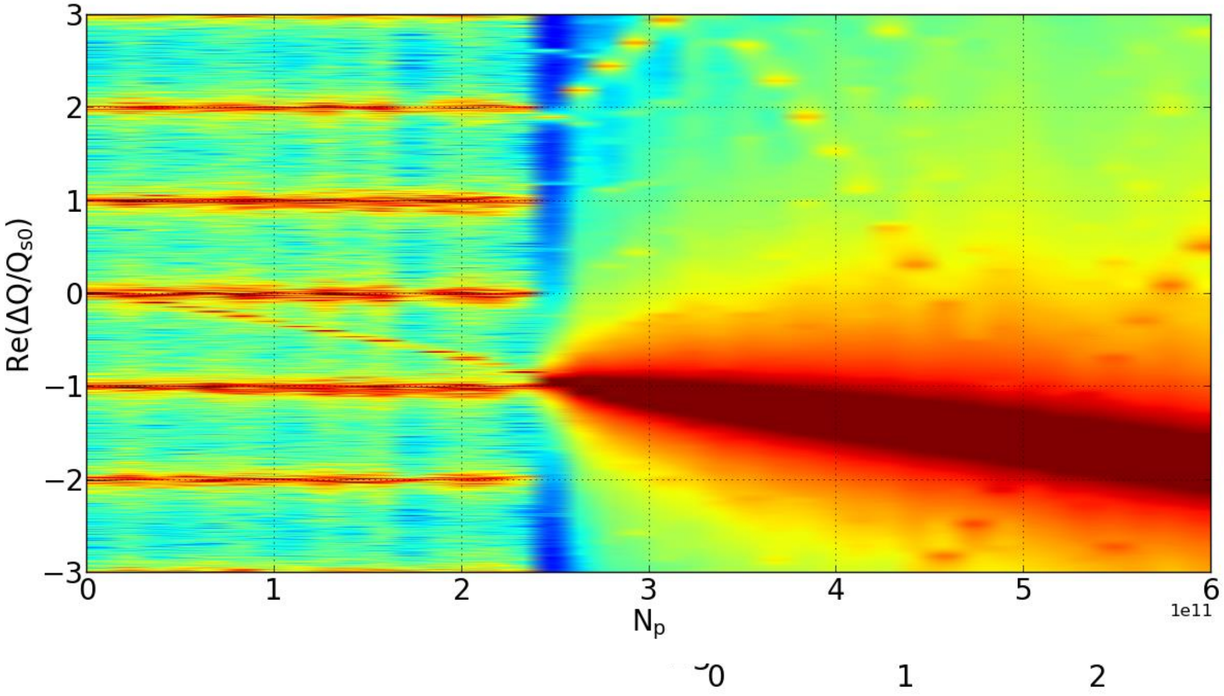


On the letf the plot of the TMCI considering a wake with 100nm of NEG and a beam length of 3.5mm



On the right the plot of the TMCI considering a wake with 100nm of NEG and a beam length of 12.1mm

TMCI analyzes using wake with different NEGs : 100nm, **150 nm** and 200 nm



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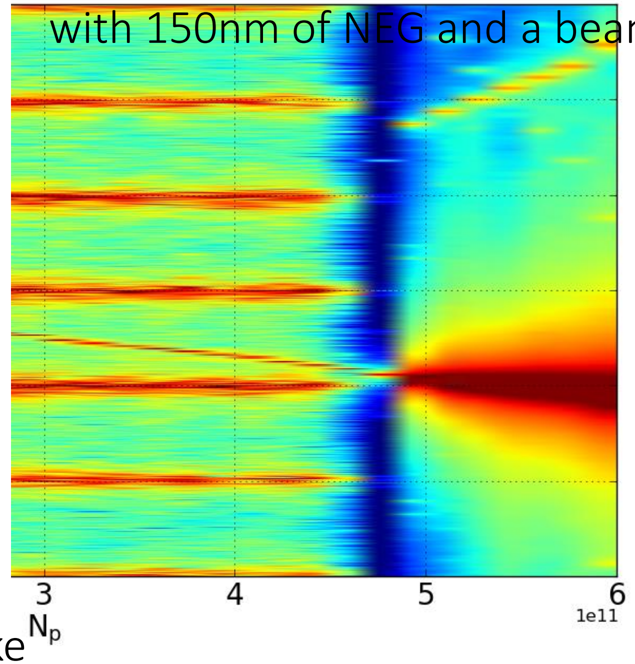
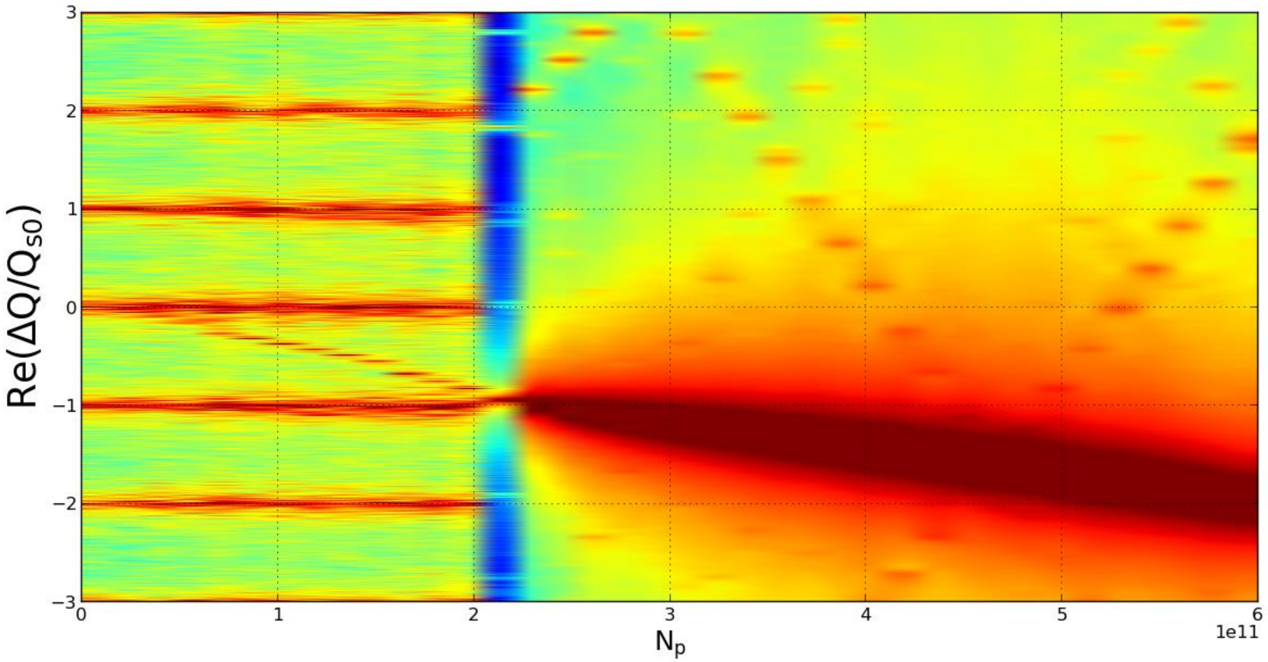
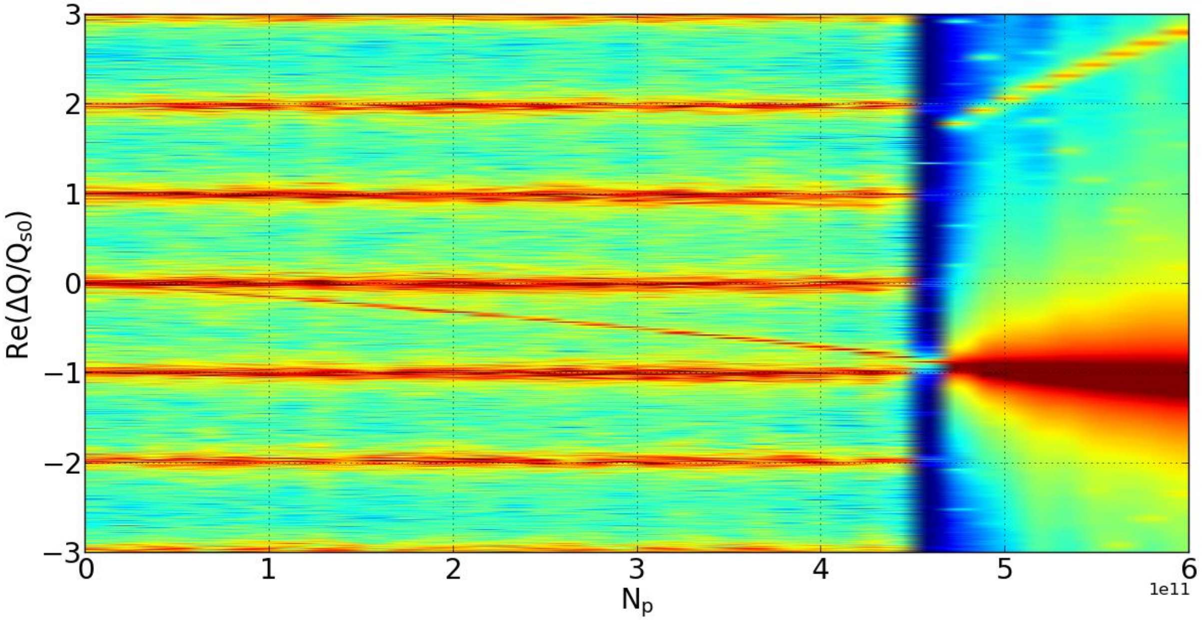


On the right the plot of the TMCI considering a wake with 150nm of NEG and a beam length of 12.1mm

TMCI analyzes using wake with different NEGs : 100nm,150 nm and **200 nm**



On the letf the plot of the TMCI considering a wake with 200nm of NEG and a beam length of 3.5mm



On the right the plot of the TMCI considering a wake with 200nm of NEG and a beam length of 12.1mm