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Collective effects in the booster synchrotron

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Parameter list: Z-pole and booster (injection)

Table 6.1: FCC-ee injector parameters.

Parameter [unit]	Z		W		H		$t\bar{t}$	
Type of filling	Initial	Top-up	Initial	Top-up	Initial	Top-up	Initial	Top-up
No. of BR cycles	10	1	10	1	10	1	20	1

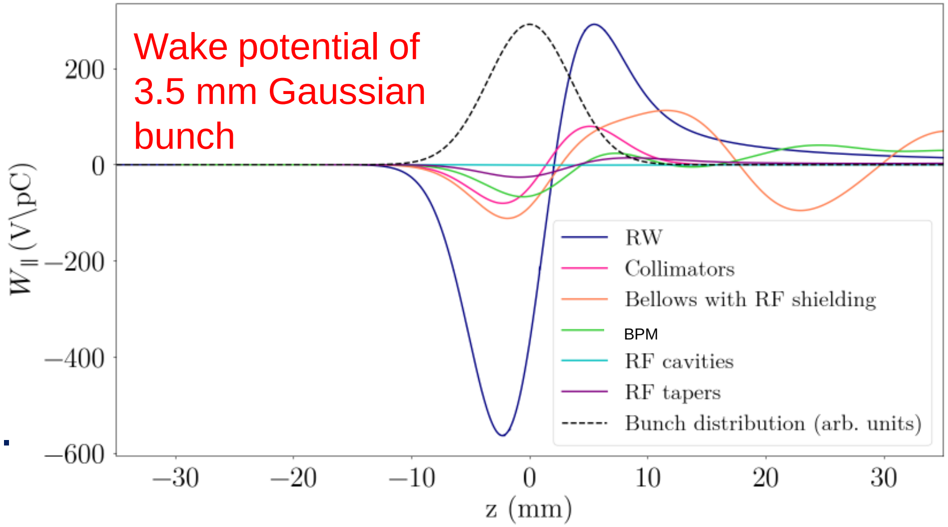
parameter	Z	Booster	
Beam energy (GeV)	45.6	20	
Bunch population [10^{11}]	1.7	.34 (1.7/5)	
Energy spread(SR/BS) [10^{-3}]	0.38/1.32	.166	
Energy loss/turn (MeV)	36.0	1.33	
RF frequency (MHz)	400	400	
RF voltage (MV)	100	60	
Arc optics		60° ph adv	90° ph adv
Mom compaction [10^{-6}]	14.8	14.8	7.27
Synchrotron tune	0.025	0.030	0.021
Bunch length [mm](SR/BS)	3.5/12.1	1.26	0.88

Z-pole impedance vs booster

- The thresholds at Z pole without BS are 2.5×10^{11} ppb for microwave instability and 4.2×10^{11} ppb for TMCI, but with BS they are much higher.

- The main responsible of the instabilities is the RW impedance due to a copper beam pipe of 35 mm of radius with a thin coating of NEG.

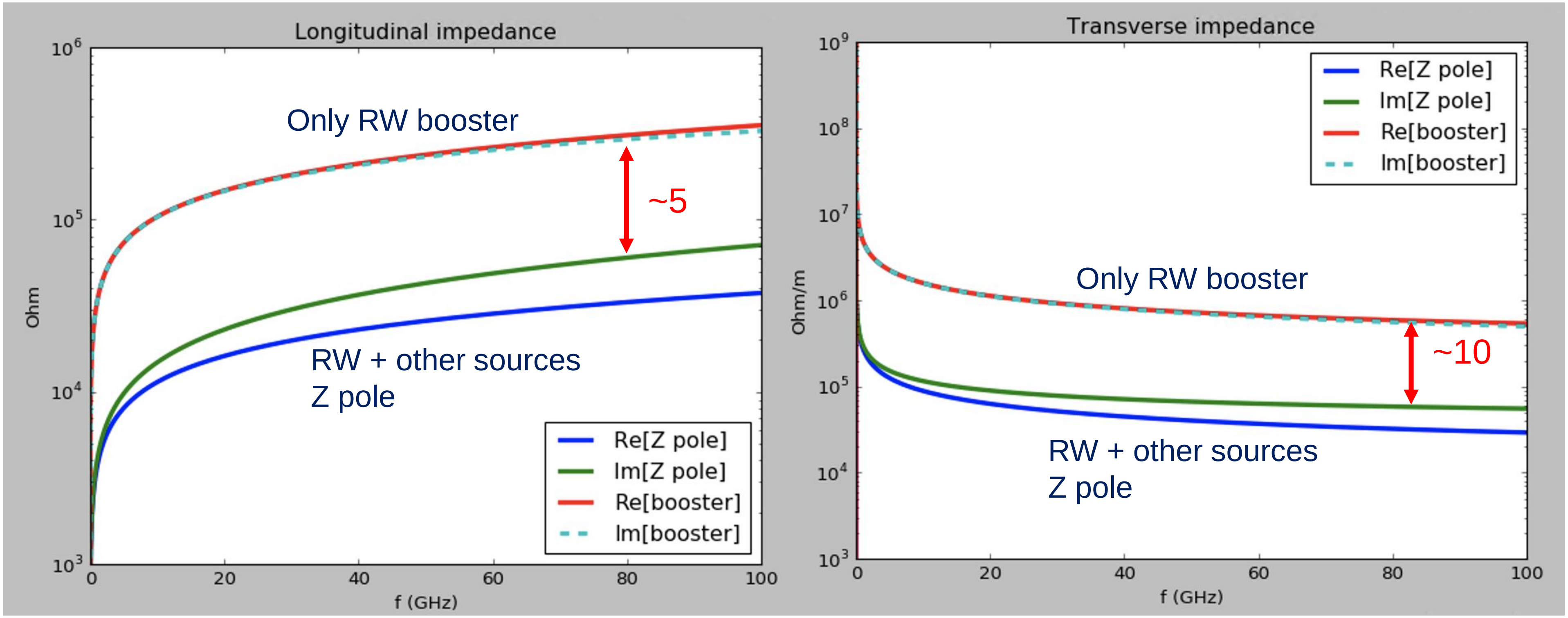
- For the booster the beam pipe is 25 mm and it is made of stainless steel.



- The resistivity of stainless steel is about 40 times larger than that of copper at room temperature.

- The longitudinal impedance is proportional to r^{-1}, and the transverse one to r^{-3} $\rightarrow$ for the booster we have a larger factor of 1.4 and 2.7 respectively.

RW impedance: Z-pole vs booster



Some scaling considerations: microwave instability

$$I_{th} \propto \frac{\sqrt{2\pi}\,\alpha_c (E/e)(\sigma_{\varepsilon 0}/E)^2 \sigma_{z0}}{R|Z/n|}$$

$$\frac{I_{th}^b}{I_{th}^Z} = \frac{(7.3/14.8) \times (20/45.6) \times (.166/.38)^2 \times (.88/3.5)}{(5/1)} = 0.002 \simeq \frac{1}{500}$$

NB1: radiation damping time is about 4.9 s compared with 0.414 s of Z pole (12 times larger)

NB2: for the 60 degrees phase advance optics (Z/W operations) the ratio is 0.006

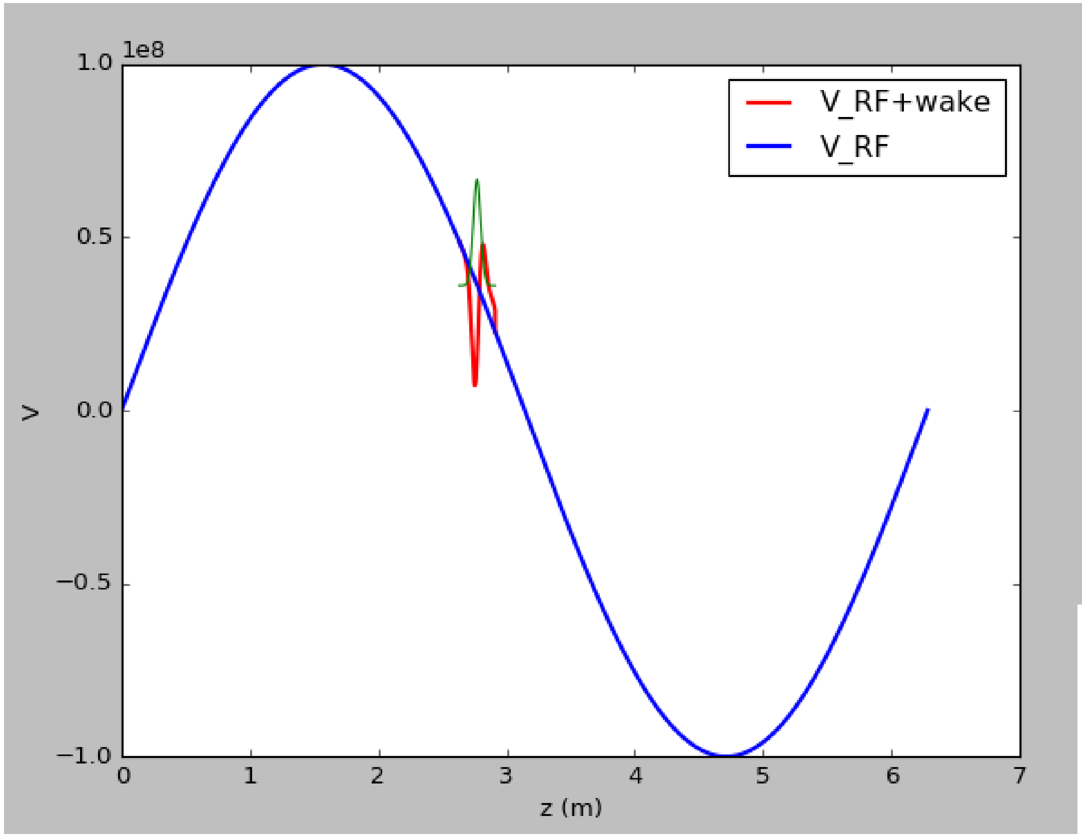
Some scaling considerations: TMCI

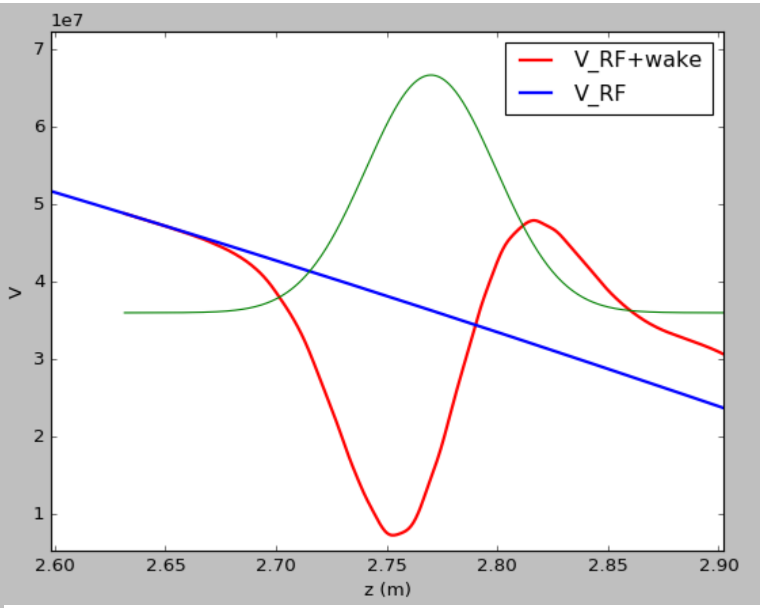
$$I_{th} \propto \frac{4(E/e)\nu_s}{R\sum\left\{\left[\mathrm{Im}\, Z_T\right]\beta_y\right\}} \frac{4\sqrt{\pi}}{3}\sigma_z$$

$$\frac{I_{th}^{b}}{I_{th}^{Z}} = \frac{(20/45.6) \times (0.021\,/0.025) \times (.88/3.5)}{(10/1) \times (269/389)} \simeq 0.01$$

Average beta inversely propotional to machine tune

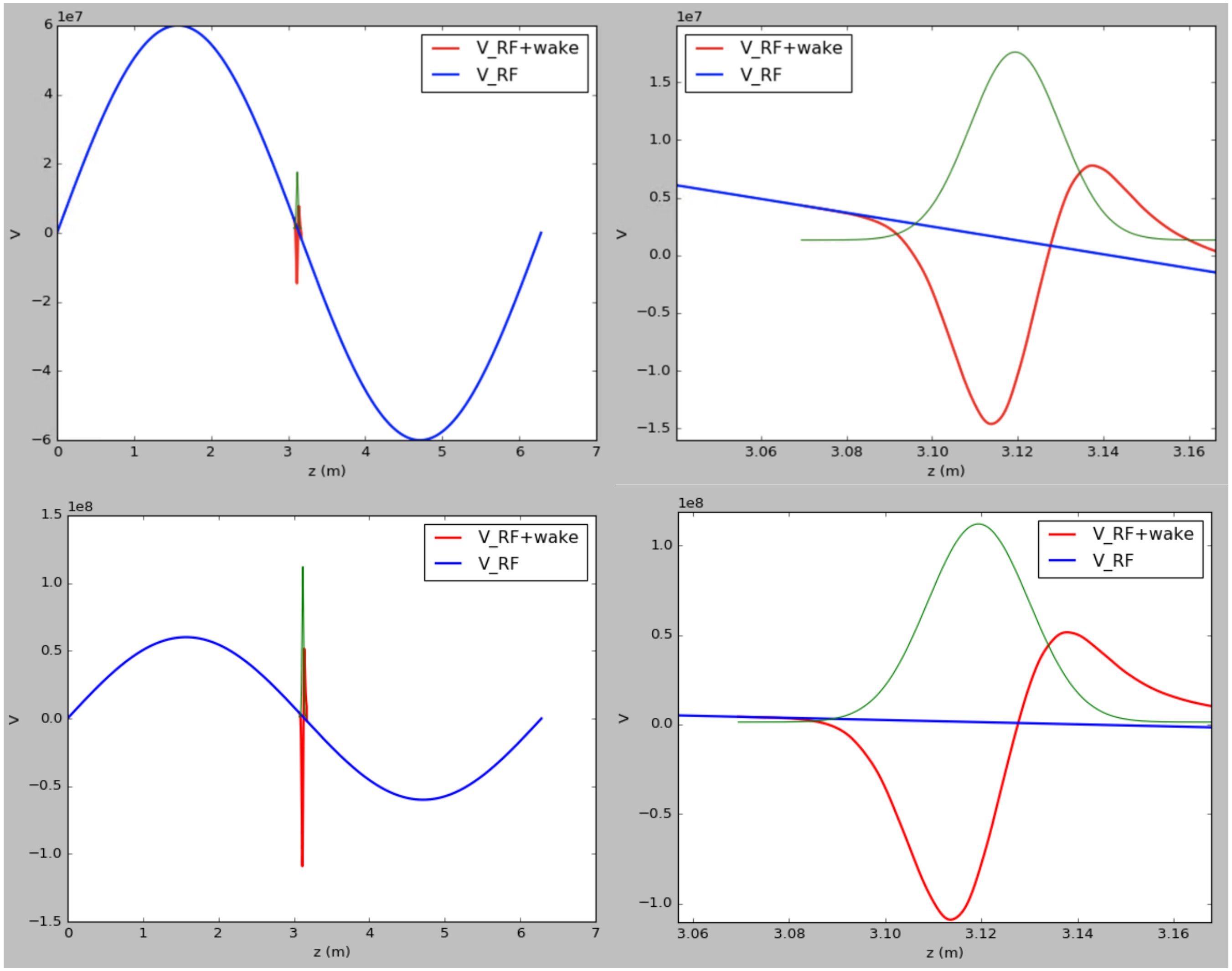
Induced voltage for Z-pole at 2.3×10^{11} ppb





nominal bunch length: $\sigma_z = 3.5$ mm

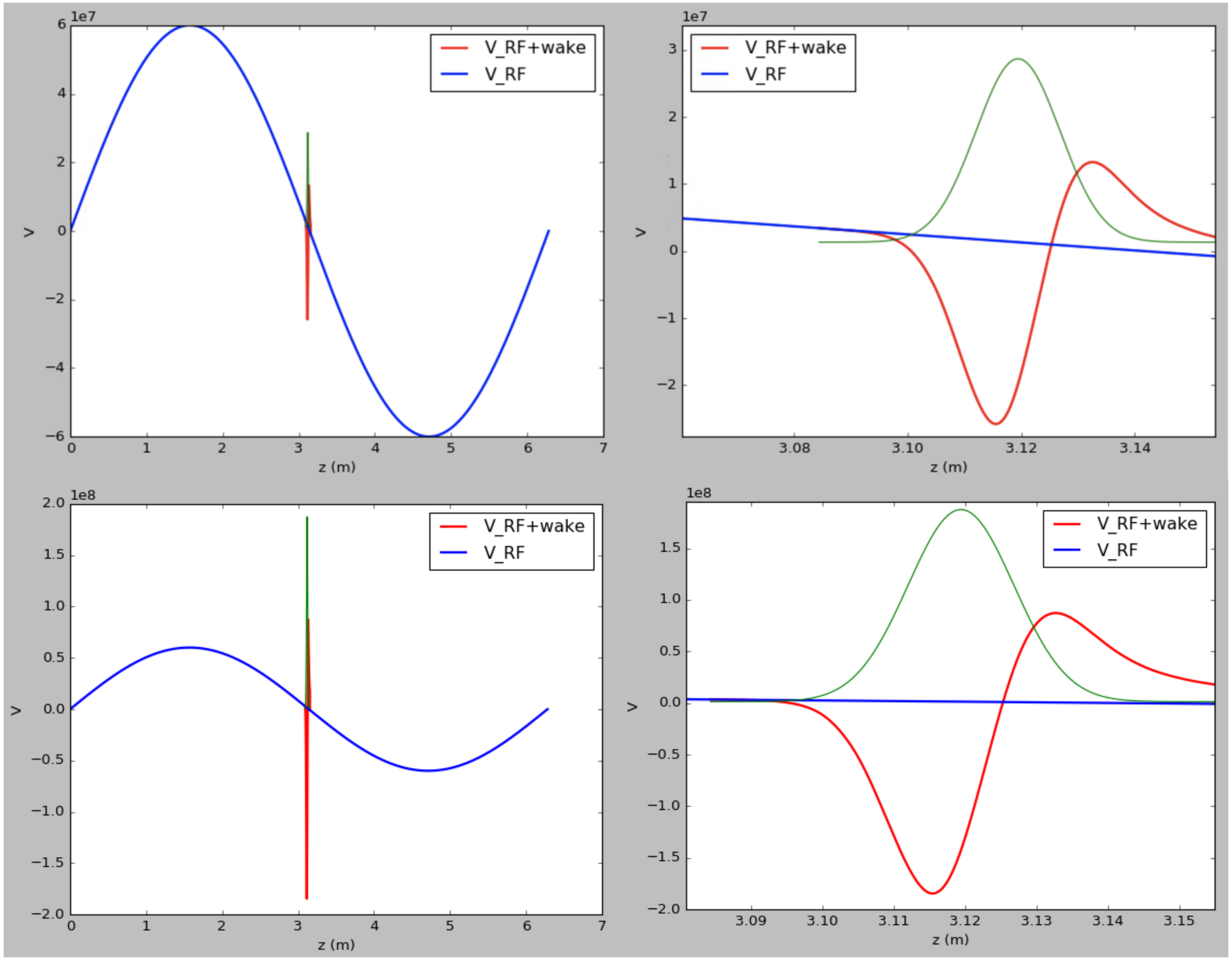
Induced voltage for booster with 60º optics



Np= 0.5x10^{10} ppb, 60º phase advance optics, nominal bunch length $\sigma_z = 1.26$ mm

Np= 3.4x10^{10} ppb, 60º phase advance optics, nominal bunch length $\sigma_z = 1.26$ mm

Induced voltage for booster with 90º optics

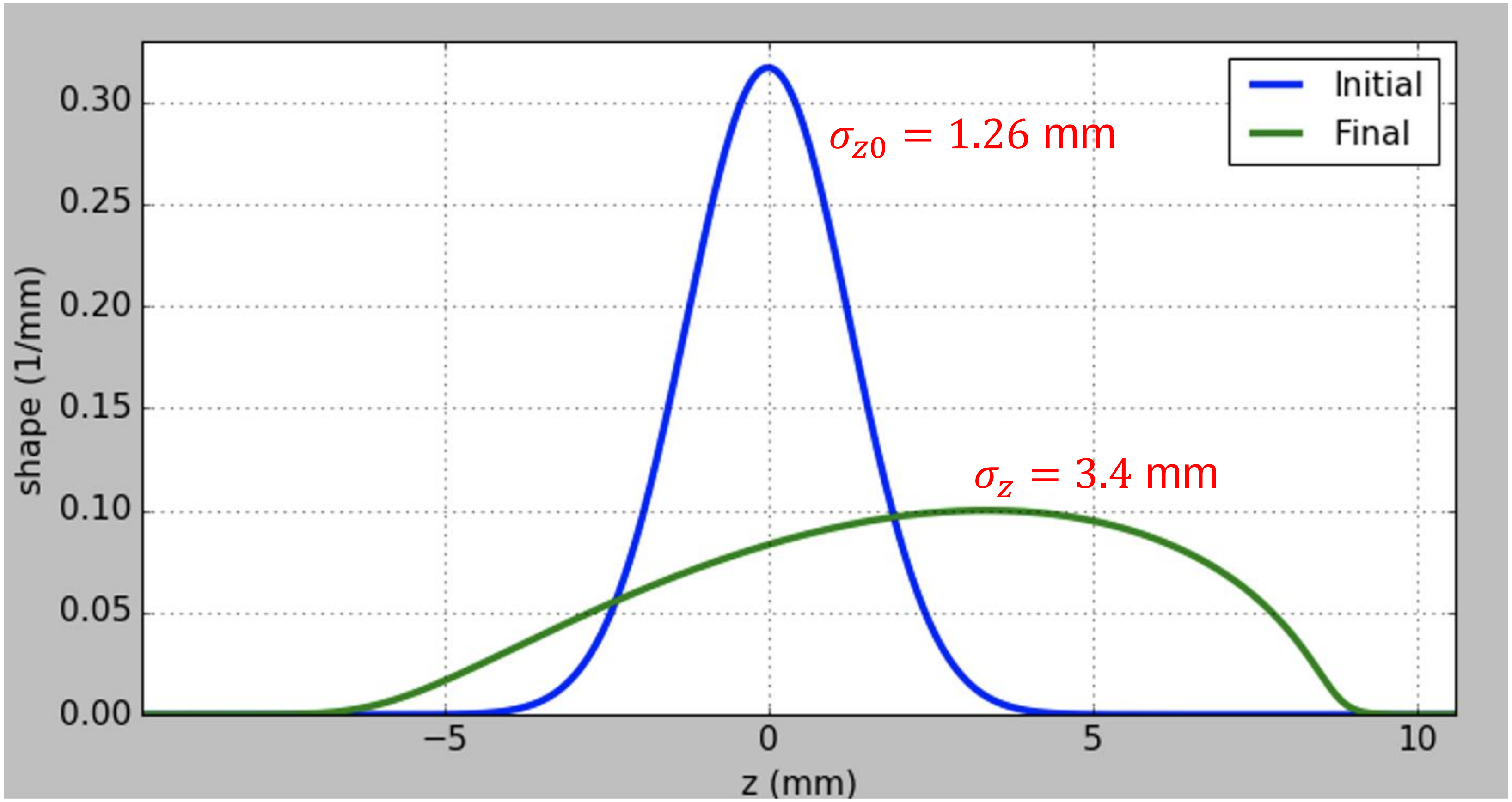


Np= 0.5×10^{10} ppb, 90º phase advance optics, nominal bunch length $\sigma_z = 0.88$ mm

Np= 3.4×10^{10} ppb, 90º phase advance optics, nominal bunch length $\sigma_z = 0.88$ mm

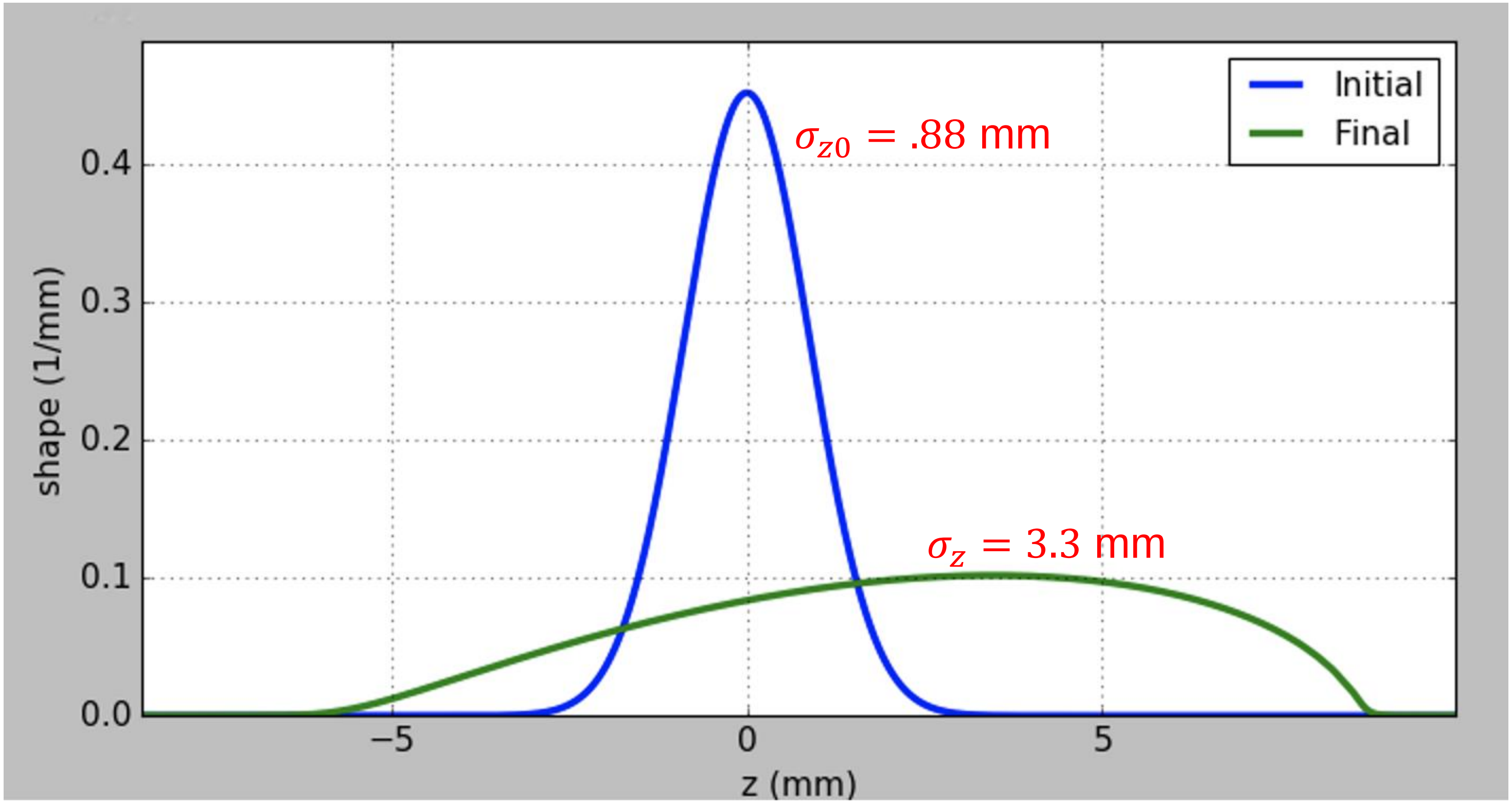
Haissinski

60° phase advance, 0.5e10 ppb

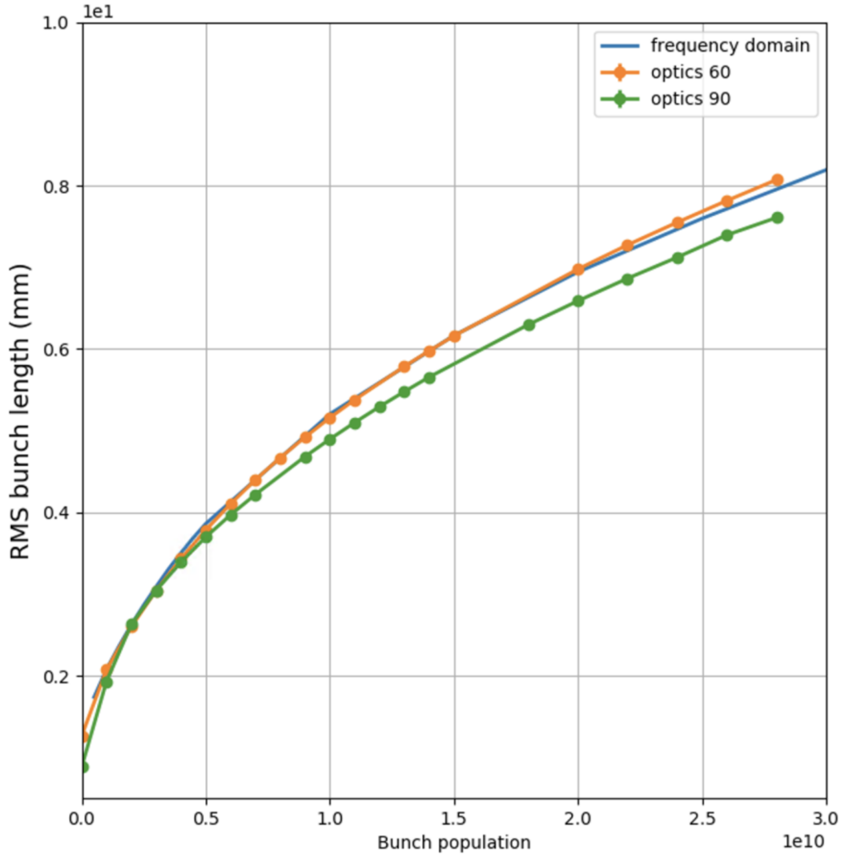


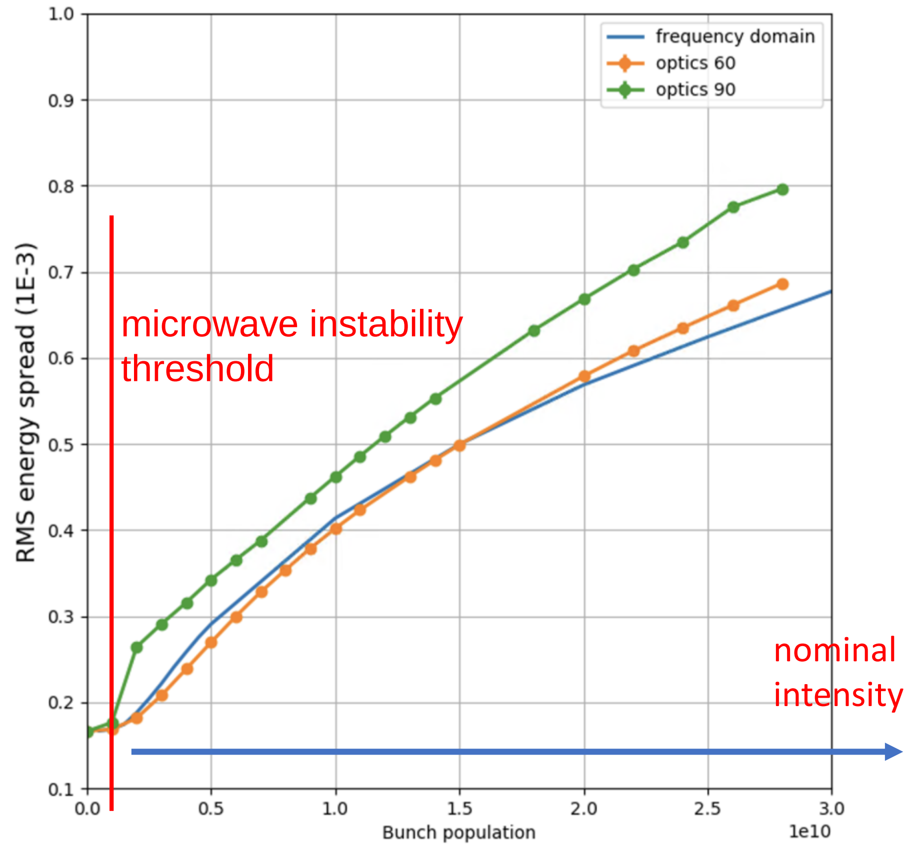
Haissinski

90˚ phase advance, 0.5e10 ppb



Longitudinal beam dynamics simulations

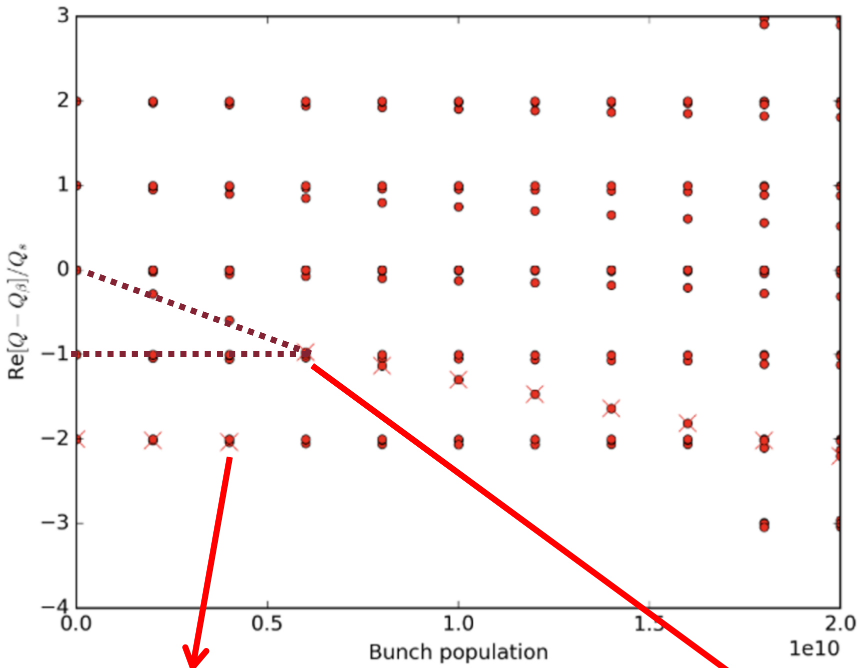


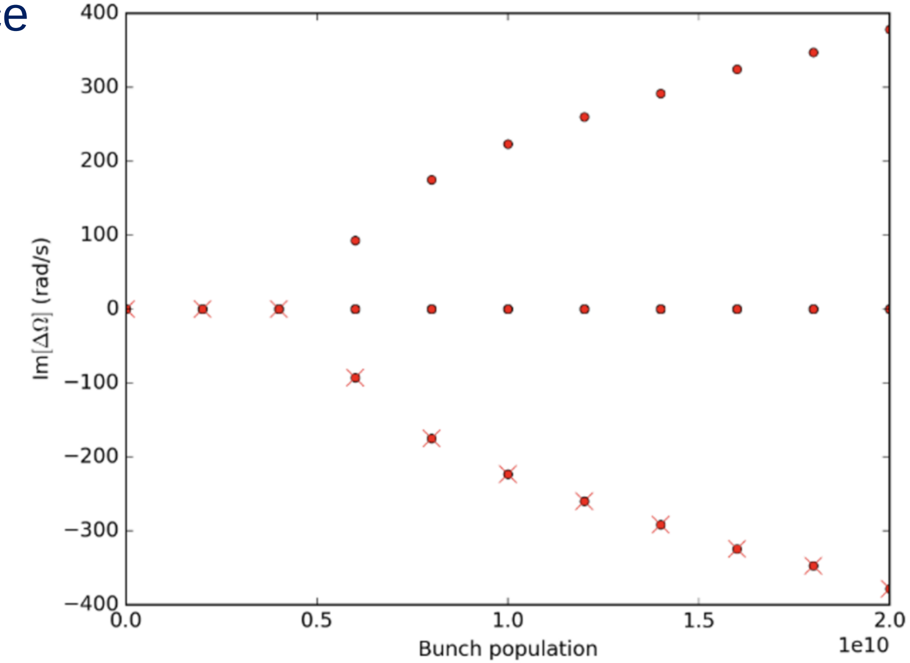


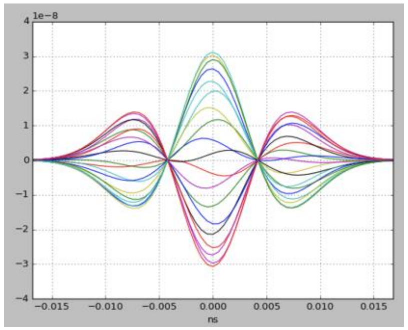
Preliminary results

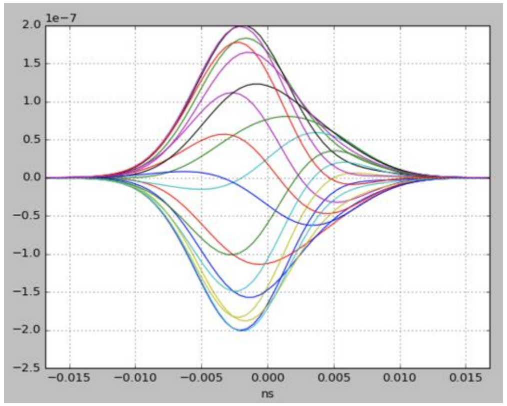
TMCI threshold

DELPHI code, optics 60° phase advance



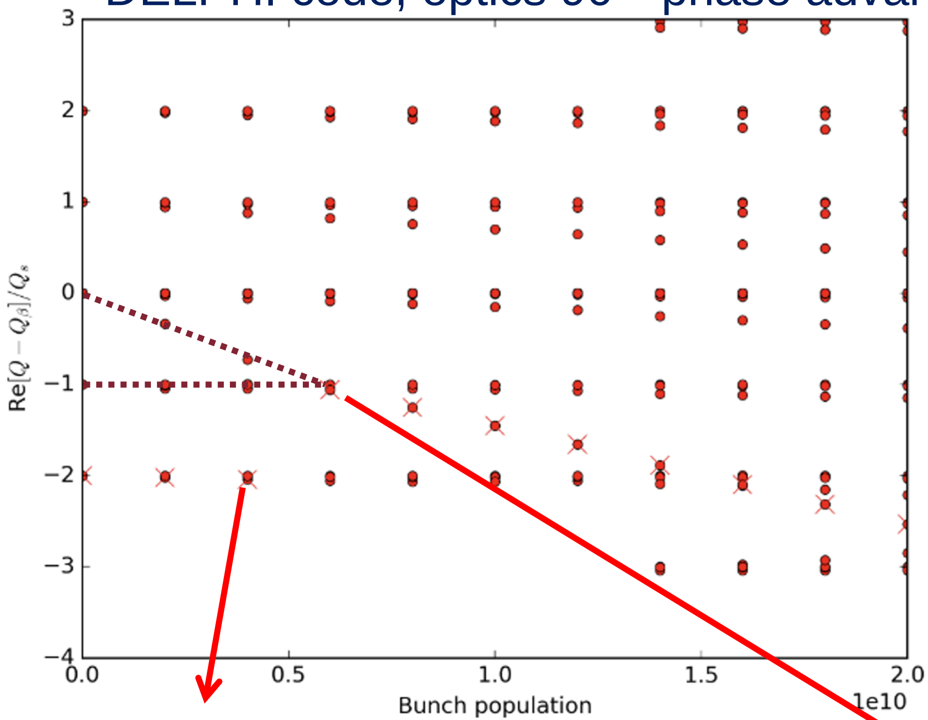


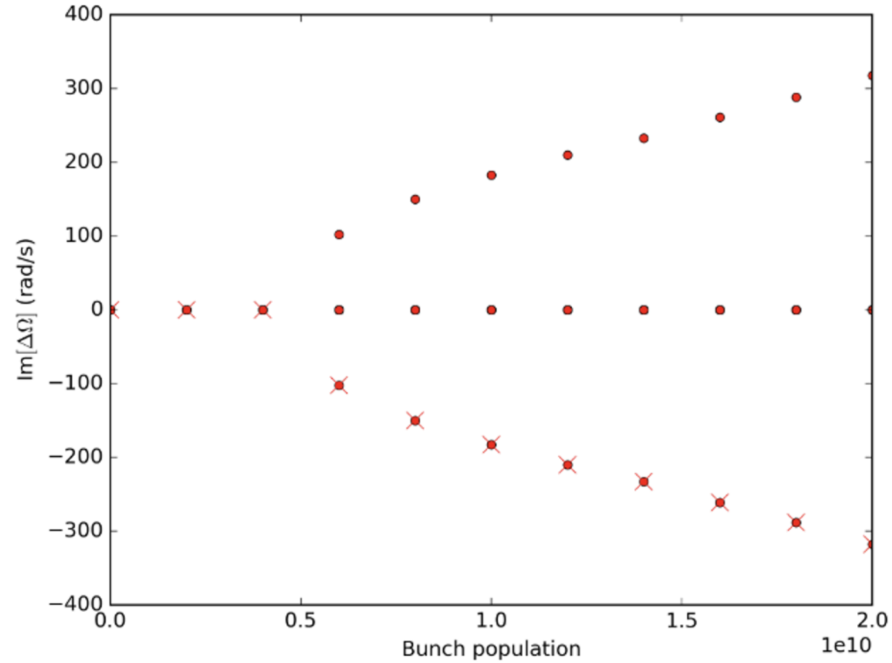


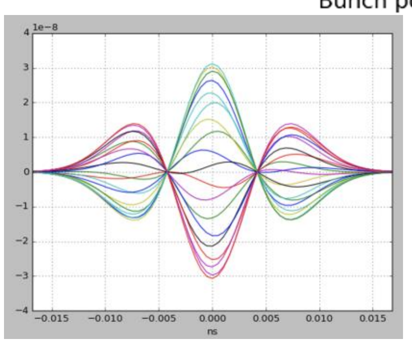


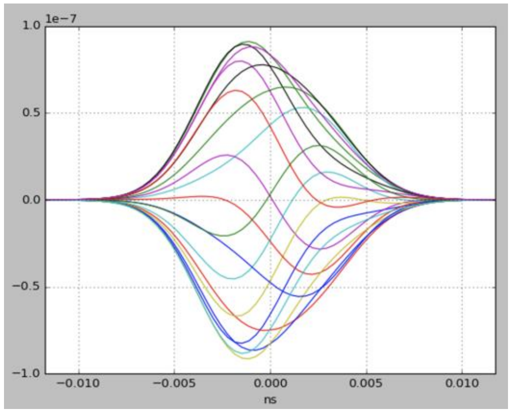
TMCI threshold

DELPHI code, optics 90° phase advance









RW transverse coupled bunch instability
60º optics

- Hp: azimuthal mode m=0, a Gaussian bunch, one single frequency line of coherent oscillation modes coupling the transverse RW impedance. The growth rate can be obtained with

$$\alpha = -\frac{cN_b I_b}{4\pi (E/e) Q_\beta} \mathrm{Re}\left[Z_\perp(\omega_q)\right] \qquad \mathrm{Re}[Z_\perp(\omega)] = \mathrm{sgn}(\omega)\frac{L}{2\pi b^3}\sqrt{\frac{2Z_0 c}{\sigma_c|\omega|}}$$

- where

$$w_q = w_0\left(qN_b + m + Q_b\right) \qquad w'_q = w_q - x\frac{w_b}{a_c}$$

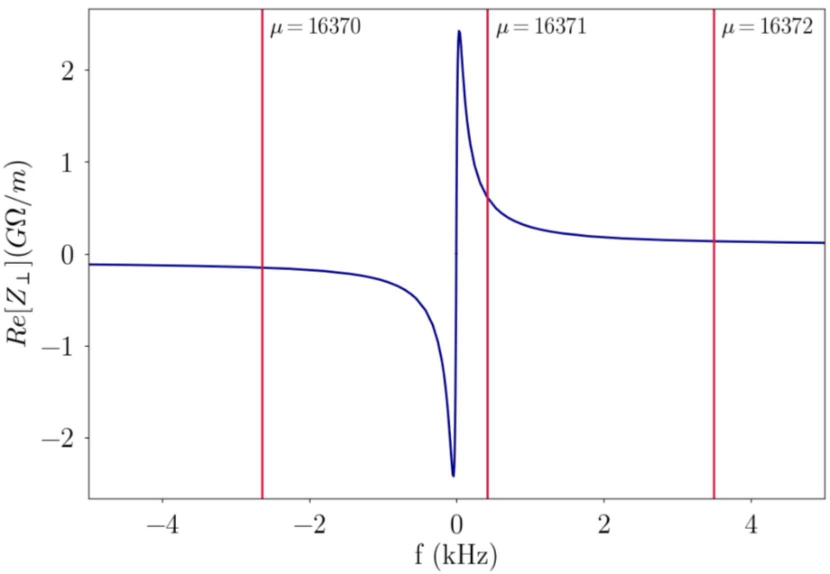
-1 16640 16370 269.05

e.g.

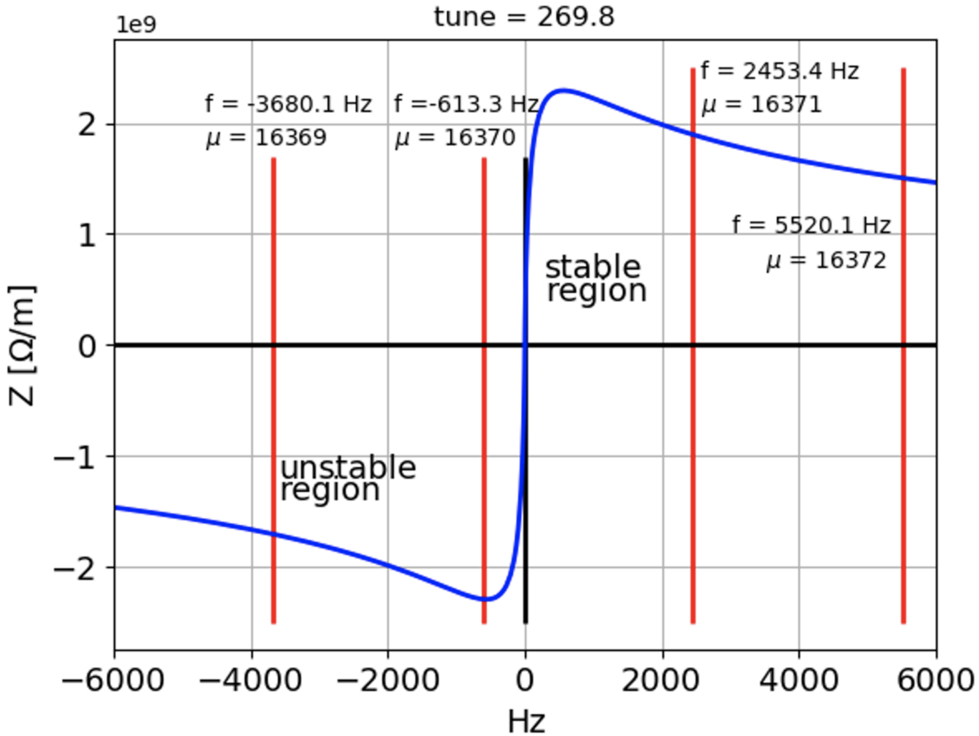
269.05 ➡ $\omega_q = -0.95\omega_0$

269.95 ➡ $\omega_q = -0.05\omega_0$

RW Transverse coupled bunch instability
60º optics



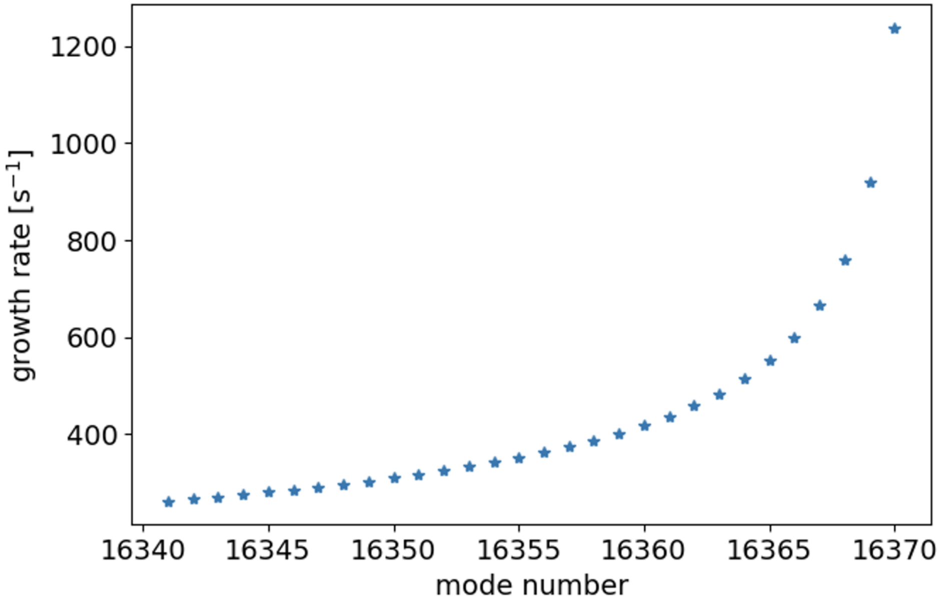
Z pole: real part of the RW impedance for a copper beam pipe of 35 mm.

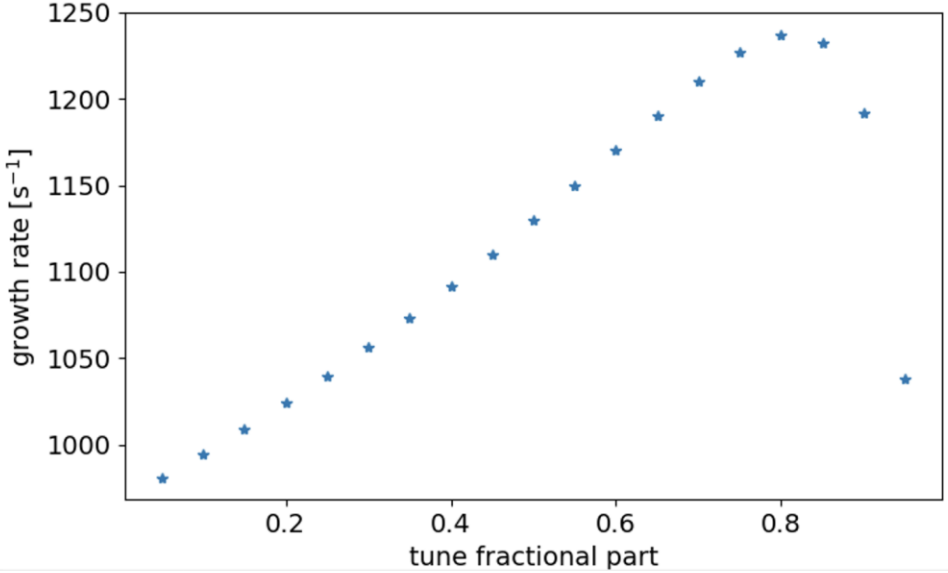


Booster: real part of the RW impedance for a stainless steel beam pipe of 25 mm.

For the booster, due to the stainless steel, the peak of the impedance at low frequency is larger with respect to copper, and, differently from the Z pole, a variation of the fractional part of the tune affects only slightly the growth rate.

RW Transverse coupled bunch instability
60º optics





The rise time is in the order of 1 ms or a bit less, and it changes only slightly with the fractional part of the tune. This rise time corresponds to about 3 turns, a factor of ~ 2 larger with respect to the TCBI of the collider in the Z-pole configuration.
As in the collider, new feedback schemes are required.

Conclusions

- The RW impedance of 100 km of stainless steel with a beam pipe of 25 mm radius has a strong impact on the beam dynamics of the booster.
- Thresholds of TMCI and microwave instability are lower than the nominal intensity.
- Methods to mitigate the effects of the instabilities or to put the thresholds to higher values should be investigated.
- Transverse coupled bunch instability due to RW is a factor of about 2 larger than in the collider.
- We also need to evaluate the effect on beam dynamics of the other impedance sources.

Thank you very much for your attention