SAPIENZA
UNIVERSITÀ DI ROMA
DIPARTIMENTO DI SCIENZE DI BASE
E APPLICATE PER L' INGEGNERIA

Single-beam collective effects in FCC-ee

M. Migliorati

Acknowledgements:

E. Belli, R. Calaga, R. Kersevan, K. Oide, S. Persichelli, E. Shaposhnikova, G. Stupakov, F. Zimmermann, D. Zhou, M. Zobov

Parameter list - FCC-ee Z-pole, crab waist, 2 IPs

parameter	Z	W	H	t
Circumference (km)	100	100	100	100
Beam energy (GeV)	45.5	80	120	175
Beam current (mA)	1450	152	30	6.6
RF frequency (MHz)	400	400	400	400
RF Voltage (GV)	0.2	0.8	3	10
Mom compaction [10^{-5}]	0.7	0.7	0.7	0.7
Bunch length [mm](*)	1.63	1.98	2.0	2.1
Energy spread(*)	3.7×10^{-4}	6.5×10^{-4}	1.0×10^{-3}	1.4×10^{-3}
Synchrotron tune	0.025	0.037	0.056	0.075
Bunches/beam	90300	5162	770	78
Bunch population [10^{11}]	0.33	0.6	0.8	1.7
Betatron tune	350	350	350	350

(*) without beamstrahlung (no collision)

Resistive wall impedance

RW impedance for a circular cross section in the range: $\frac{\chi c}{b} \ll \omega \ll \frac{c\chi^{-\frac{1}{3}}}{b}$, $\chi = \frac{1}{Z_0 \sigma_c c b}$

$$\frac{Z_{||}(\omega)}{L} = \frac{Z_0 c}{\pi} \frac{1}{[1 + i\mathrm{sgn}(\omega)]2bc\sqrt{\frac{\sigma_c Z_0 c}{2|\omega|}} - ib^2\omega}$$

$$\frac{Z_{\perp}(\omega)}{L} = \frac{Z_0 c^2}{\pi} \frac{2}{[\mathrm{sgn}(\omega) + i]cb^3\sqrt{2\sigma_c Z_0 c|\omega|} - ib^4\omega^2}$$

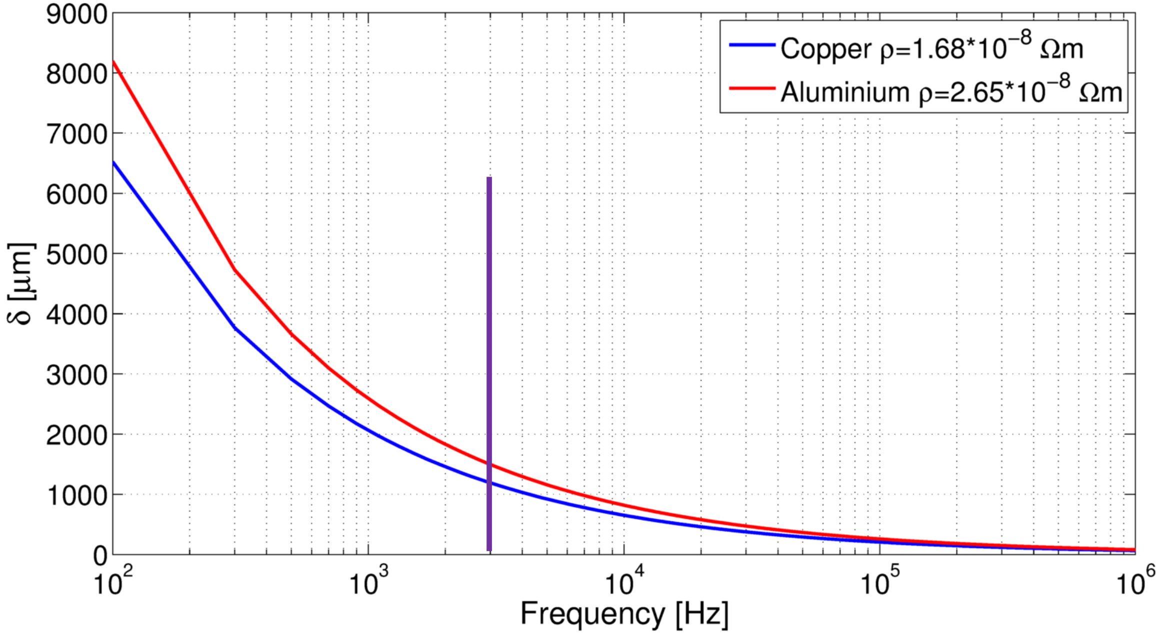
negligible up to f ~ 10^{11} Hz

The transverse impedance is more sensitive to the beam pipe radius and it scales with b^{-3}.

The RW impedance $\propto \sqrt{\rho} \rightarrow$ between copper and aluminium there is a factor of ~ **1.26**

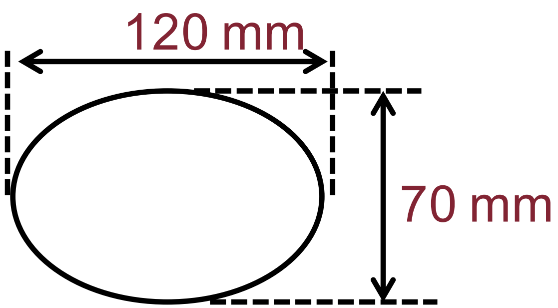
skin depth << the wall thickness

- At the revolution frequency of 3 kHz, the skin depth is ~1.5 mm for aluminium and ~1.2 mm for copper



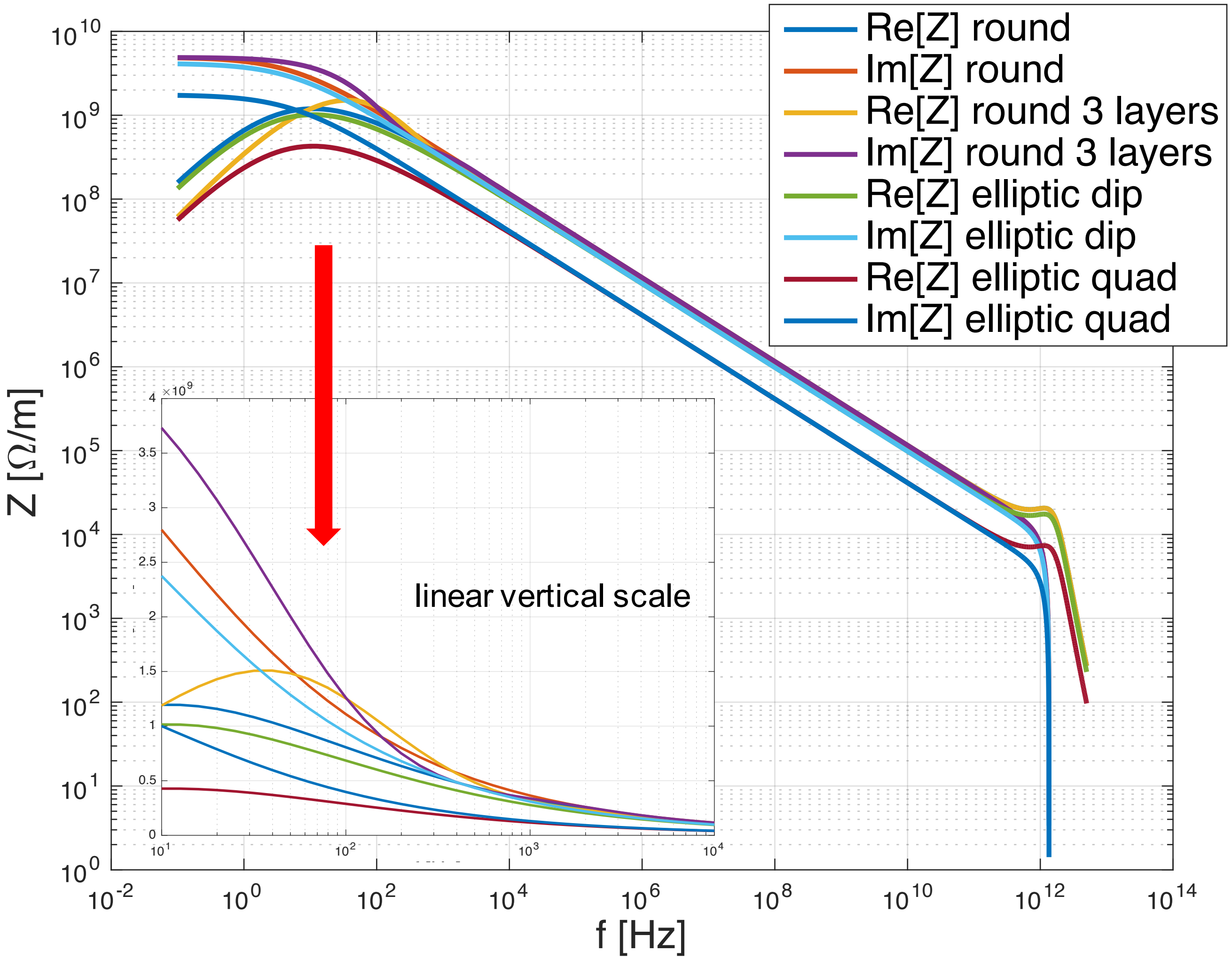
RW transverse impedance for for aluminium and diameter 70 mm round, one and three layers, 70x120 mm elliptic

For copper we reduce the impedance by a factor ~ 1.26



70 mm

Dip x	0.49	Dip y	0.85
Quad x	-0.36	Quad y	0.36
Tot x	0.33	Tot y	1.22



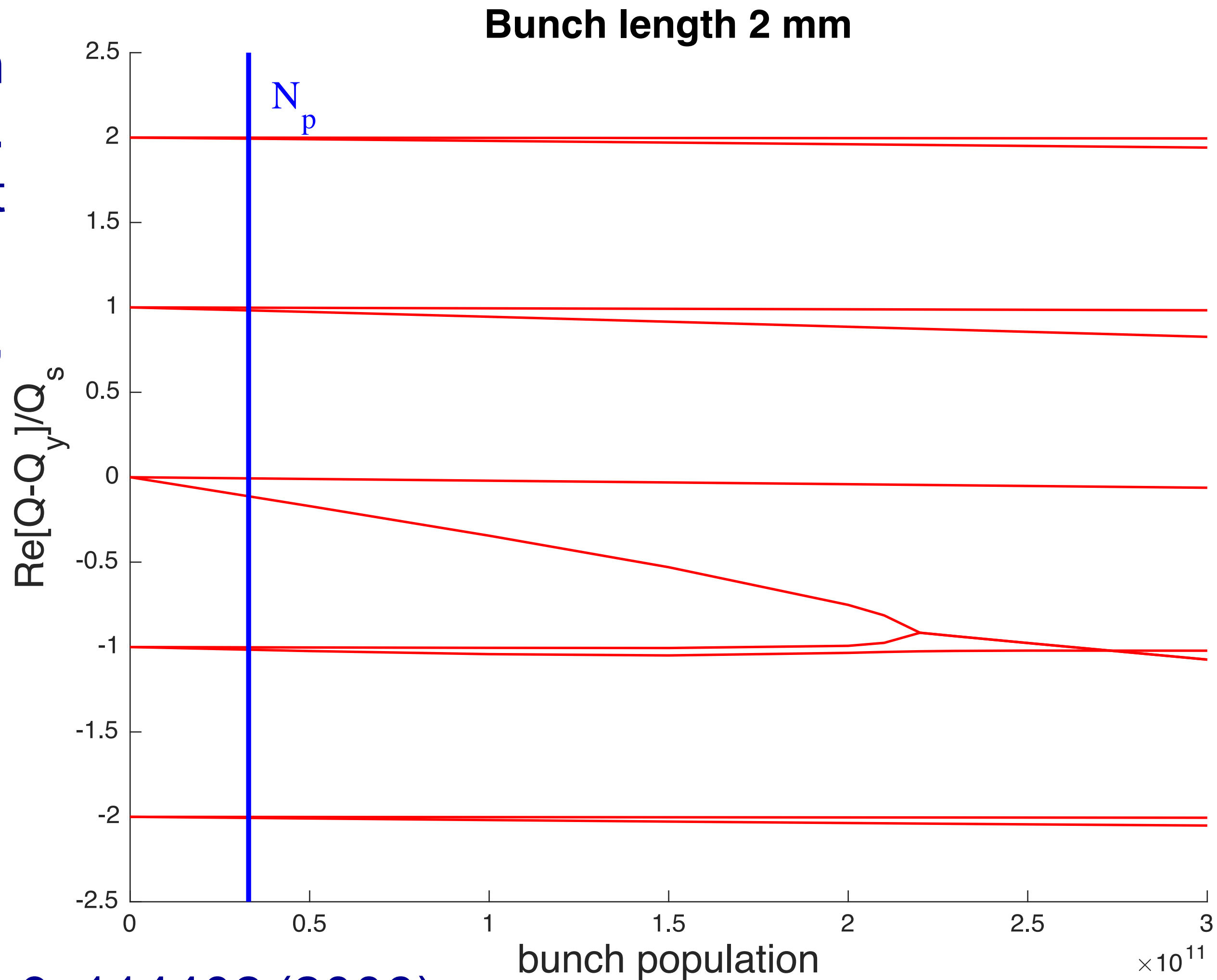
In the 3 layers case there is the aluminium (first layer) with 4 mm thickness, then dielectric (6 mm), and iron with resistivity of 1×10^{-7} Ωm [code of N. Mounet, PhD Thesis at EPFL.]

RW impedance and TMCI

- TMCI obtained with DELPHI code, N. Mounet, PhD Thesis at EPFL.
- Round chamber, 70 mm, aluminium, 3 layers.
- Threshold roughly

$$\propto \sigma^{\frac{1}{2}}, \propto Q_\beta$$

- Quadrupolar impedance (for elliptic geometry) does not contribute to the TMCI but it gives rise to incoherent tune shift, see, e.g., PRST-AB 9, 114402 (2006)



Coupled bunch instability – transverse RW

- 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

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

- where

$$\omega_q = \omega_0\left(qN_b + \mu + Q_\beta\right) \qquad \omega'_q = \omega_q - \xi\frac{\omega_\beta}{\alpha_c} \qquad G_\perp(x) = e^{-x^2} I_0\left(x^2\right) \cong 1$$

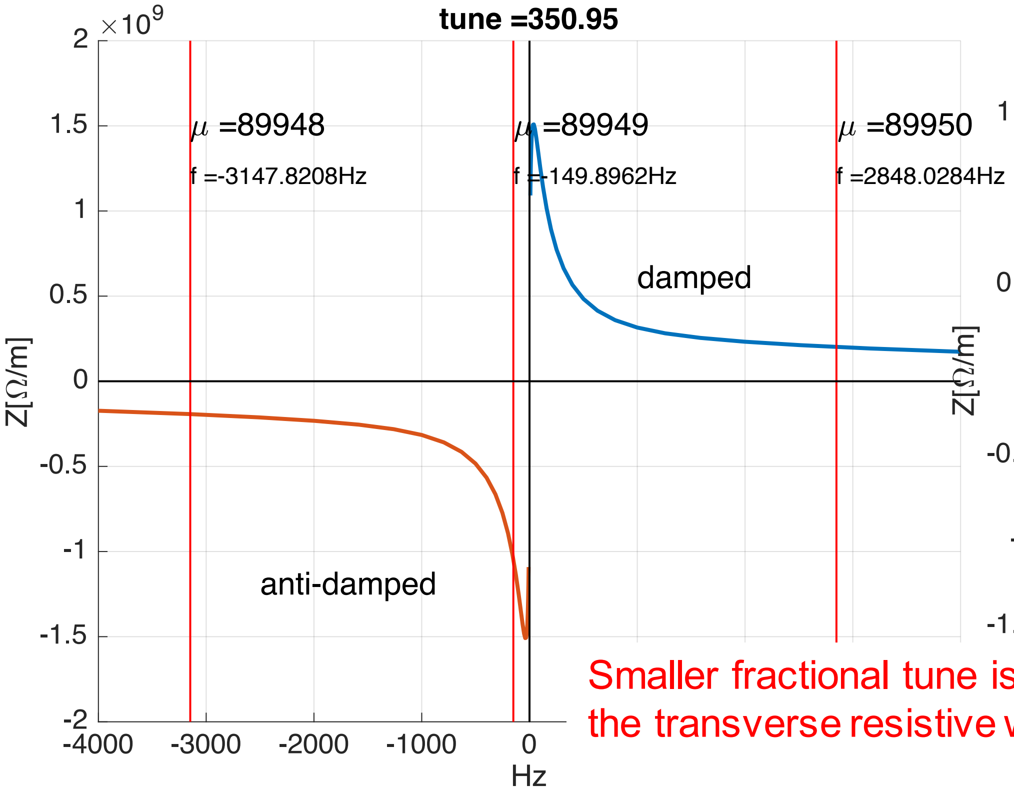
(q = -1, N_b = 90300, μ = 89949, Q_β = 350.05) e.g.

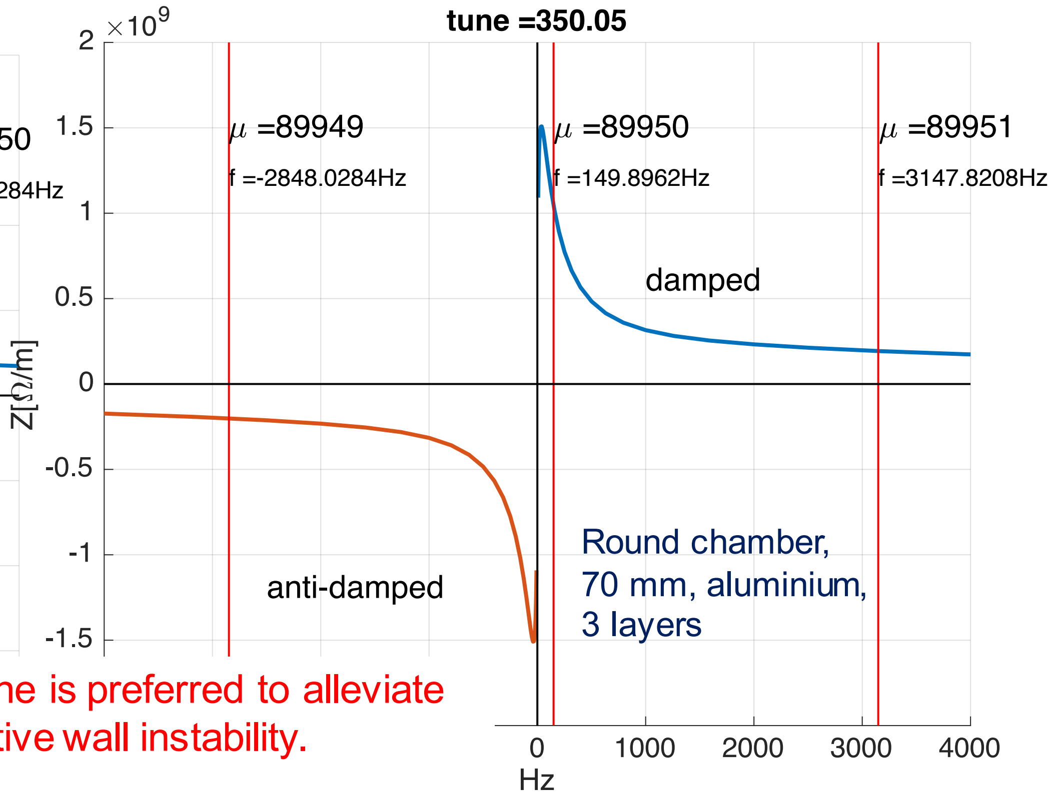
350.05 ➡ $\omega_q = -0.95\omega_0$

350.95 ➡ $\omega_q = -0.05\omega_0$

Coupled bunch instability – transverse RW

- The most dangerous instability occurs at the betatron line with the lowest negative frequency. The growth rate strongly depends on the fractional part of the tune





Smaller fractional tune is preferred to alleviate the transverse resistive wall instability.

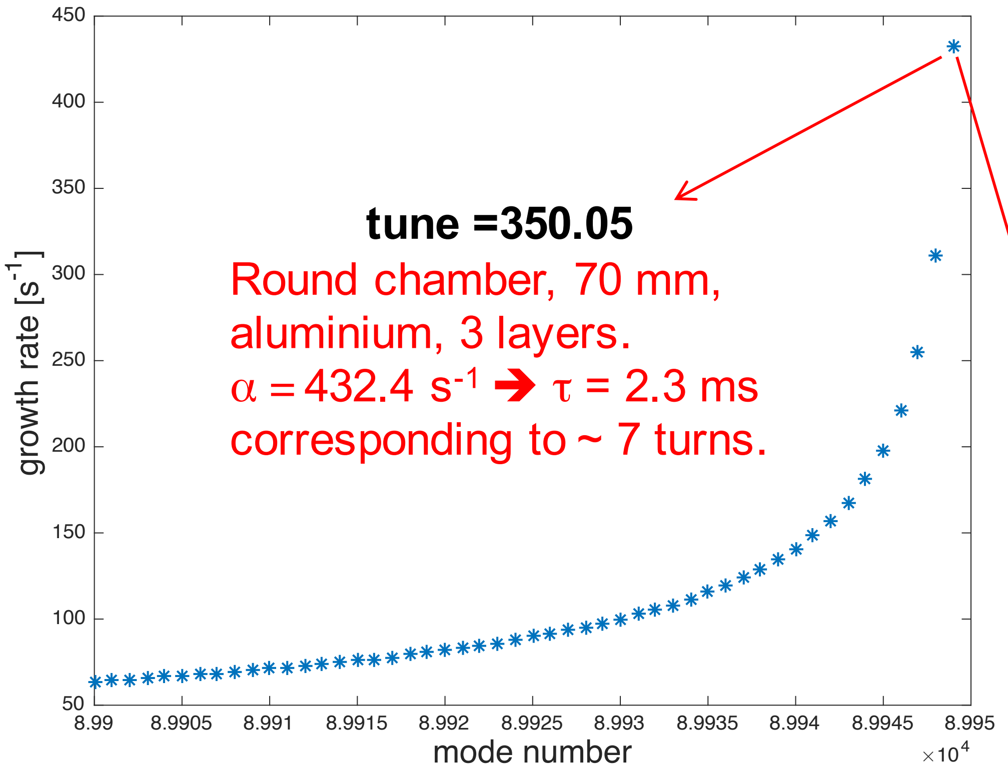
Coupled bunch instability – transverse RW

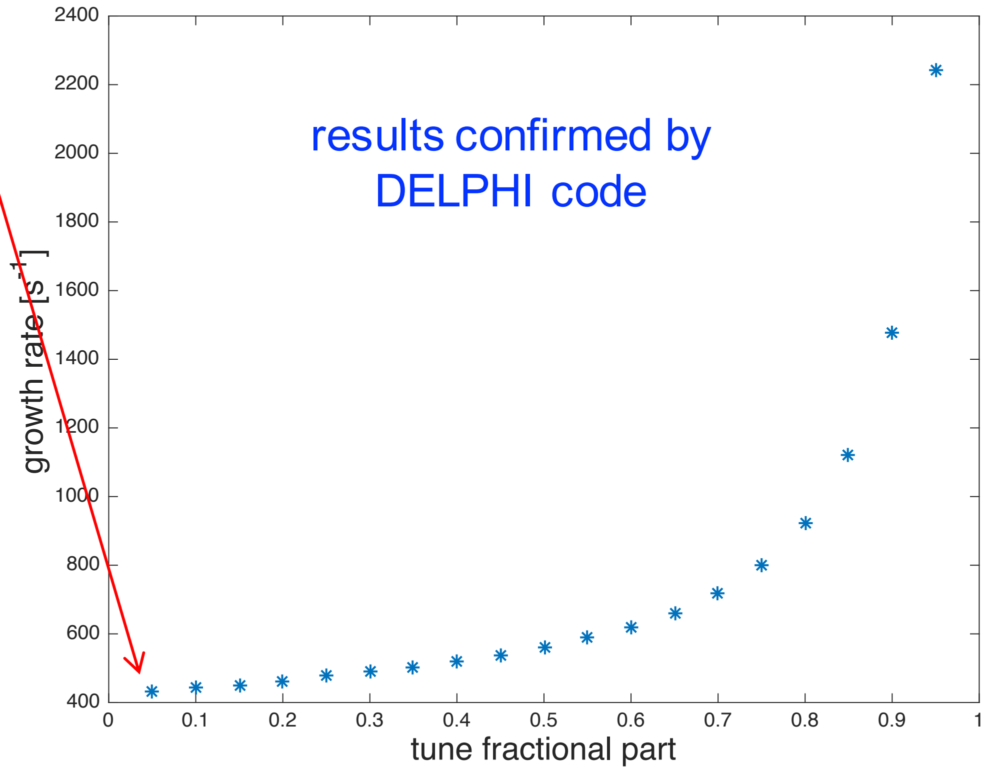
The worst case (lowest energy and highest beam current) is the Z-pole

beam current

$$\alpha = \frac{c N_b I_b}{4\pi (E/e) Q_\beta} \frac{L}{2\pi b^3} \sqrt{\frac{L Z_0}{\pi |1-\nu_\beta| \sigma_c}} \, G_\perp\left(\frac{\sigma_z}{c}\omega'_q\right)$$

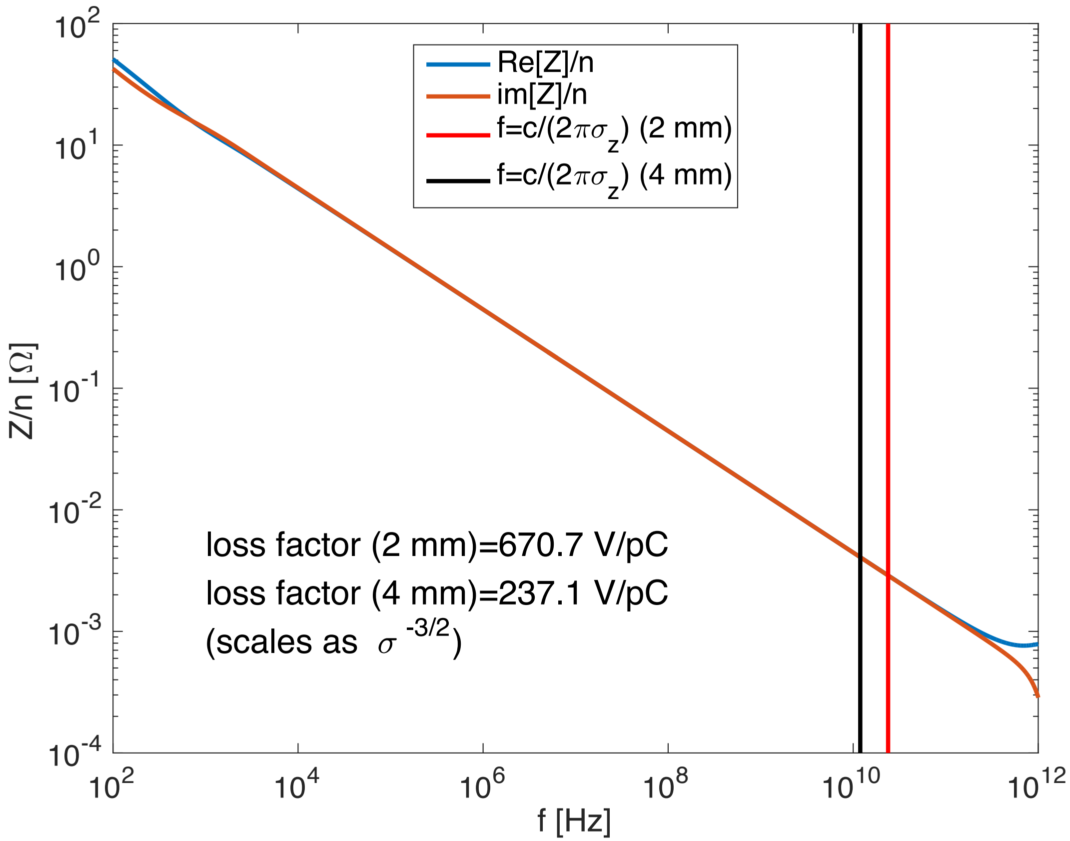
energy

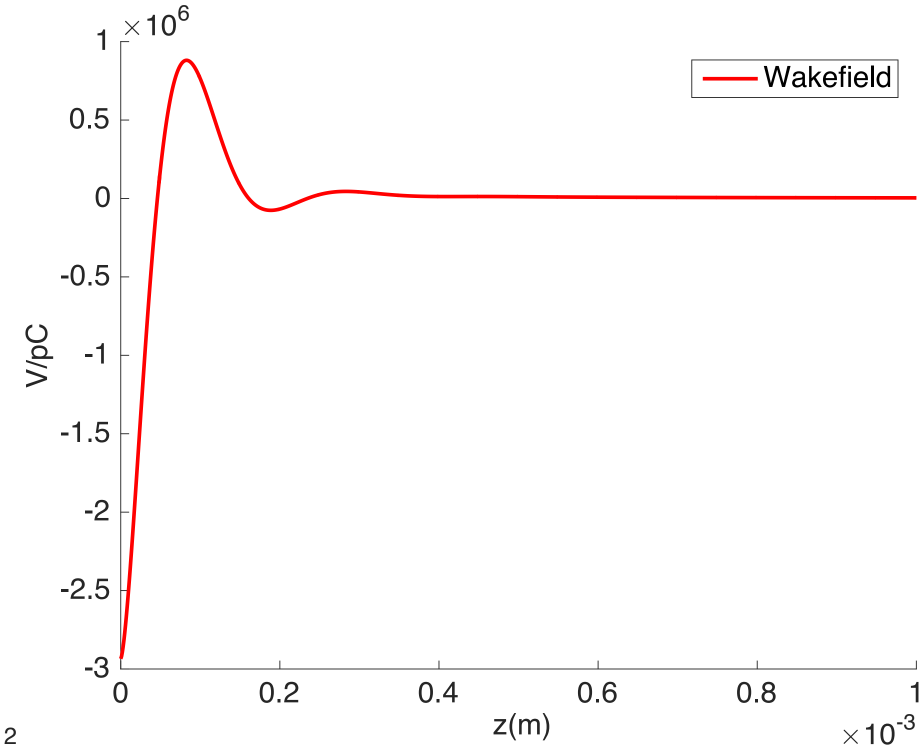




Longitudinal resistive wall impedance

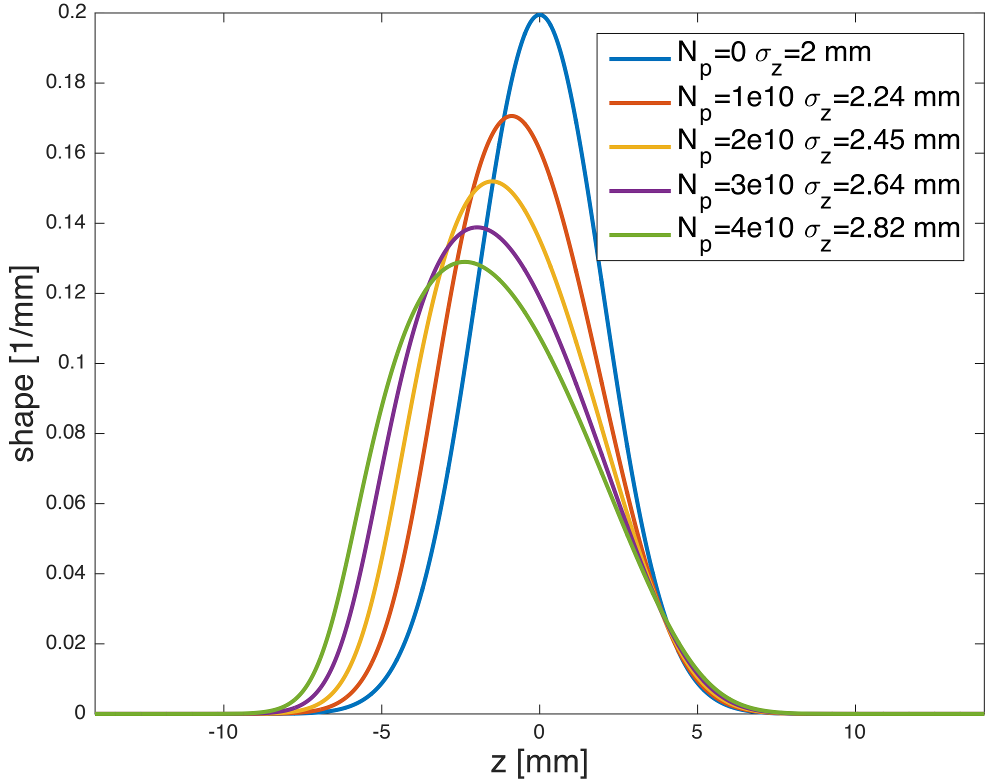
- Longitudinal impedance Z/n, round chamber, 70 mm, aluminium, 3 layers





Longitudinal resistive wall impedance, effects on beam dynamics

Haissinski equation and potential well distortion



Simulations with tracking codes to study microwave instability require a high number of slices. Alternative approaches (e.g. Vlasov solvers) are under investigation.

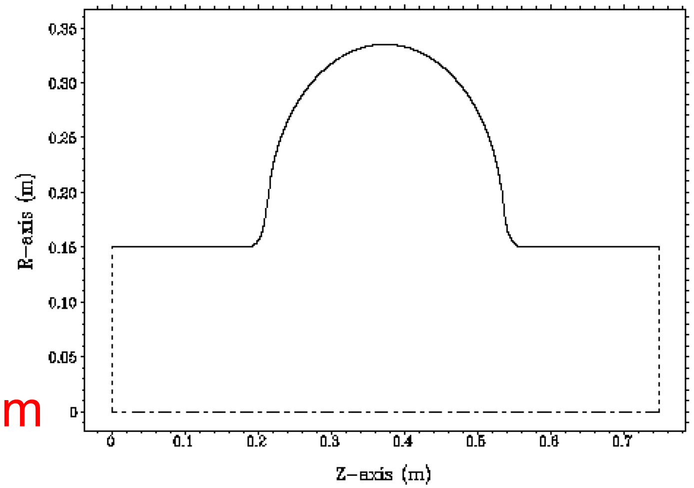
A first estimate of the microwave instability threshold using the criterion presented in [K.L.F. Bane, Y. Cai, G. Stupakov, SLAC PUB -14150, June 2010] gives $N_{th} \cong 8\times10^{10}$. Further studies are needed.

Potential well distortion gives about a 30% of increase in bunch length at the nominal bunch population ($N_{th} = 3\times10^{10}$).

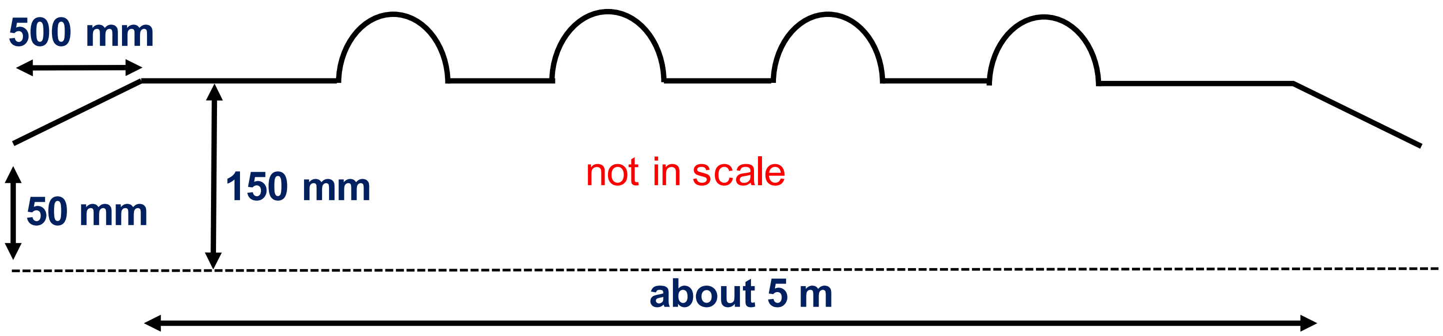
Conclusion: RW is an important source of impedance in both longitudinal and transverse planes, and we use it as a 'reference' to compare the impedance contribution of other elements.

RF system

- 400 MHz cavities have been considered with a single cell. Round tapers are at both ends of a 4-cavity ensemble.



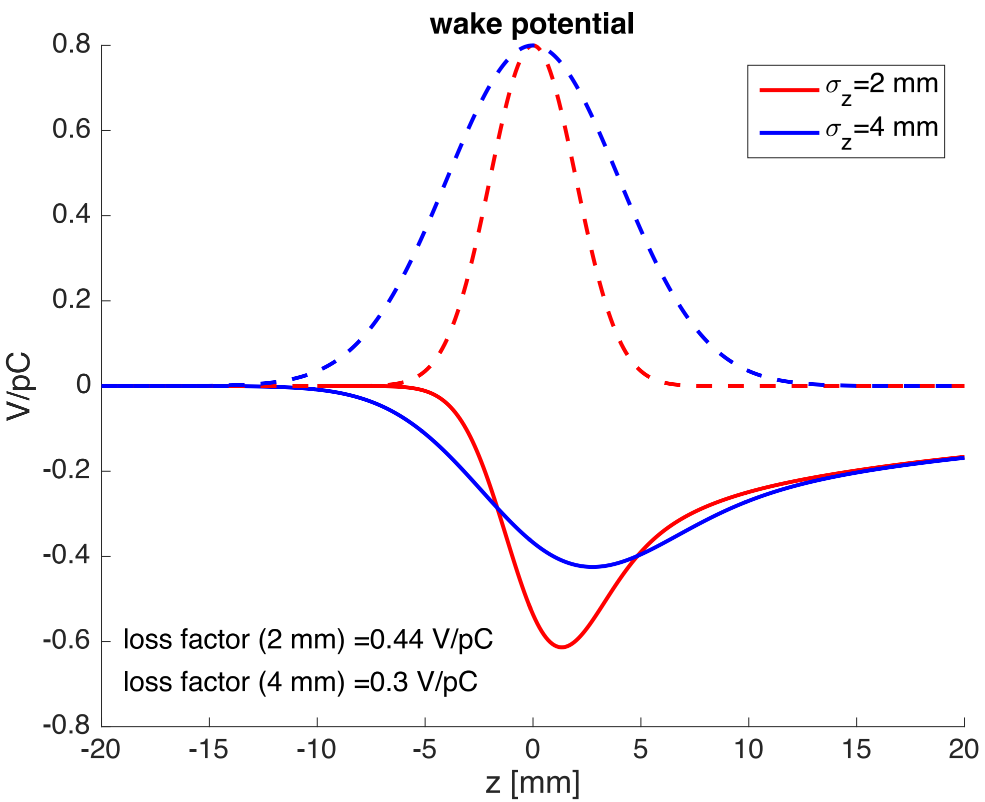
Total: 100 cavities
25 double circular tapers from 150 mm to 50 mm



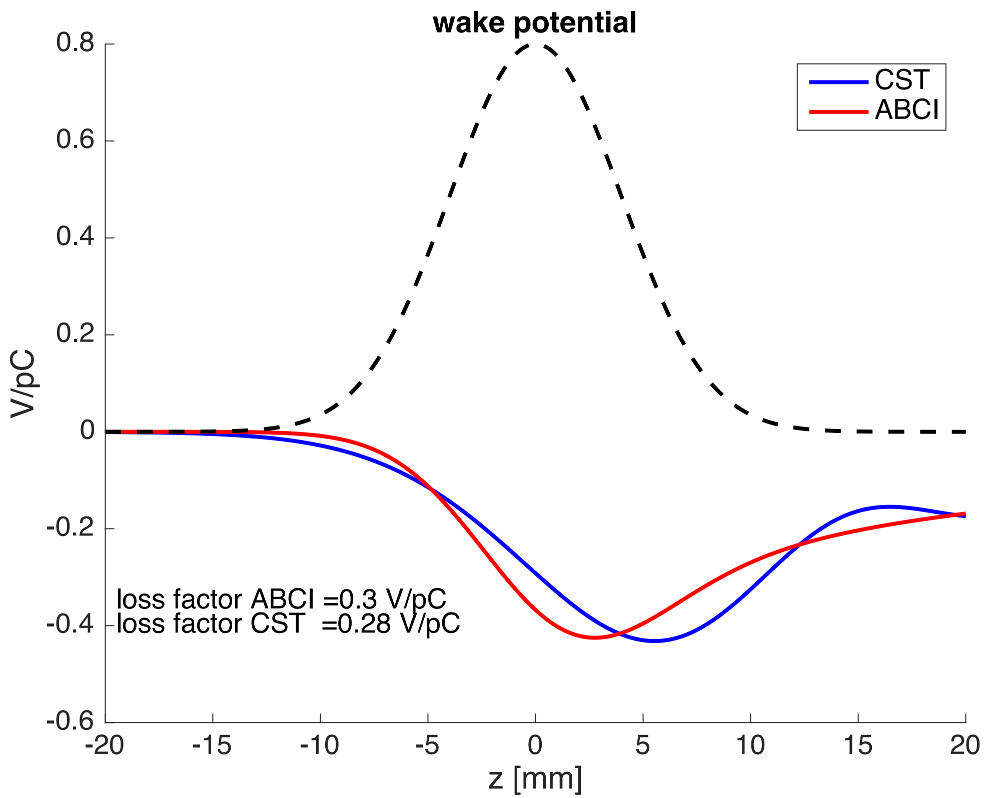
In addition there must be tapers from 50 mm radius round pipe to 120x70 mm elliptic beam pipe. Anyway just two of them can be used at both ends of the two RF sections.

RF system: single cell

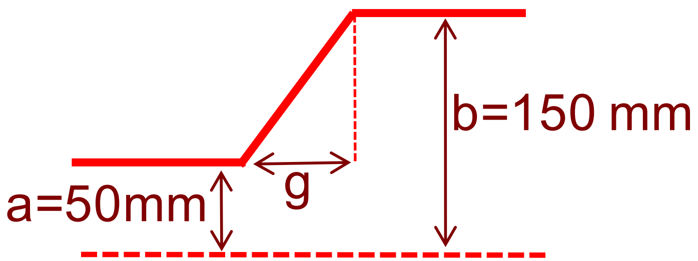
ABCI results

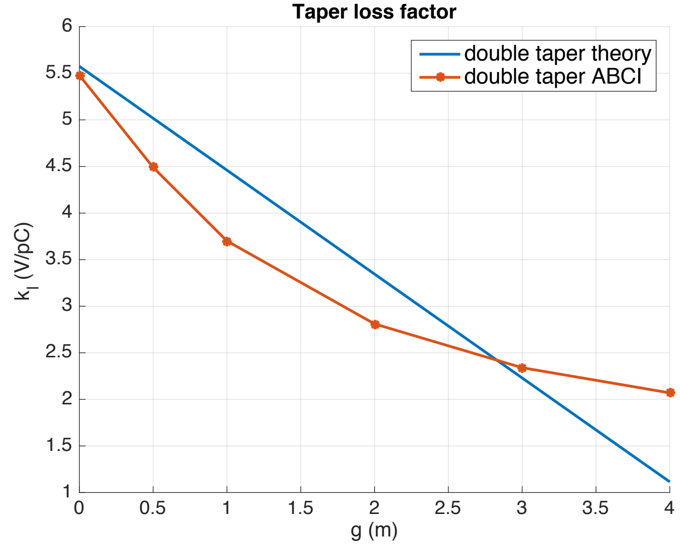


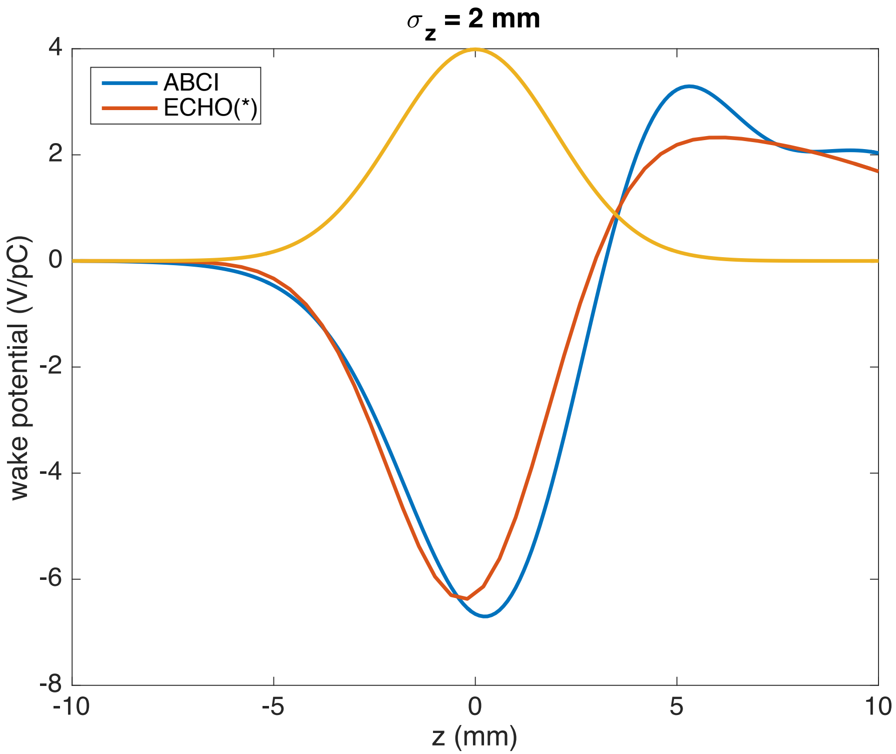
ABCI vs CST (σ_z=4 mm)

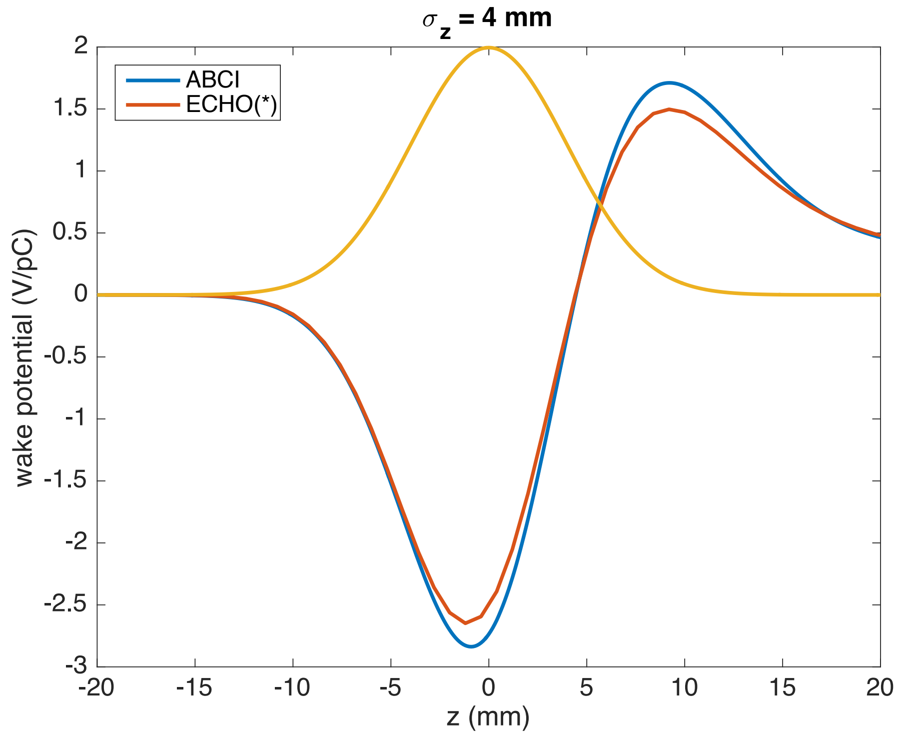


Circular tapers





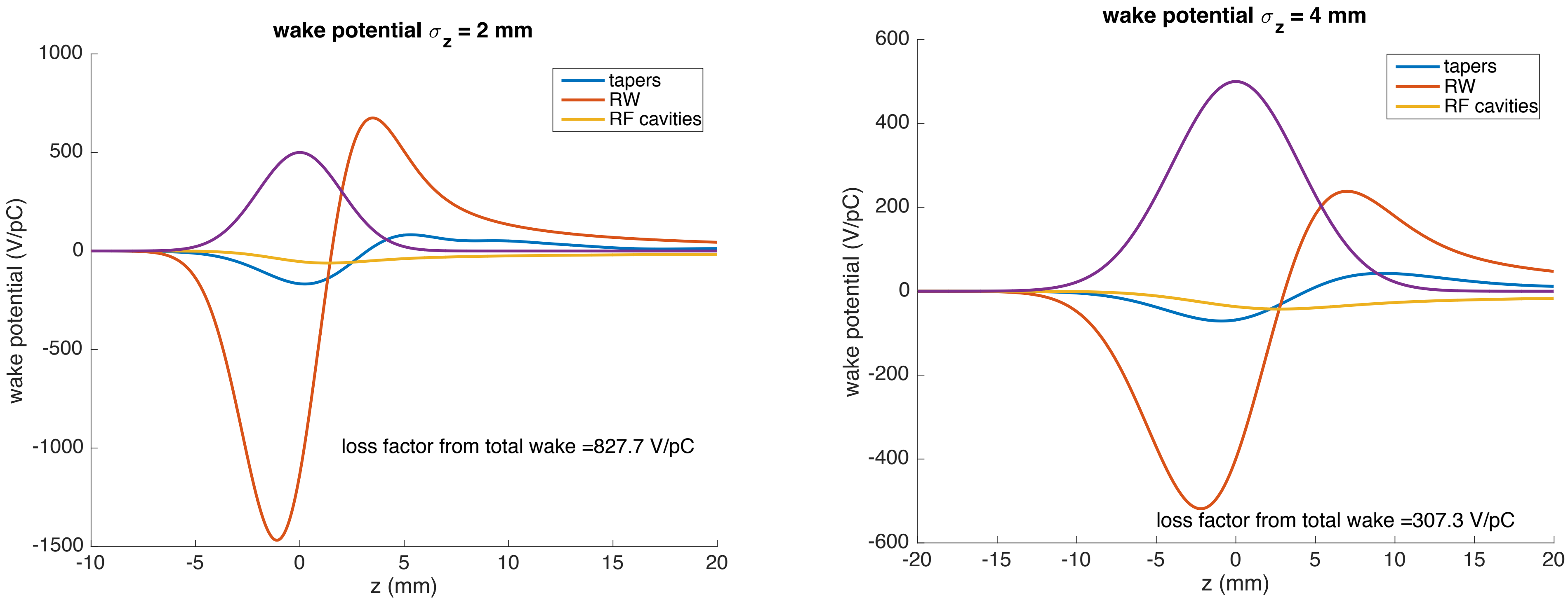




(*) Courtesy of G. Stupakov

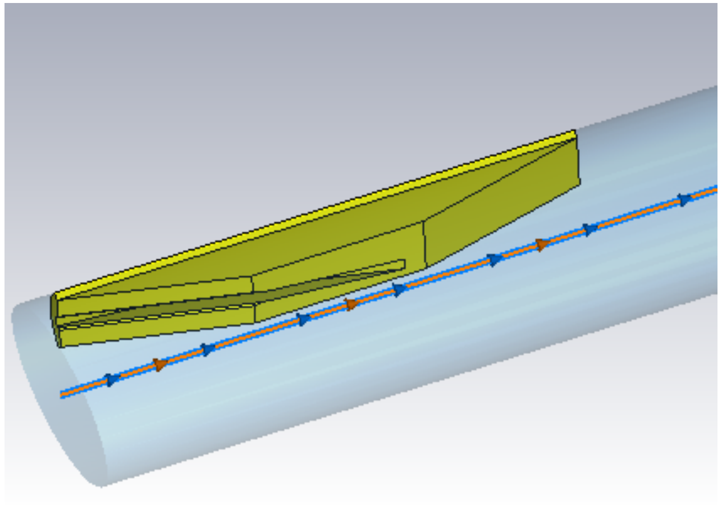
Longitudinal Impedance Budget

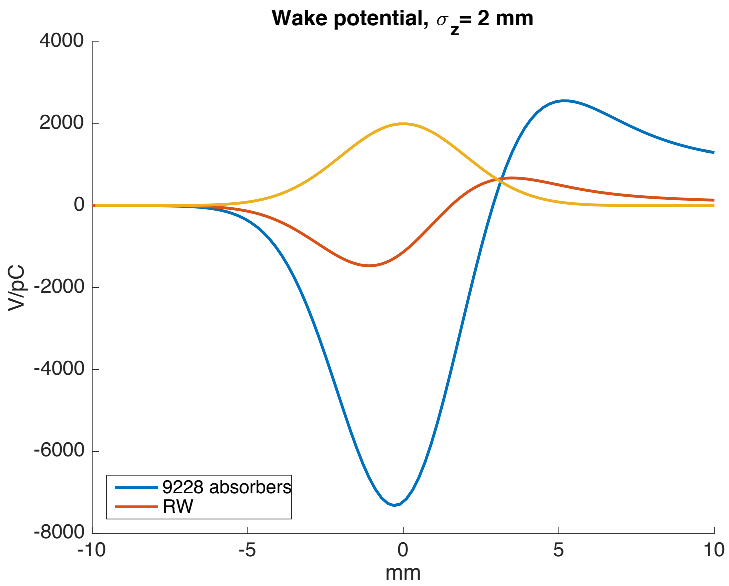
	σ_z = 2 mm	σ_z = 4 mm
Element	k_{loss} [V/pC]	k_{loss} [V/pC]
Resistive wall (Al, 70 mm, circular)	670.7	237.1
100 RF cavity	44.3	30.5
25 double taper	112.3	39.5
Total	827.3	307.1

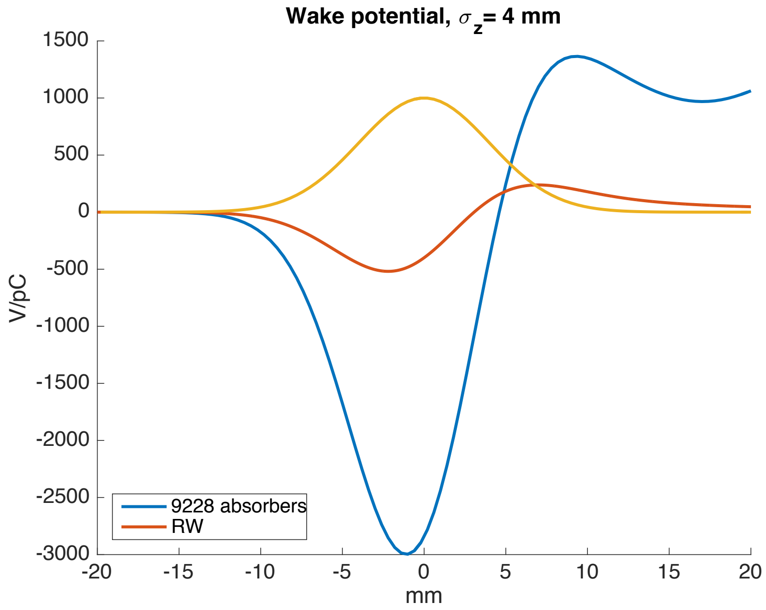


Contribution of absorbers to total wake potential

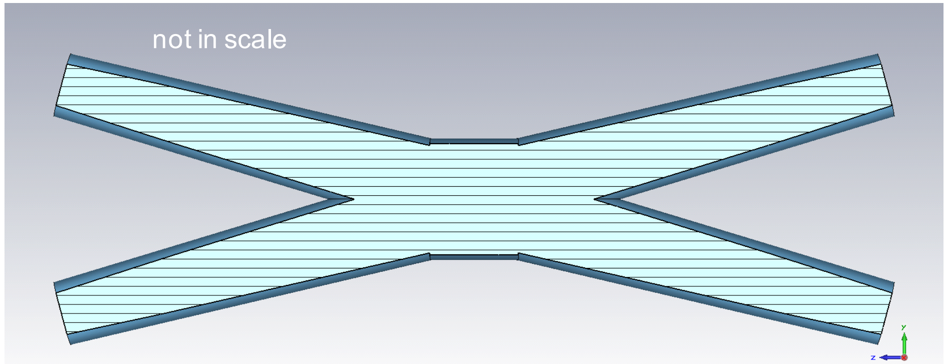
The wake potential of the single absorber has been evaluated by considering a rectangular geometry with two absorbers at each side for symmetry reasons (G. Stupakov).
The contribution of a single absorber could be neglected, but due their high number (9228), the wake potential results 4-6 time higher than the total resistive wall. Even if this represents a rough estimate, the order of magnitude seems to be prohibitively large.





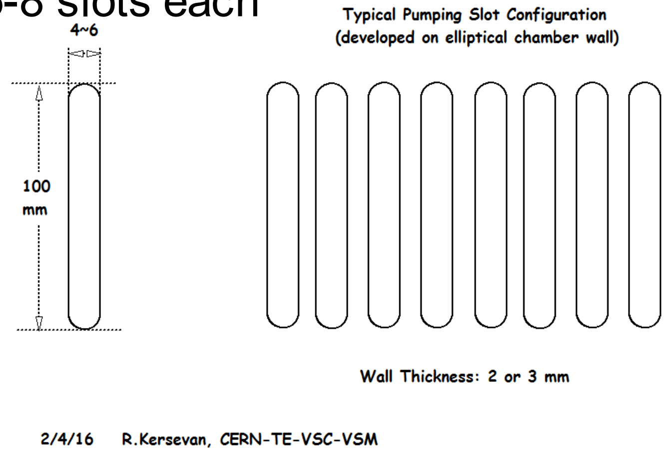


Other work in progress

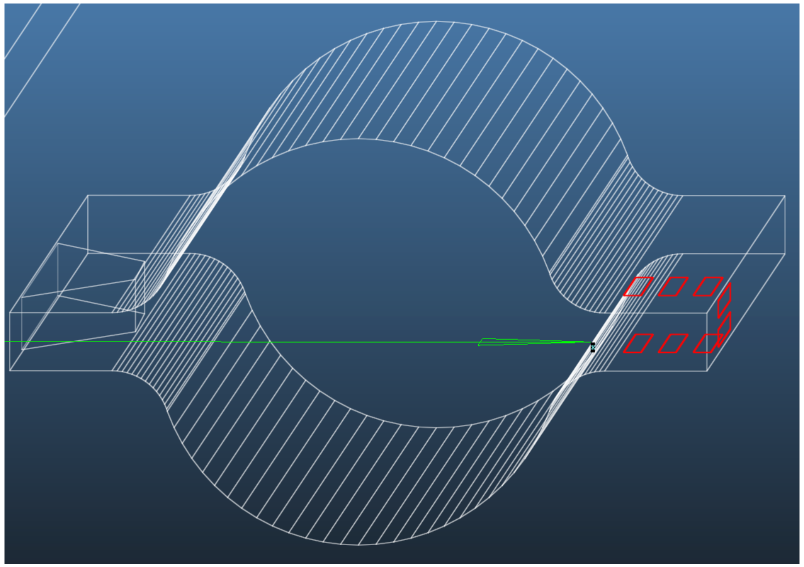


Interaction region

Pumping slots: 6152 dipoles with 6-8 slots each



Preliminary calculations based on G. Stupakov, Phys. Rev. E, vol 51, p. 3515, 1995, give a small contribution with respect to the RW. More work is needed and, maybe 3D simulations



Fast ion and e-cloud instabilities are also under study

Other solution for absorbers and pumping slots are under study …
(Courtesy of R. Kersevan)

Longitudinal coupled bunch instability

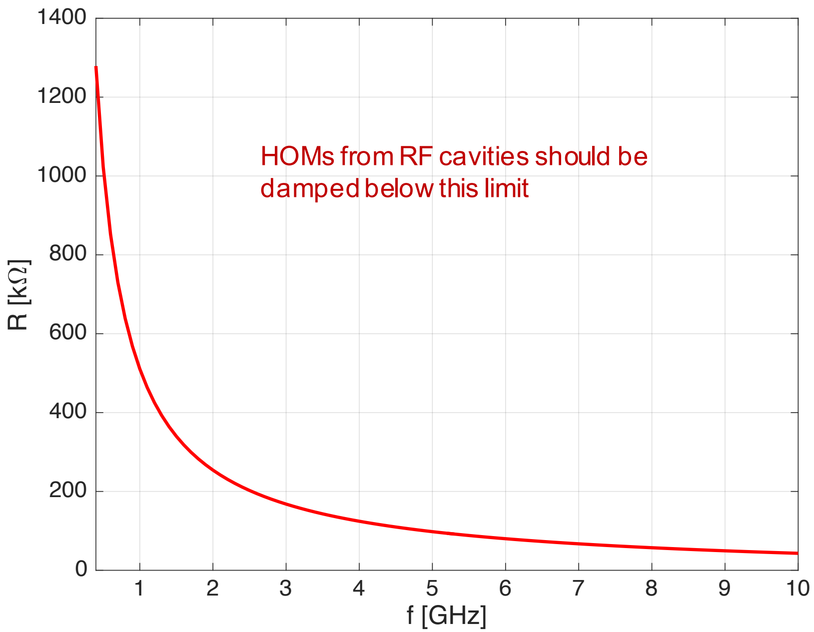
- Trapped HOMs can produce coupled bunch instability.
- In the worst case of resonant condition, the grow rate of the instability is

$$\alpha = \frac{\alpha_c I_0 f R_s}{2(E/e)Q_s} G(x) \qquad G(x) = \frac{2}{x^2} e^{-x^2} I_1\left(x^2\right) \qquad x = \frac{2\pi f}{c}\sigma_z$$

- Without any feedback, this grow rate can only be compensated by the natural damping rate (~1300 turns). In this situation the maximum shunt resistance of a HOM is given by

$$R_s = \frac{2(E/e)Q_s}{\alpha_c I_0 f \tau_z} G(x) \cong \frac{512}{f\,[\mathrm{GHz}]} G(x)\ \mathrm{k\Omega}$$

longitudinal maximum shunt impedance



Conclusions

- RW is an important source of impedance and collective effects. It produces:
- Transverse mode coupling instability. It is a threshold effect. The threshold is higher than the design single bunch current.
- Transverse coupled bunch instability. Not a threshold effect. Rise time of the order of few turns. Cures should be studied (e.g. feedback system, see A. Drago presentation).
- Microwave instability. It has to be studied in detail to understand if some actions are required in order to increase its threshold (e.g. increase the momentum compaction?).
- Due to the important contribution of RW, other sources of impedance are compared with it.
- Contribution of RF cavities and tapers have been evaluated in the longitudinal case.
- Other devices have been studied, and others have to be taken into account (pumping slots, interaction chamber, bellows, …)
- Studies on fast ion and e-cloud instabilities are in progress.
- Parameters and machine elements are in a continuous evolution and therefore collective effects may change.

Thank you very much for your attention