INFN

SAPIENZA UNIVERSITÀ DI ROMA

DIPARTIMENTO DI SCIENZE DI BASE E APPLICATE PER L' INGEGNERIA

FUTURE CIRCULAR COLLIDER Innovation Study

FCC-ee collective effects: introduction and overview (including Full Energy Booster)

M. Migliorati

C. Antuono, E. Belli, E. Carideo, D. De Arcangelis, D. Quartullo,

C. Zannini, Y. Zhang, M. Zobov

The Future Circular Collider Innovation Study (FCCIS) receives funding from the European Union's Horizon 2020 research and innovation programme under grant No 951754. The information herein only reflects the views of its authors and the European Commission is not responsible for any use that may be made of the information.

FCC Week 2021 – FCC WP2 session on collective effects

Overview	Mauro Migliorati
Impedance database and single-bunch thresholds	Emanuela Carideo
Status of bellows and flanges impedance studies	Chiara Antuono
Combined effect of impedance and beam-beam	Yuan Zhang
SuperKEKB collimation	Takuya Ishibashi

FCC-ee main parameters

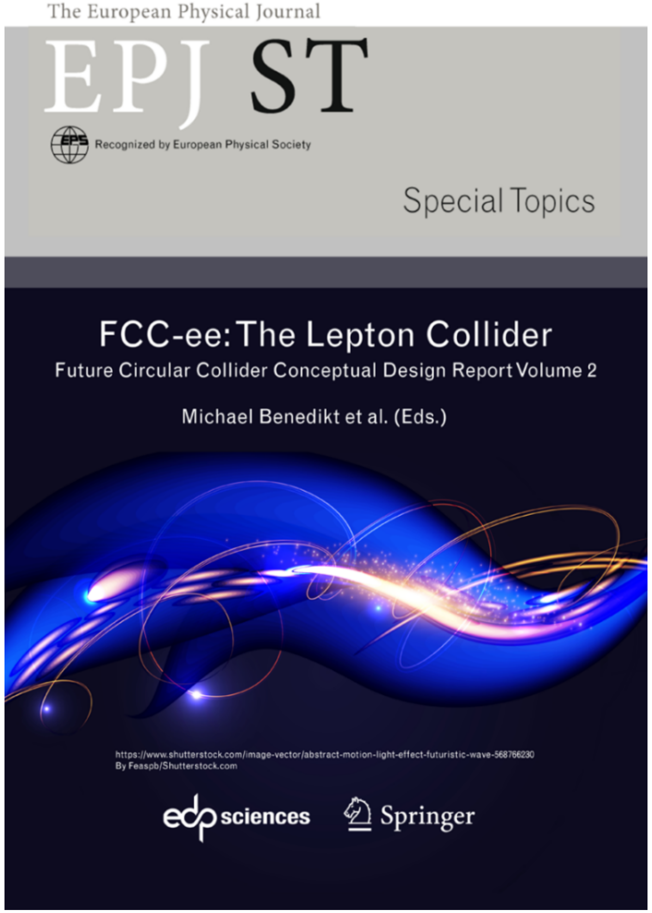


Table 2.1. Machine parameters of the FCC-ee for different beam energies.

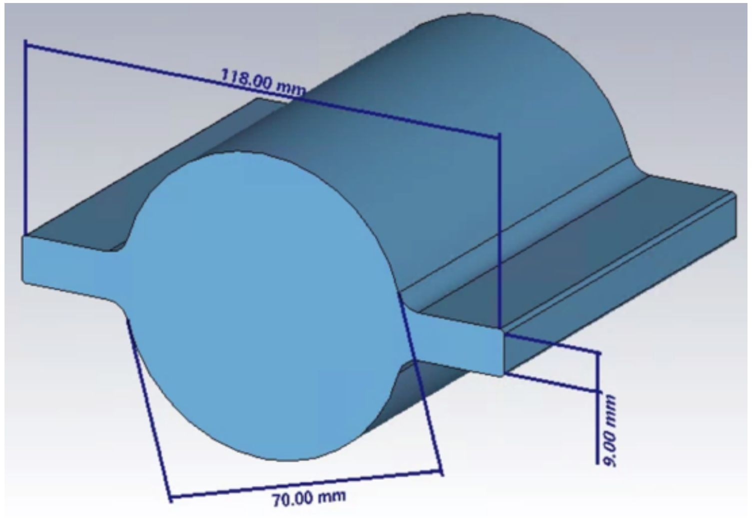
	Z	WW	ZH	$t\bar{t}$	
Circumference (km)	97.756				
Bending radius (km)	10.760				
Free length to IP ℓ^* (m)	2.2				
Solenoid field at IP (T)	2.0				
Full crossing angle at IP θ (mrad)	30				
SR power / beam (MW)	50				
Beam energy (GeV)	45.6	80	120	175	182.5
Beam current (mA)	1390	147	29	6.4	5.4
Bunches / beam	16640	2000	328	59	48
Average bunch spacing (ns)	19.6	163	994	2763[a]	3396[a]
Bunch population (10^{11})	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x (nm)	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y (pm)	1.0	1.7	1.3	2.7	2.9
Horizontal size at IP σ_x^* (μm)	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ_y^* (nm)	28	41	36	66	68
Energy spread (SR/BS) σ_δ (%)	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z (mm)	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Energy loss / turn (GeV)	0.036	0.34	1.72	7.8	9.2
RF frequency (MHz)	400			400 / 800	
RF voltage (GV)	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Synchrotron tune Q_s	0.0250	0.0506	0.0358	0.0818	0.0872
Longitudinal damping time (turns)	1273	236	70.3	23.1	20.4
RF bucket height (%)	1.9	3.5	2.3	3.36	3.36
Energy acceptance (DA) (%)	±1.3	±1.3	±1.7	−2.8 +2.4	

Lowest beam energy: highest beam current, lowest emittances, and longest damping times

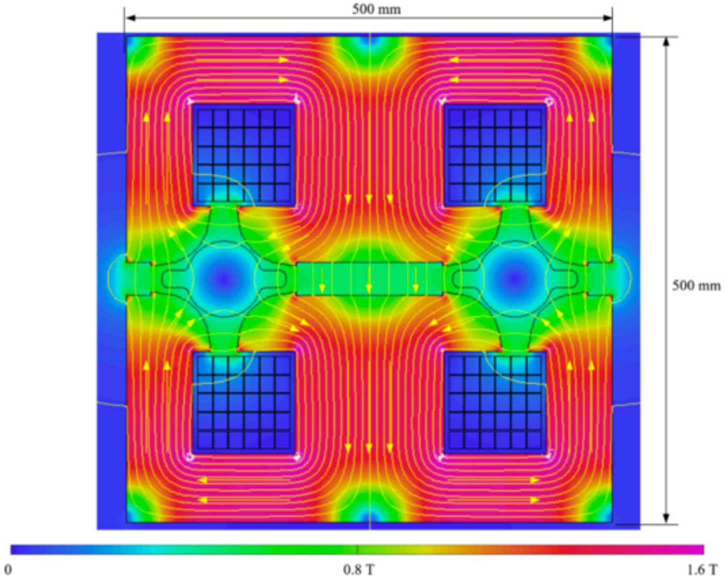
Overview of wakefields and coupling impedances

Beam pipe cross section

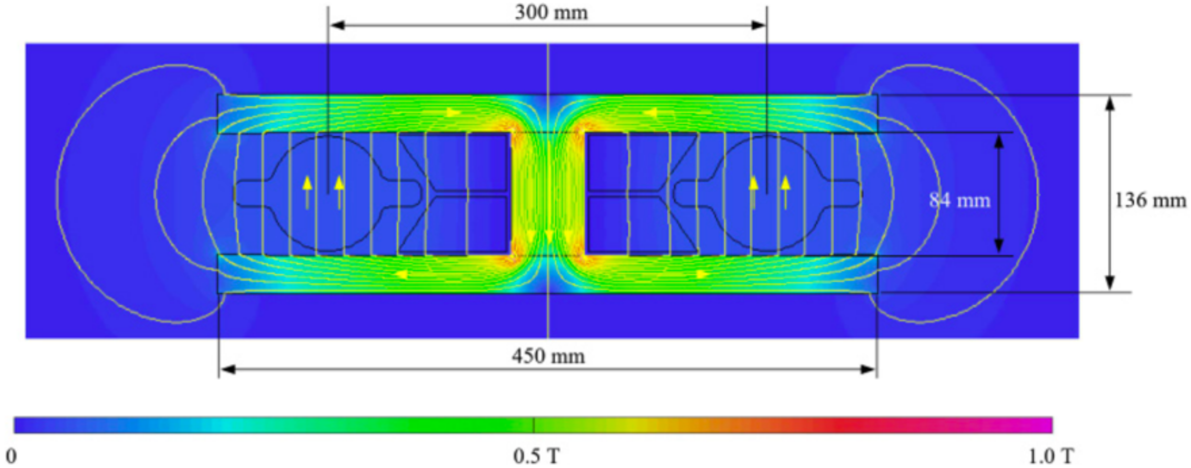
3D model of the FCC-ee vacuum chamber



Cross-section of the main quadrupole, for a 10 T/m gradient.



Main bending magnet; the outline of vacuum chambers with side winglets is also shown.

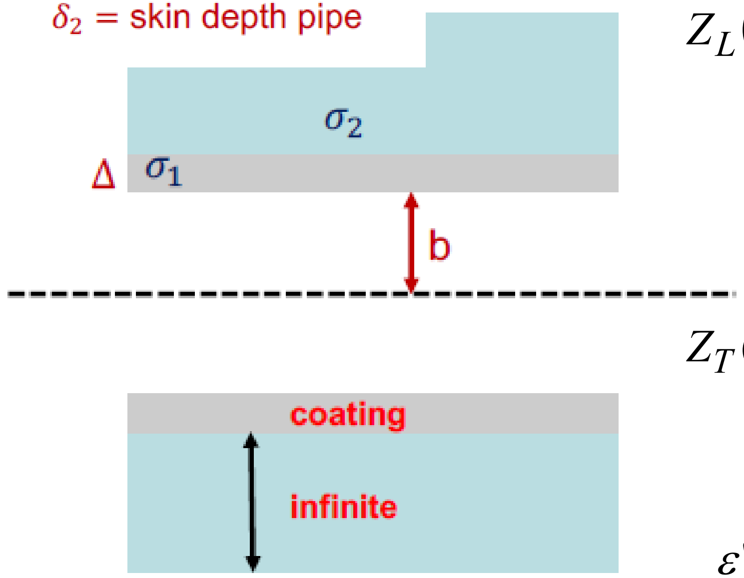


Overview of wakefields and coupling impedances

RW is a dominant source of wakefield and coupling impedance.
For its evaluation we considered a circular beam pipe (ignoring the winglets).

A coating is required to suppress the e-cloud in the positron ring and/or for pumping needs in both rings.

Δ = coating thickness
δ_1 = skin depth coating
δ_2 = skin depth pipe



$$Z_L(\omega) = \frac{Z_0\omega}{4\pi c b}\left[(\mathrm{sgn}(\omega) - i)\delta_1 \frac{\alpha \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right] + 1}{\alpha + \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right]}\right]$$

$$Z_T(\omega) = \frac{Z_0}{2\pi b^3}\left[1 - i\,\mathrm{sgn}(\omega)\right]\delta_1 \left[\frac{\alpha \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right] + 1}{\alpha + \tanh\left[\frac{1 - i\,\mathrm{sgn}(\omega)}{\delta_1}\Delta\right]}\right]$$

$$\varepsilon' = \varepsilon_r \varepsilon_0 + i\sigma/\omega; \quad \lambda = \frac{1 - i\,\mathrm{sgn}(\omega)}{\delta}; \quad \alpha = \frac{\lambda_1 \varepsilon'_2}{\lambda_2 \varepsilon'_1}$$

if
$\Delta \ll \delta_1$

Overview of wakefields and coupling impedances

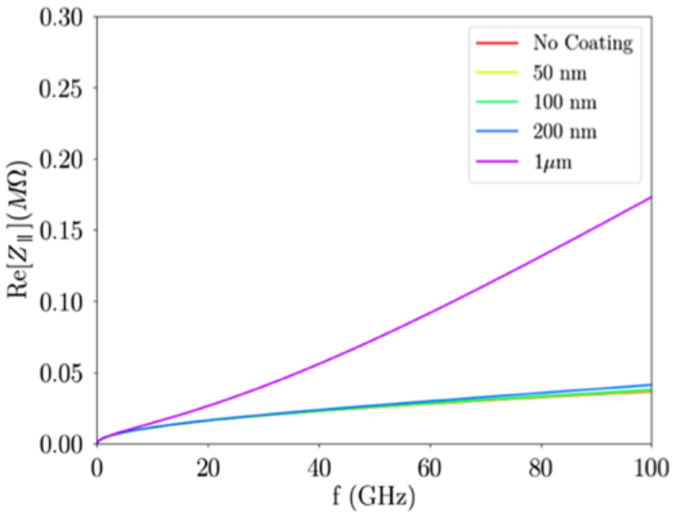
$$\frac{Z_{||}(\omega)}{C} \simeq \frac{Z_0\omega}{4\pi cb}\left\{[\mathrm{sgn}(\omega) - i]\delta_2 - 2i\Delta\left(1 - \frac{\sigma_1}{\sigma_2}\right)\right\}$$

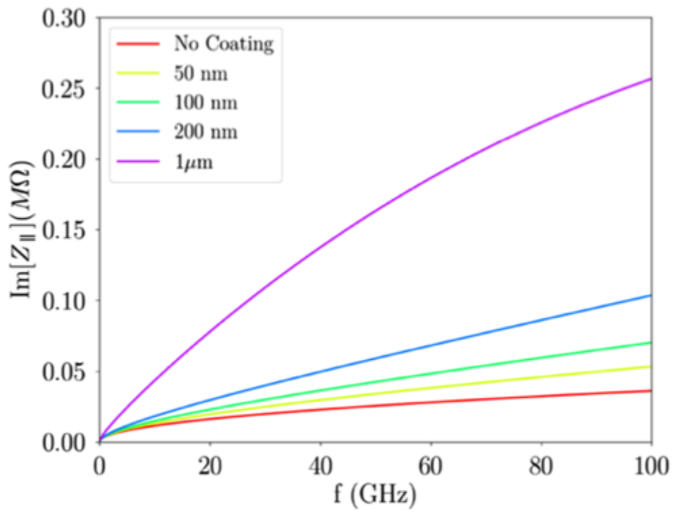
$$\frac{Z_{\perp}(\omega)}{C} = \frac{Z_0}{2\pi b^3}\left\{[sgn(\omega) - i]\delta_2 - 2i\Delta\left(1 - \frac{\sigma_1}{\sigma_2}\right)\right\}$$

1. The real part of the impedance does not depend on the coating (no power losses due to the coating).

2. The imaginary part has an additional term linear with the coating thickness.

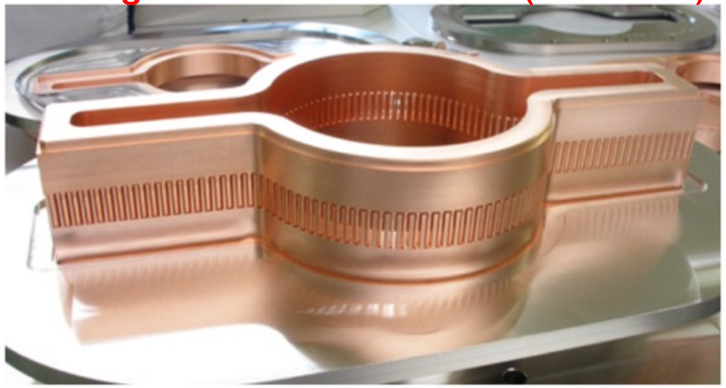
These results have been confirmed by the code IW2D, developed at CERN, which evaluates the wakes and impedances of a generic multilayer circular (or flat) vacuum chamber.

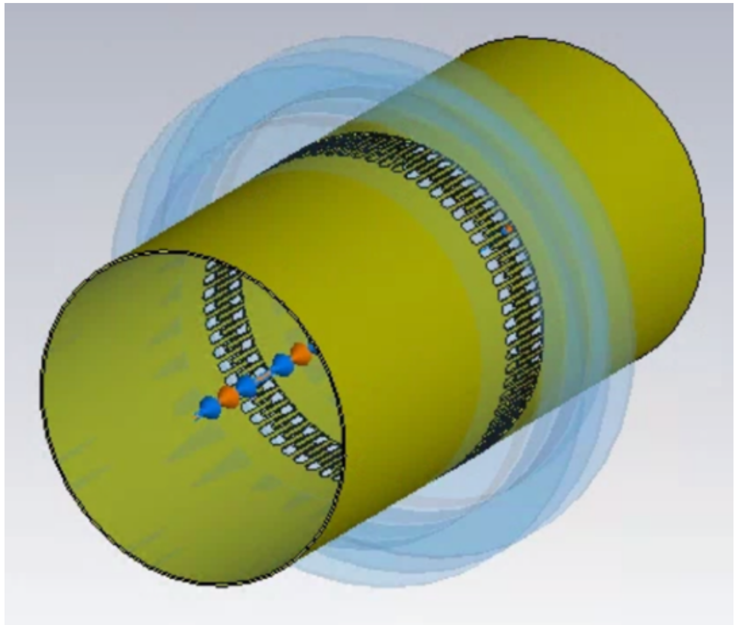


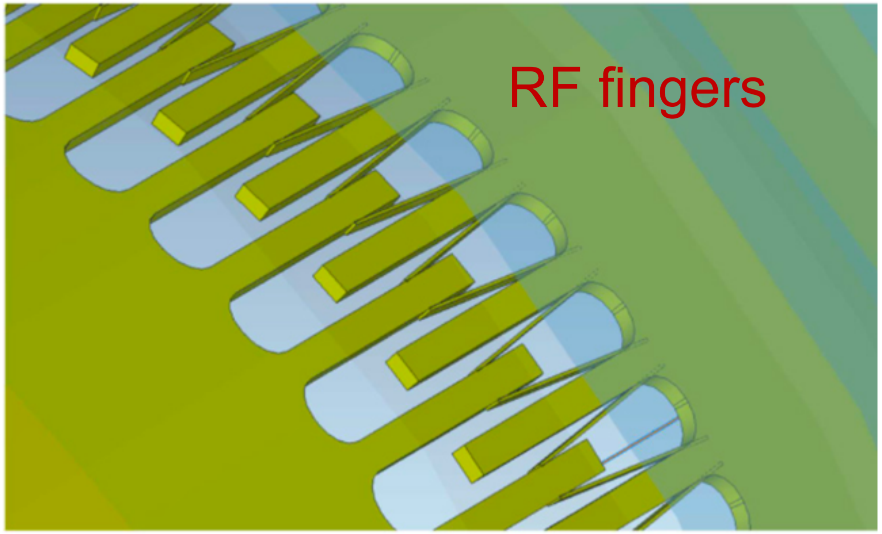


Overview of wakefields and coupling impedances

Y. Suetsugu, Japan-Italy Collaboration Meeting "Crab Factories" 2008 (INFN-LNF)







A comment on the number of bellows:

- 2900 dipole arcs 24 m long. We consider bellows every 8 m → 2900*3=8700
- 2900 quads/sextupoles arcs

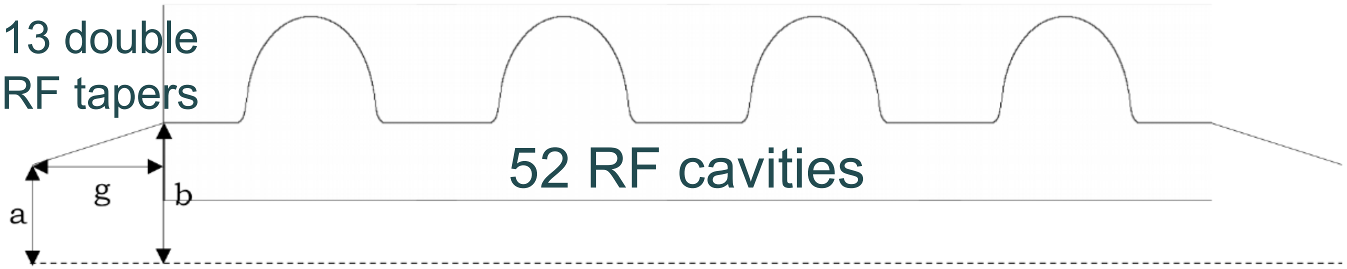
total of 11600 bellows plus:

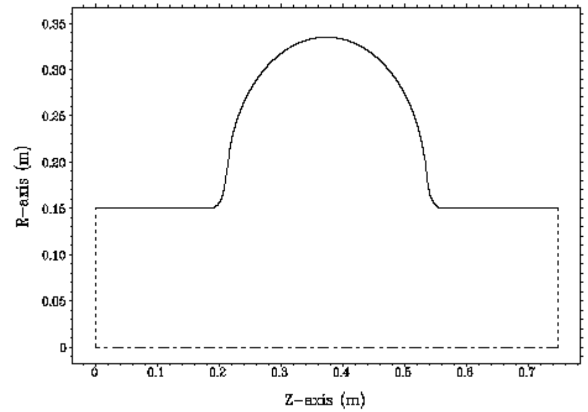
- RF, injection system, collimators, …

As a pessimistic estimation we have considered 20000 bellows

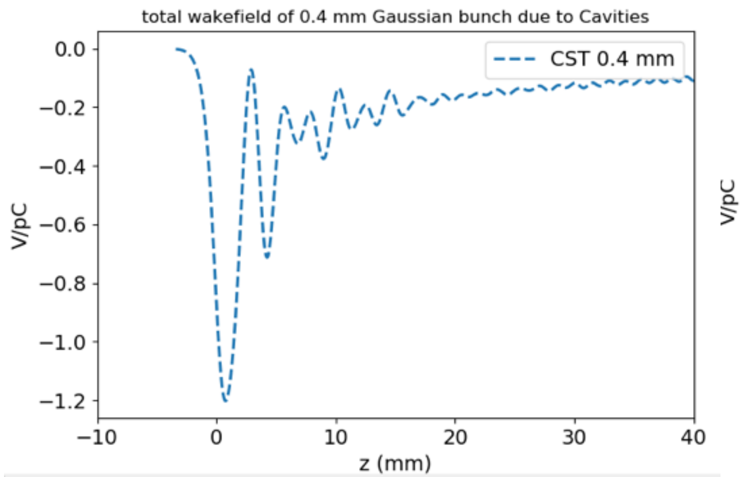
Overview of wakefields and coupling impedances

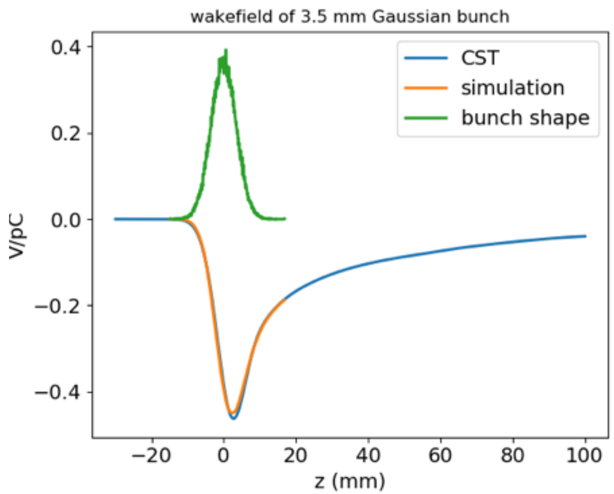
The wake fields and impedance have been evaluated for some important vacuum chamber components

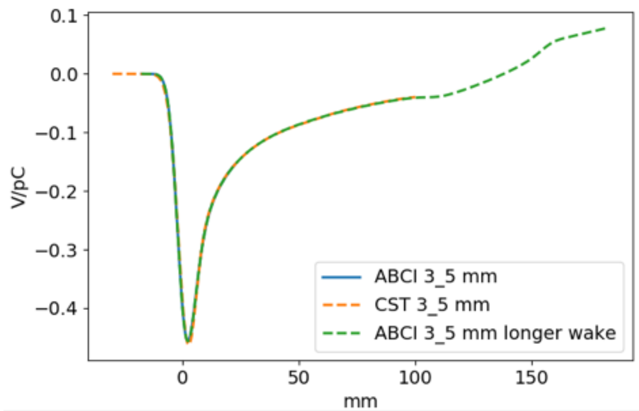




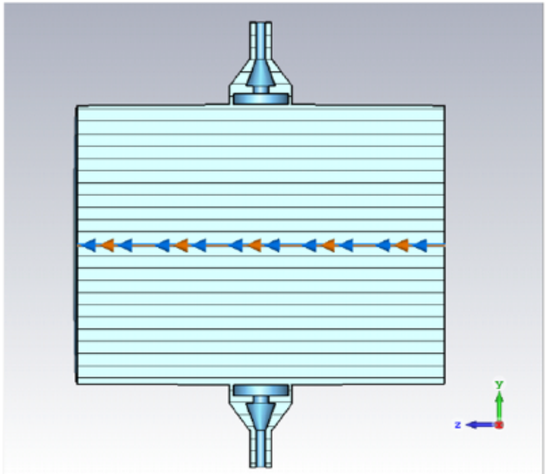
Tapers: transition from radius a = 50 mm outside the cryomodule to radius b = 150 mm inside the cryomodule (or vice-versa).
We assumed g = 0.5 m



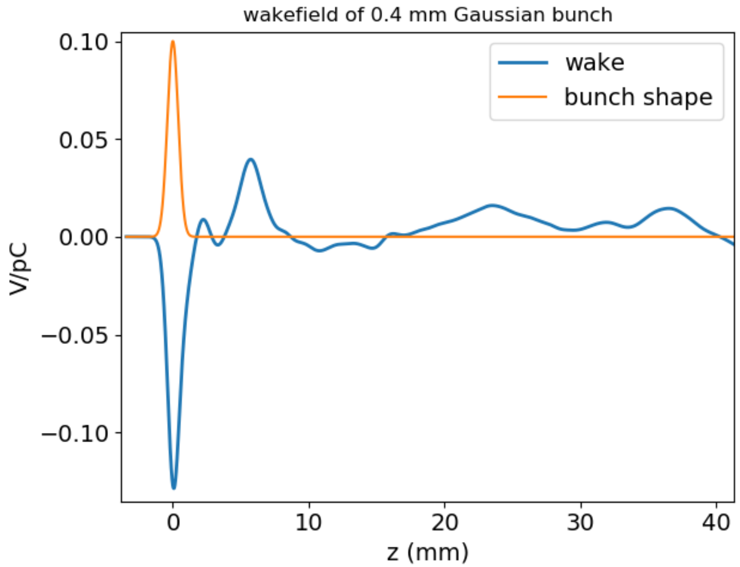


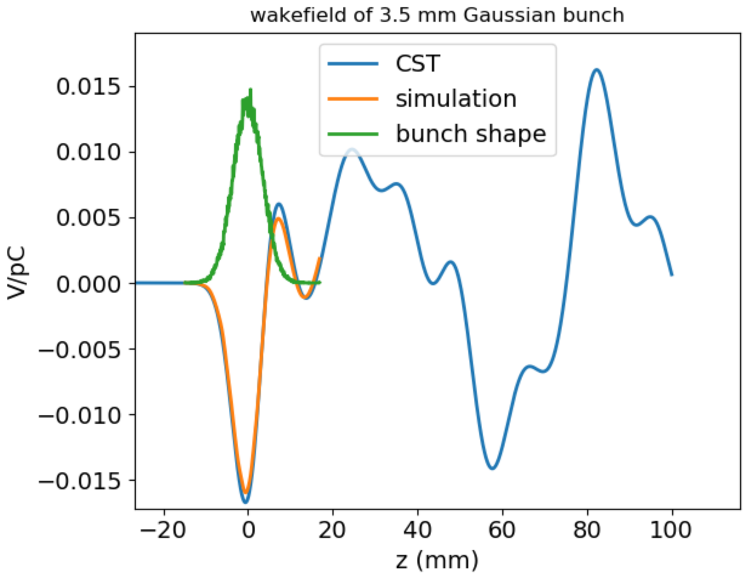


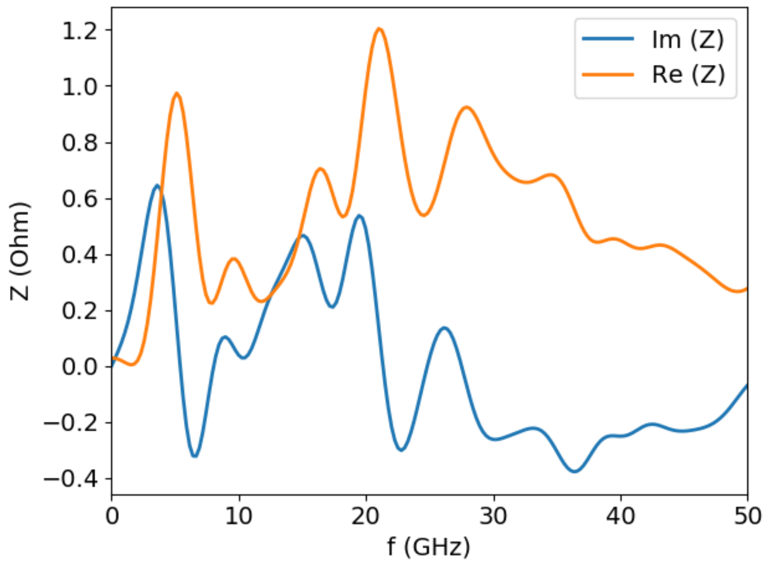
Overview of wakefields and coupling impedances



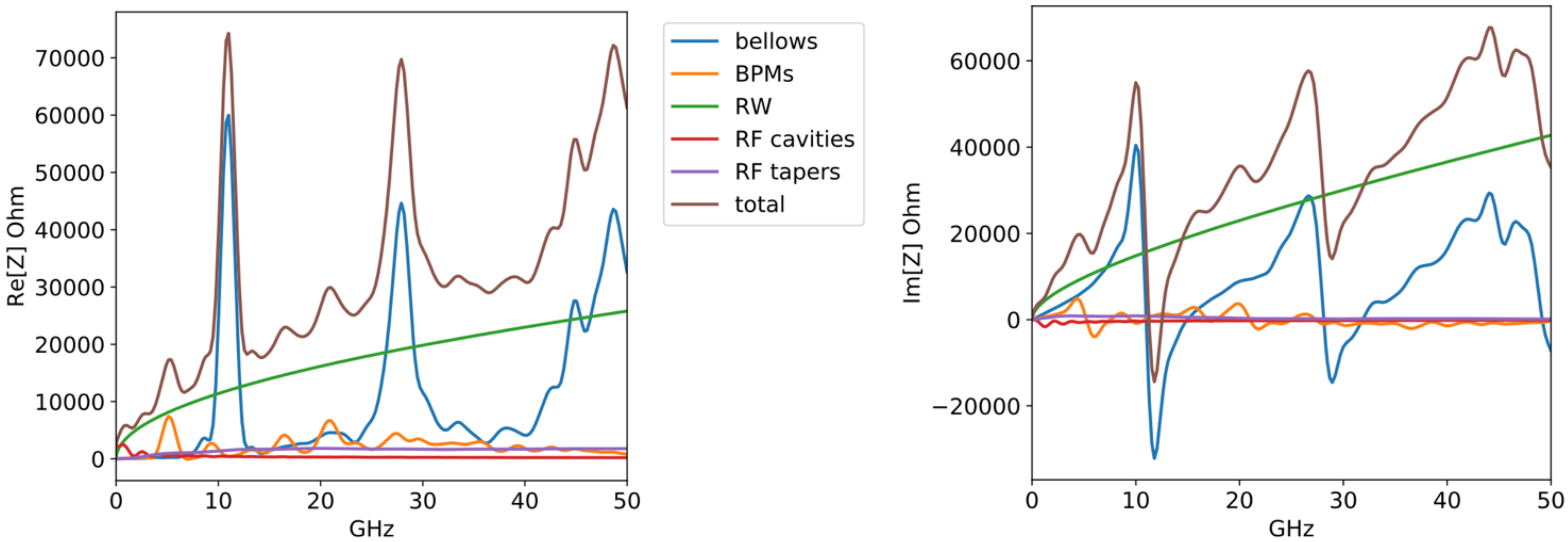
4000
BPMs







Overview of wakefields and coupling impedances



Some comments on the impedance budget and collective effects

- FCC-ee is still an ongoing project, and as we evaluate new devices, the total machine impedance increases more and more

- We are still missing several important devices, such as the collimation system, vacuum flanges, …

- On the other hand, the impedance evaluated so far already demonstrates how this machine can become critical due to collective effects (see next talks)

- The instabilities shown in the following talks will change based on the new impedance contributions that will gradually be added, but they suggest that we need to look for possible mitigation solutions.

Single beam instabilities

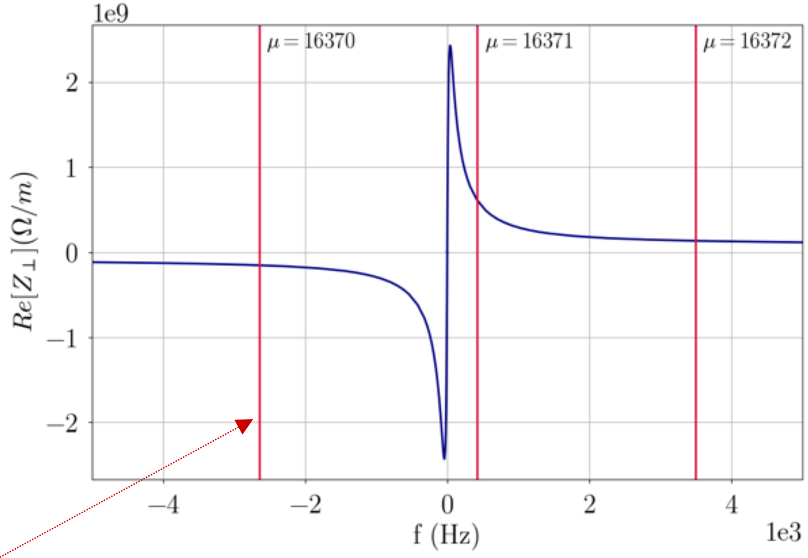
Transverse Coupled Bunch Instability (TCBI)

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

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

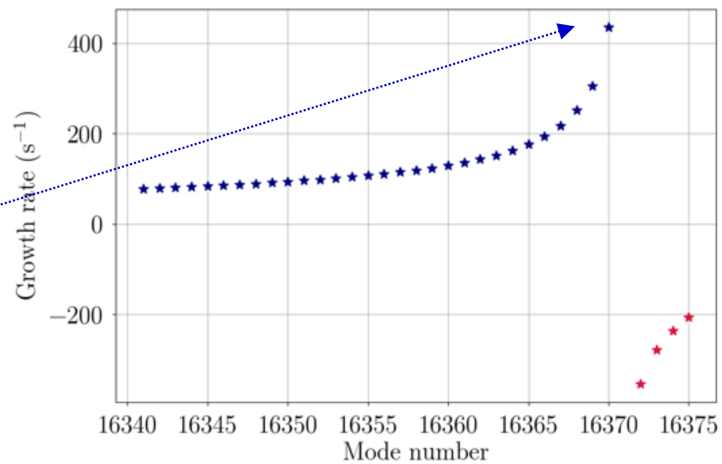
$$\omega_q = \left(qM + \mu + Q_\beta\right)\omega_0$$

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



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

Its growth time is about 7 revolution turns



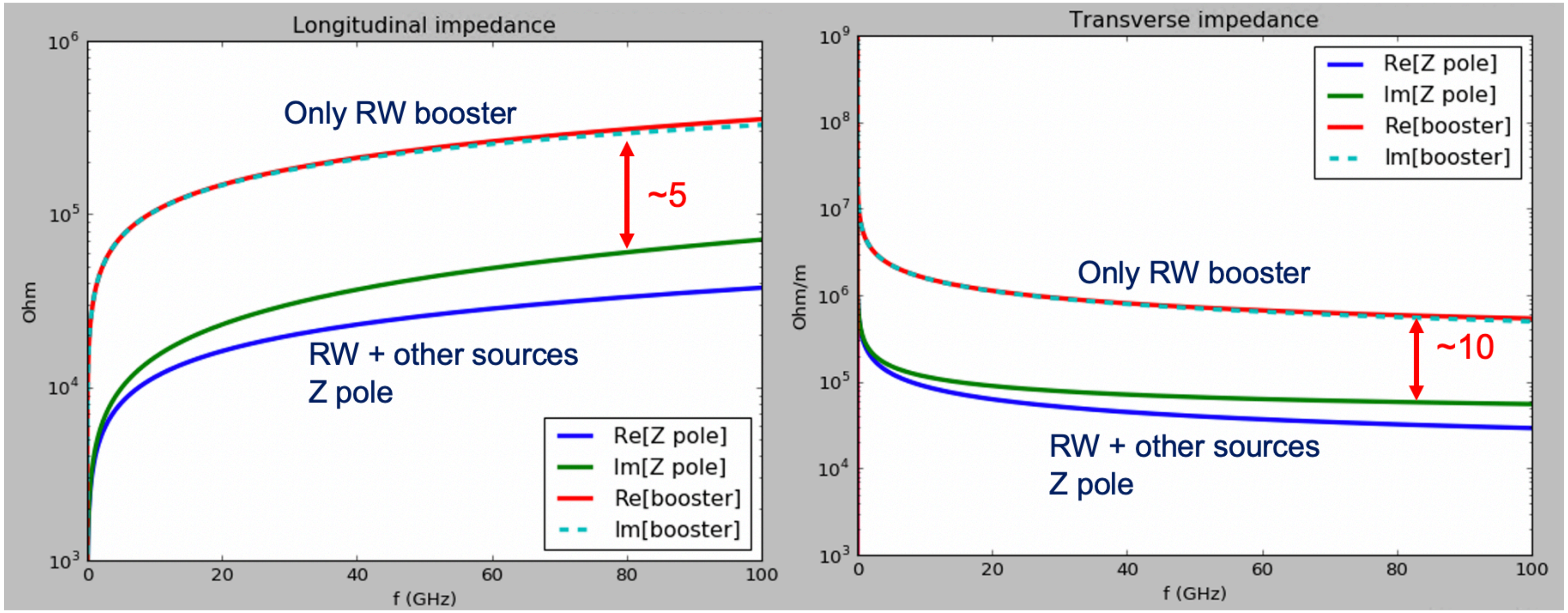
A robust feedback is required for the instability suppression!

Parameter list comparison: Z-pole and booster (injection)

parameter	Z	Booster	
Beam energy (GeV)	45.6	20	
Bunch population [10^{11}]	1.7	.213	
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

RW impedance in the Booster

- The main source of impedance for FCC-ee is the RW due to a copper beam pipe of 35 mm of radius
- For the booster the beam pipe is 25 mm and it is made of stainless steel
- The resistivity of stainless steel is 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.

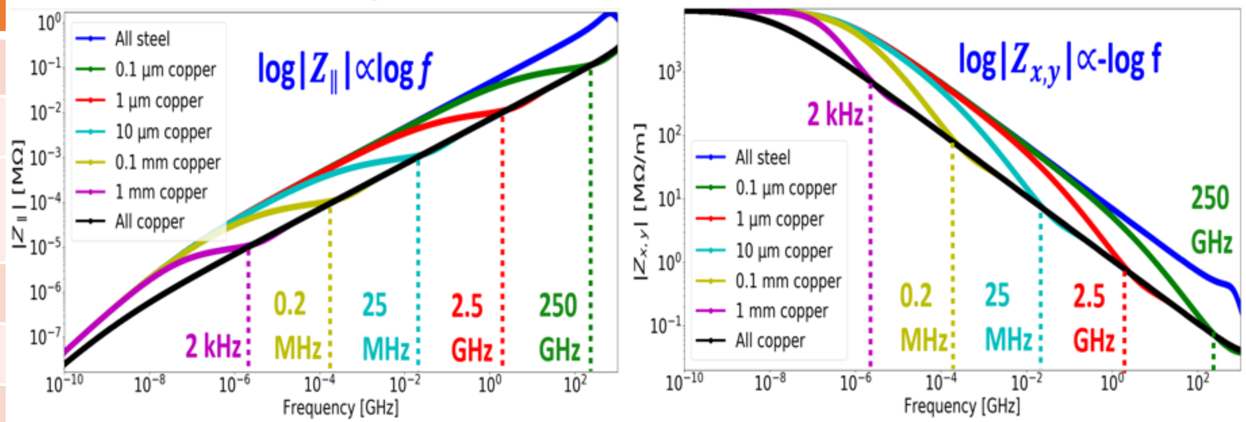


FCCee-Booster Beam Dynamics Studies

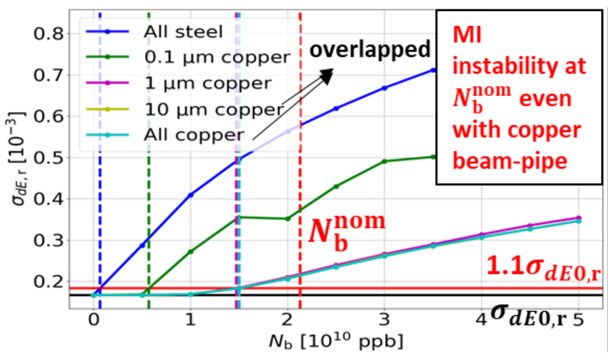
1) Simulated parameters

Parameters	Value
Machine circumference (C_r)	97.756 km
Beam energy at injection (E_0)	20 GeV
SR 1 σ rel. energy spread ($\sigma_{dE0,r}$)	0.166×10^{-3}
SR energy loss per turn (U_0)	1.33 MeV
SR damping time (τ_z)	15013 turns
RF frequency (f_{rf})	400 MHz
Harmonic number (h)	130432
RF voltage (V_{rf})	60 MV
Arc phase advance (φ_a)	60°
Mom. compaction factor (α_c)	1.48×10^{-5}
Synchrotron tune (Q_s)	0.0304
SR 1 σ bunch length (σ_{z0})	1.26 mm

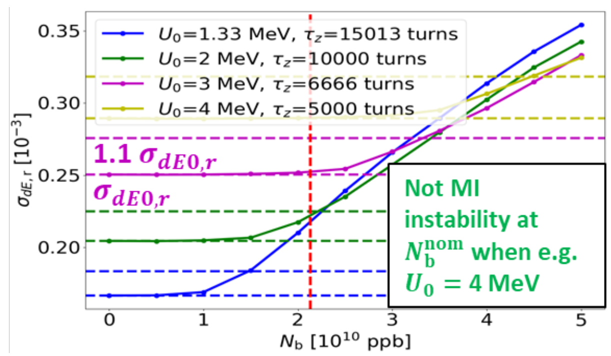
2) RW-impedance evaluation with IW2D adding a copper layer to beam-pipe



3) BLonD longitudinal beam dynamics simulations

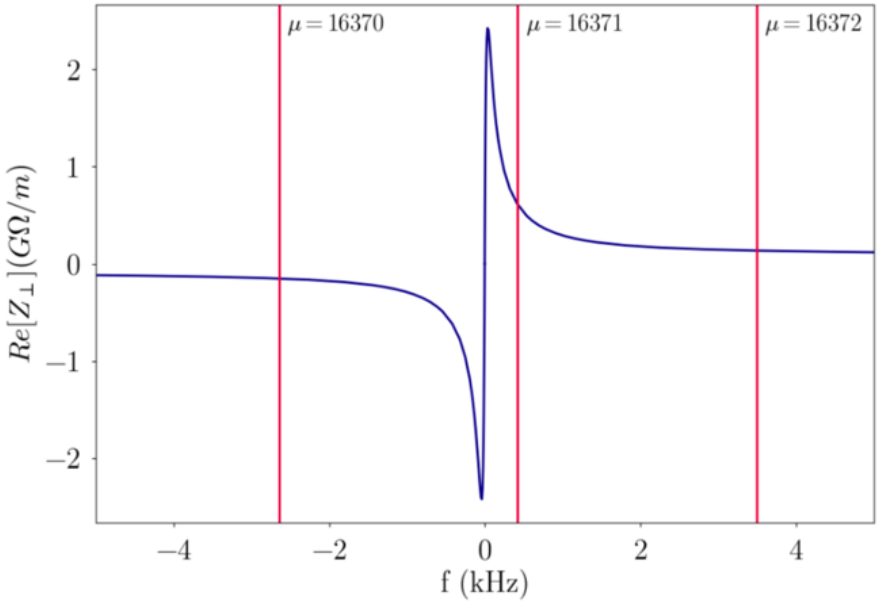


4) BLonD simulations using 1 µm copper-layer increasing SR power-loss

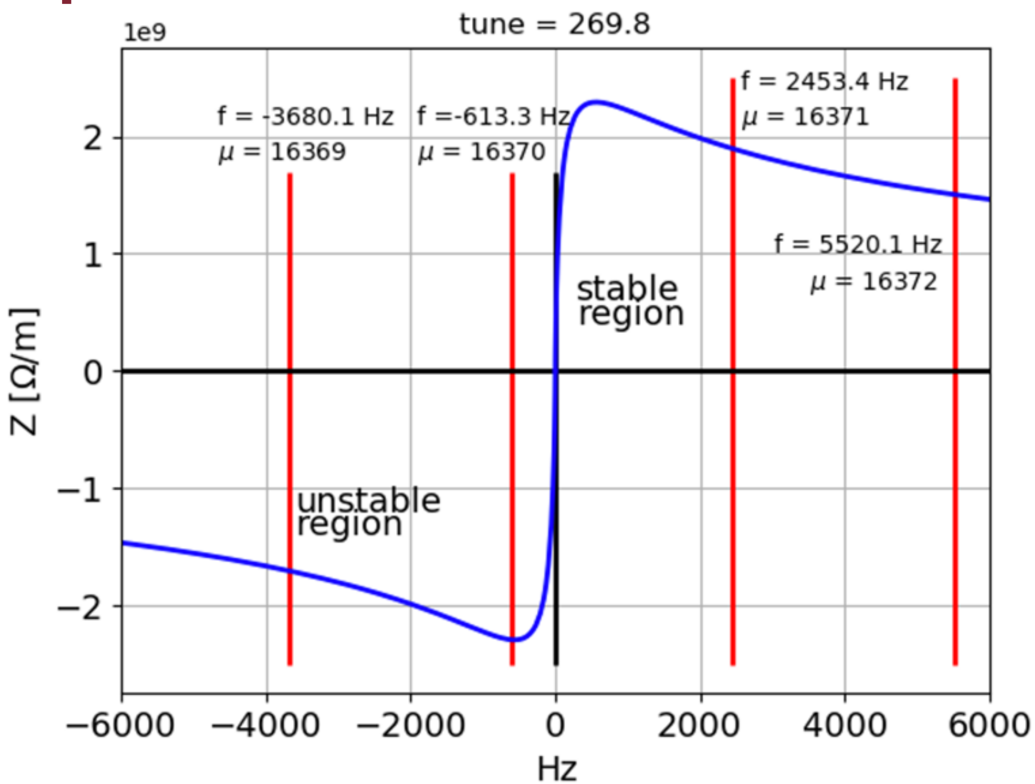


5) DELPHI shows no presence of TMCI at N_b^{nom} when $U_0 = 4$ MeV.

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. The rise time is in the order of few turns.

Challenges and future plan

- Continue the evaluation of impedance and wakefield of other machine devices (collimators, …)
- Update of some impedance sources with more realistic models (bellows – C. Antuono talk, RW, …)
- We are working on an impedance repository (see E. Carideo talk)
- Evaluate the transverse wakefields and impedances and perform PyHEADAIL simulations (only RW for the moment, see E. Carideo talk)
- Continue to investigate the interaction between beamstrahlung and longitudinal coupling impedance (see Y. Zhang talk)
- Continue to investigate possible mitigation techniques (higher harmonic cavities, higher momentum compaction, chromaticity, …)
- electron could, including the multi-bunch effects, ion instabilities
- Impedance evaluation, repository, and collective effects in the Booster
- Necessity of a feedback system for coupled bunch instabilities (in particular, for the transverse plane, also in the Booster)

Challenges and future plan

- Continue the evaluation of impedance and wakefield of other machine devices (collimators, …)
- Update of some impedance sources w ... ic models (bellows – C. Antuono talk, RW, …)
- We are working on an imped ... deo talk)
- Evaluate the transvers ... perform PyHEADAIL simul ... see E. Carideo talk)
- Continue to i ... beamstrahlung and longitudi ... hang talk)
- Continue ... gation techniques (higher harmonic cavities, hi ... paction, chromaticity, …)
- electron cou ... e multi-bunch effects, ion instabilities
- Impedance eva ... n, repository, and collective effects in the Booster
- Necessity of a feedback system for coupled bunch instabilities (in particular, for the transverse plane, also in the Booster)

Thank you for your attention