Beam-cavity interaction studies for the FCC-ee – RF frequency considerations

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Interaction of beam with cavity impedance

Main effects that need to be considered:

- Higher-order-mode power losses
- Beam loading (steady-state and transient)
- Coupled-bunch instabilities (longitudinal and transverse)

→ Operation at Z energy is the most challenging

Most of them were addressed for the CDR parameters, but

- Beam and accelerator parameters keep changing
- Alternative scenarios emerge

→ Re-evaluation of beam-cavity interaction aspects is needed

Update of parameters

Layout & placement optimization results in a smaller FCC circumference (PA31-1.0)
→ A decrease of the beam current by about 8% for all energies

Optimization of luminosity for 4 IPs
→ Higher bunch charge
→ Higher RF voltage

Parameter	FCC week 2022	CDR
Total current, J_A	1.28 A	1.39 A
Bunch intensity, N_p	2.43×10^{11}	1.7×10^{11}
Number of bunches, M_b	10000	16640
Bunch length (BS), σ	14.5 mm	12.1 mm
Total RF voltage, V_{tot}	120 MV	100 MV

These parameters will change after taking into account the precise choice based on FCC-hh RF synchronization aspects (see slides of L. Zhang)

→ What is the impact on operation at Z energy?

HOM power losses

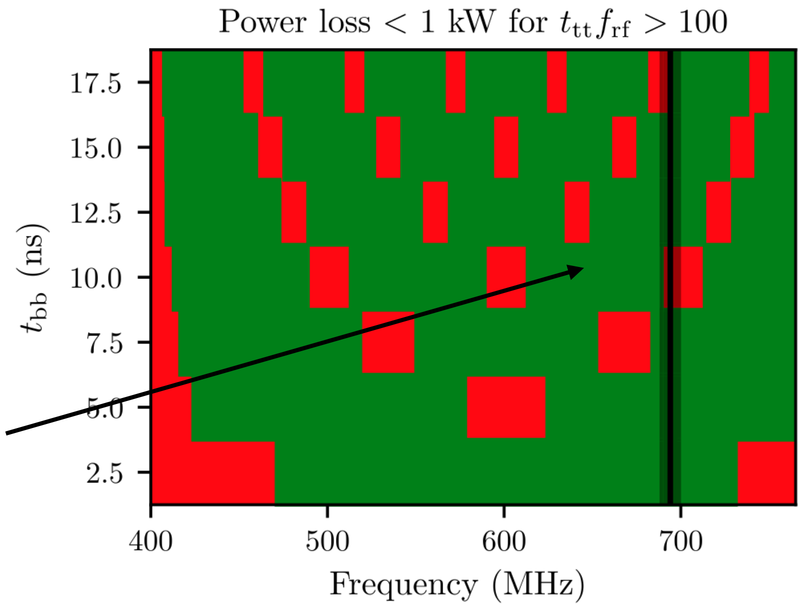
Simulated cavity impedance

Normalized Fourier harmonics of beam current

$$P = I_{b,\mathrm{DC}}^2 \sum_{k=-\infty}^{\infty} \mathrm{Re}\left[Z_{||}(k f_{\mathrm{rev}})\right] |I_k|^2$$

$I_{b,\mathrm{DC}}$ – average beam current
f_{rev} – revolution frequency
k – revolution harmonic number

Detailed analysis was performed for single-cell cavity design of 2015* with HOM below cut-off frequency of the beam pipe
→ Acceptable filling schemes were defined for operation
→ For all recent cavity designs, the first HOM is above cut-off frequency



I. Karpov, R. Calaga, E. Shaposhnikova, PRAB 21, 071001 (2018)

Impact of higher bunch charge

HOM power loss for broadband impedance can be approximated

$$P_{\mathrm{HOM}} = I_{b,\mathrm{DC}}^2 \sum_{k=-\infty}^{\infty} \mathrm{Re}\left[Z_{||}(kf_{\mathrm{rev}})\right] |I_k|^2$$

Gaussian bunches

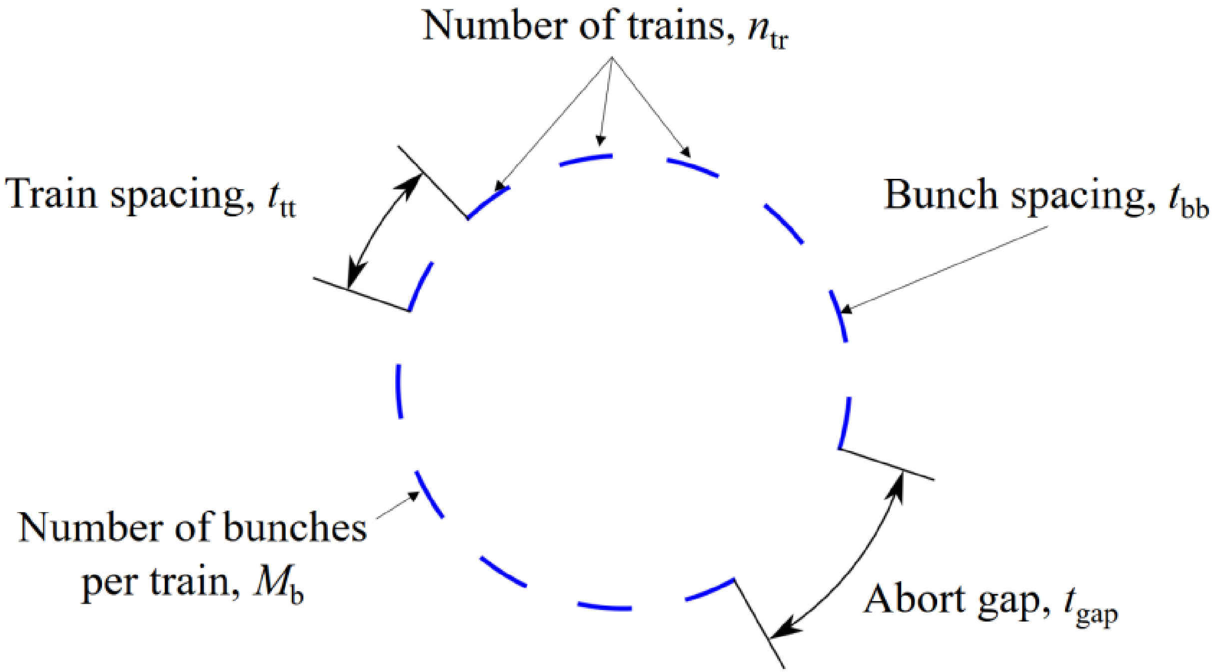
$$\approx e f_0 I_{b,\mathrm{DC}} N_p \sum_{k=-\infty}^{\infty} \mathrm{Re}\left[Z_{||}(kf_{\mathrm{rev}})\right] e^{-(2\pi k f_0 \sigma/c)^2}$$

Since bunch length scales* as $\sigma \propto \sqrt{N_p}$

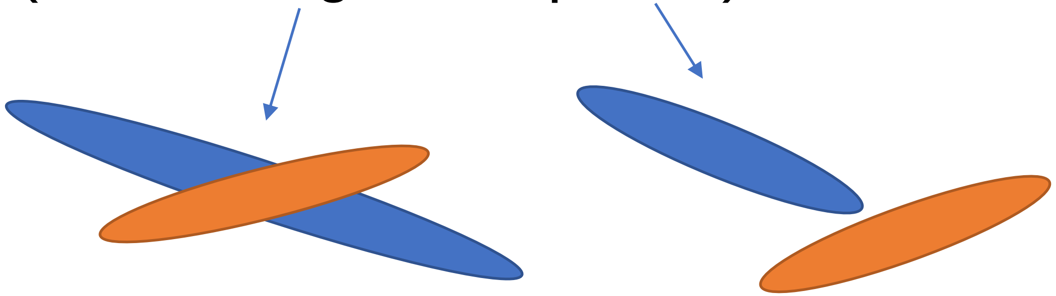
→ For the worst-case scenario, $\mathrm{Re}Z_{||}(kf_{\mathrm{rev}}) = \mathrm{const.}$, $P_{\mathrm{HOM}} \propto \sqrt{N_p}$ and thus weakly depends on parameter variations

*D. Shatilov, ICFA Beam Dyn. Newslett. 72, 30 (2017)

Transient beam loading



Gaps in machine filling will result in modulation beam parameters (bunch length and phase)



→ Might have impact on luminosity

Conventional approaches:

- Small-signal model in frequency domain*, which assumes small modulations (but we have 100% modulation of beam current!)
- Particle tracking simulations (difficult for 10000 bunches in FCC-ee Z)

→ We use steady-state time domain method**

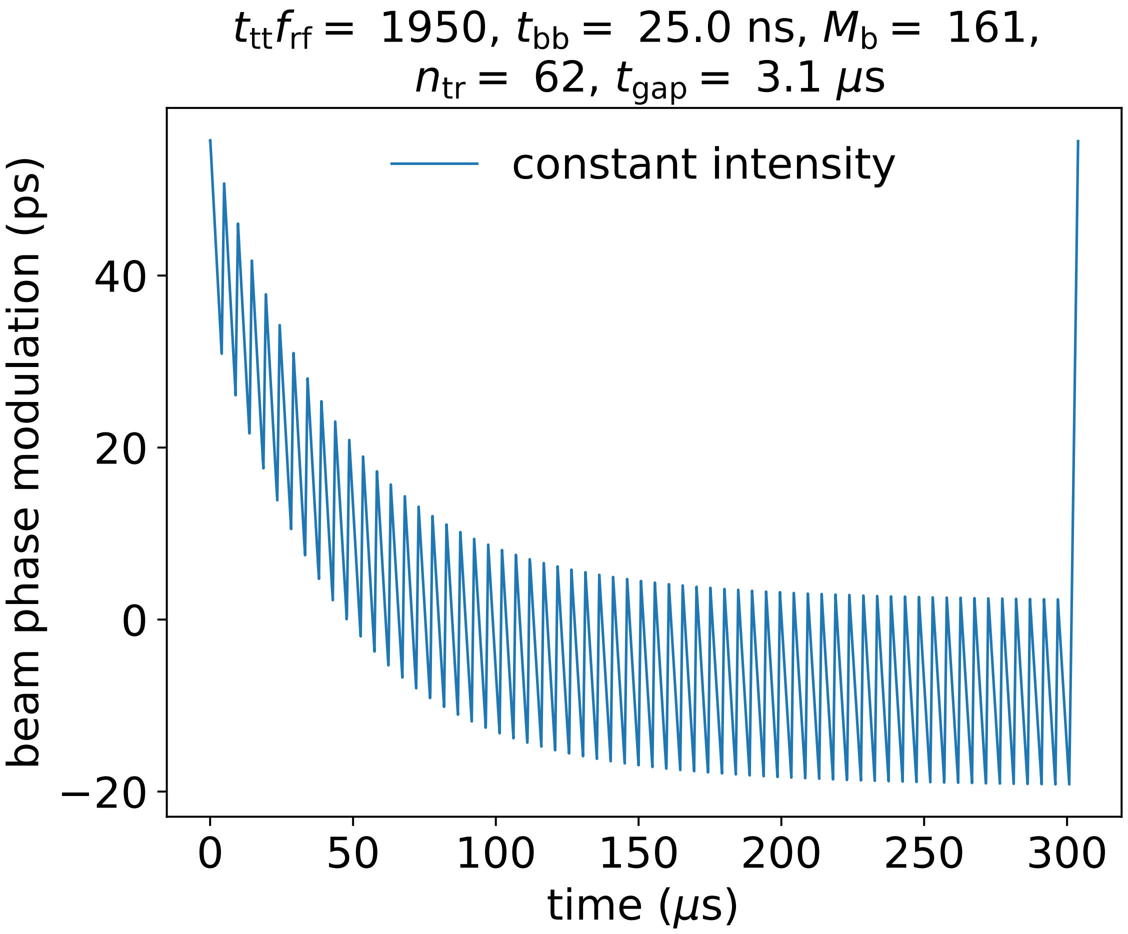
** F. Pedersen, RF Cavity feedback, CERN/PS 92-59 (1992)*

*** J. Tückmantel, CERN Report No. CERN-ATS-Note-2011- 002 TECH, 2011*

Example for single-cell cavity in FCC Z

→ There is a strong modulation due to the abort gap and a fine structure due to the gaps between trains
→ For identical rings, transients can be compensated by matching abort gaps (e.g., in PEPII, LHC,…); one gap is sufficient for 4 symmetric IPs

Imbalance of charge results in different detuning for electron and positron beams
→ Slightly different transients
→ The collision point shift is negligible for $\pm 5\ \%$ random spread of bunch charge



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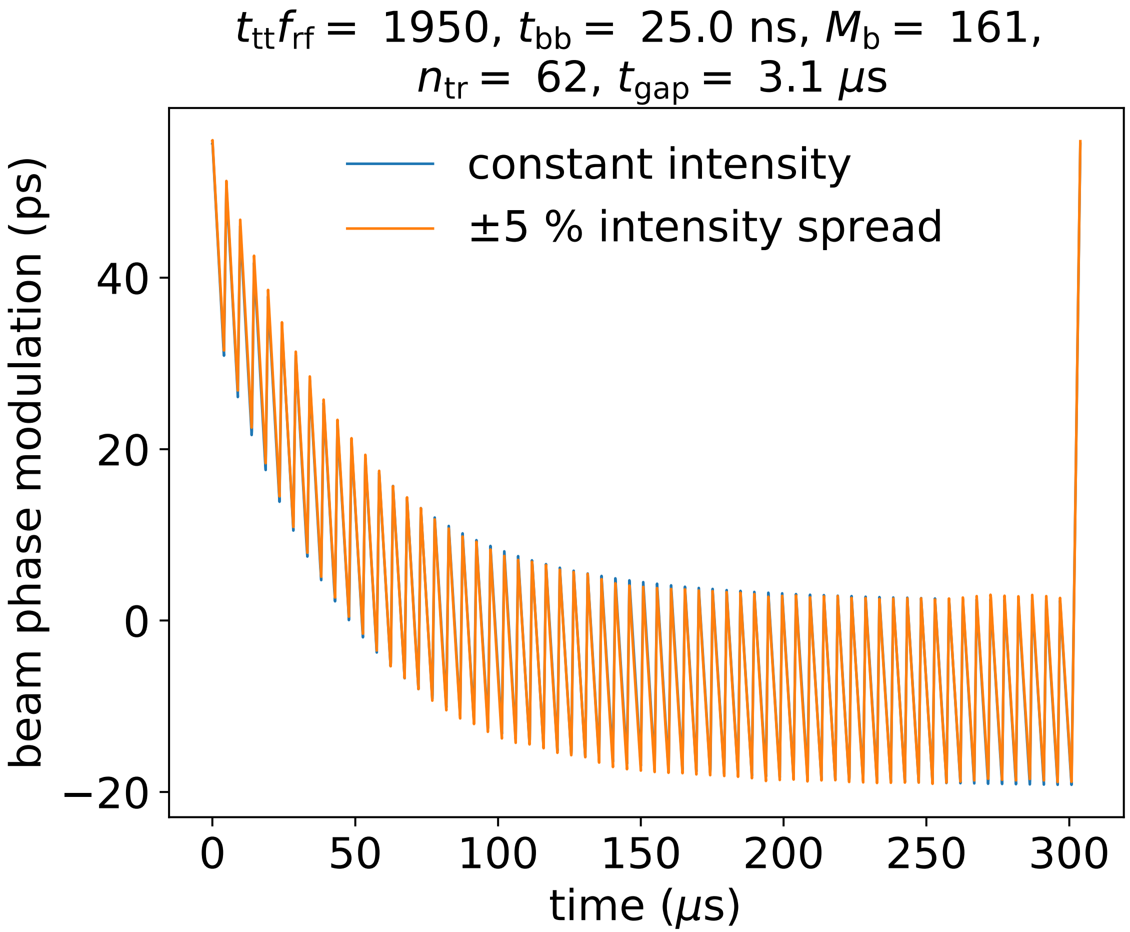

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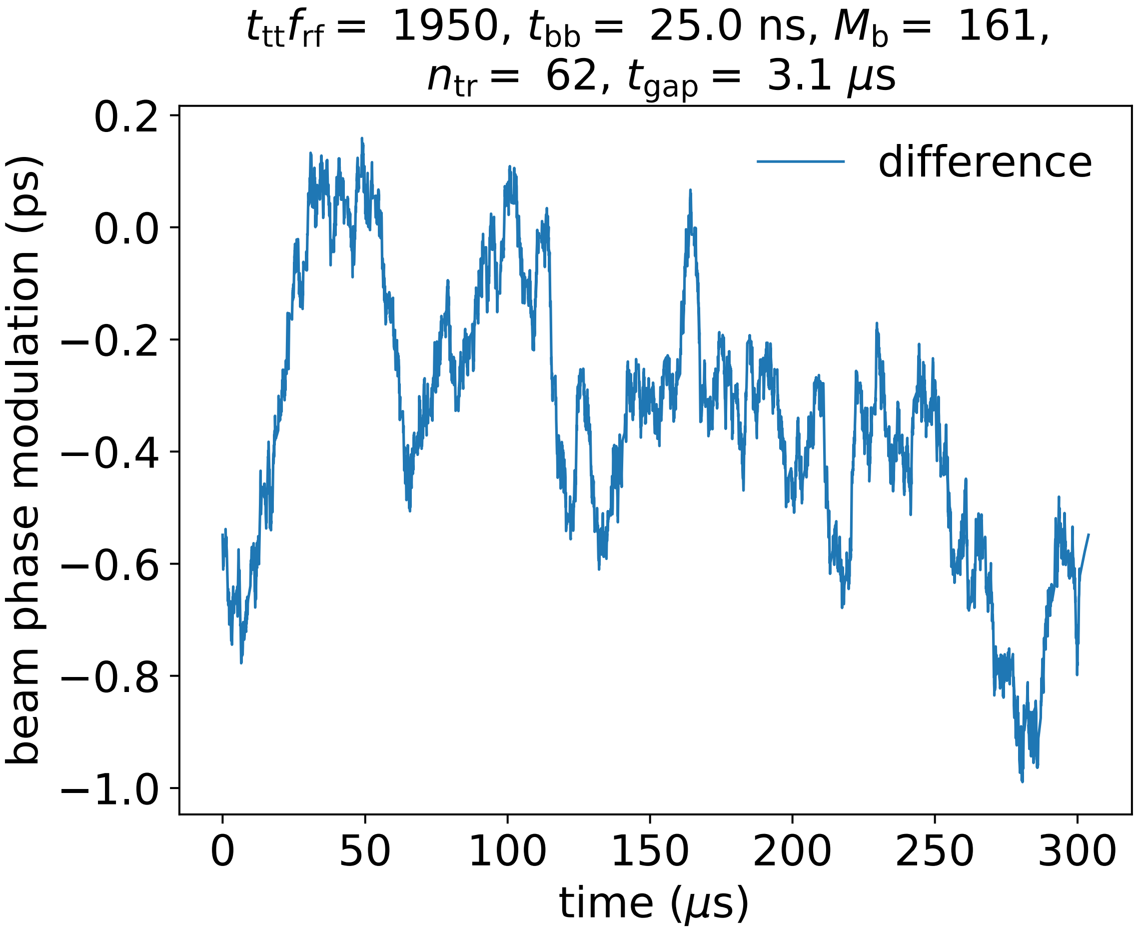


Longitudinal CBI due to fundamental mode

For short Gaussian bunches the growth rate of the mode *m* is*

$$\frac{1}{\tau_m} \approx \frac{e\eta I_{b,\mathrm{DC}} N_{\mathrm{cav}}}{4\pi E_b Q_s} \omega_{\mathrm{RF}} \{\mathrm{Re}[Z_{\mathrm{cl}}(\omega_+)] - \mathrm{Re}[Z_{\mathrm{cl}}(\omega_-)]\},$$

with $\omega_{\pm} = \omega_{\mathrm{RF}} \pm (m + Q_s)\omega_{\mathrm{rev}}$

Closed loop impedance with direct RF feedback**

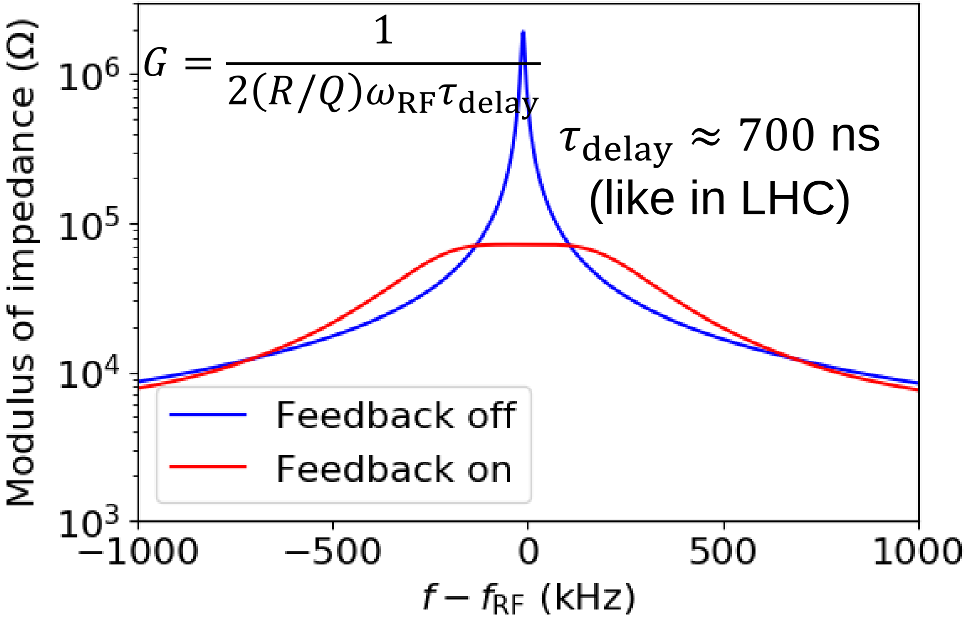
$$Z_{\mathrm{cl}}(\omega) = \frac{Z(\omega)}{1 + e^{-i\tau_{\mathrm{delay}}\omega} G e^{i\phi} Z(\omega)}$$

τ_{delay} – overall delay

$G = \frac{1}{2(R/Q)\omega_{\mathrm{RF}}\tau_{\mathrm{delay}}}$ - FB gain

ϕ – phase adjustment

Cavity impedance at fundamental, $Z(\omega)$



$G = \frac{1}{2(R/Q)\omega_{\mathrm{RF}}\tau_{\mathrm{delay}}}$

$\tau_{\mathrm{delay}} \approx 700$ ns
(like in LHC)

Passive damping sufficient if $\tau_m > \tau_{\mathrm{SR}}$ - synchrotron radiation damping time (1170 turns at Z pole)
→ Since, η, $I_{b,\mathrm{DC}}$, N_{cav}, Q_s have changed slightly, we don't expect any significant impact on beam stability

** J. L. Laclare, CAS, (1985)*

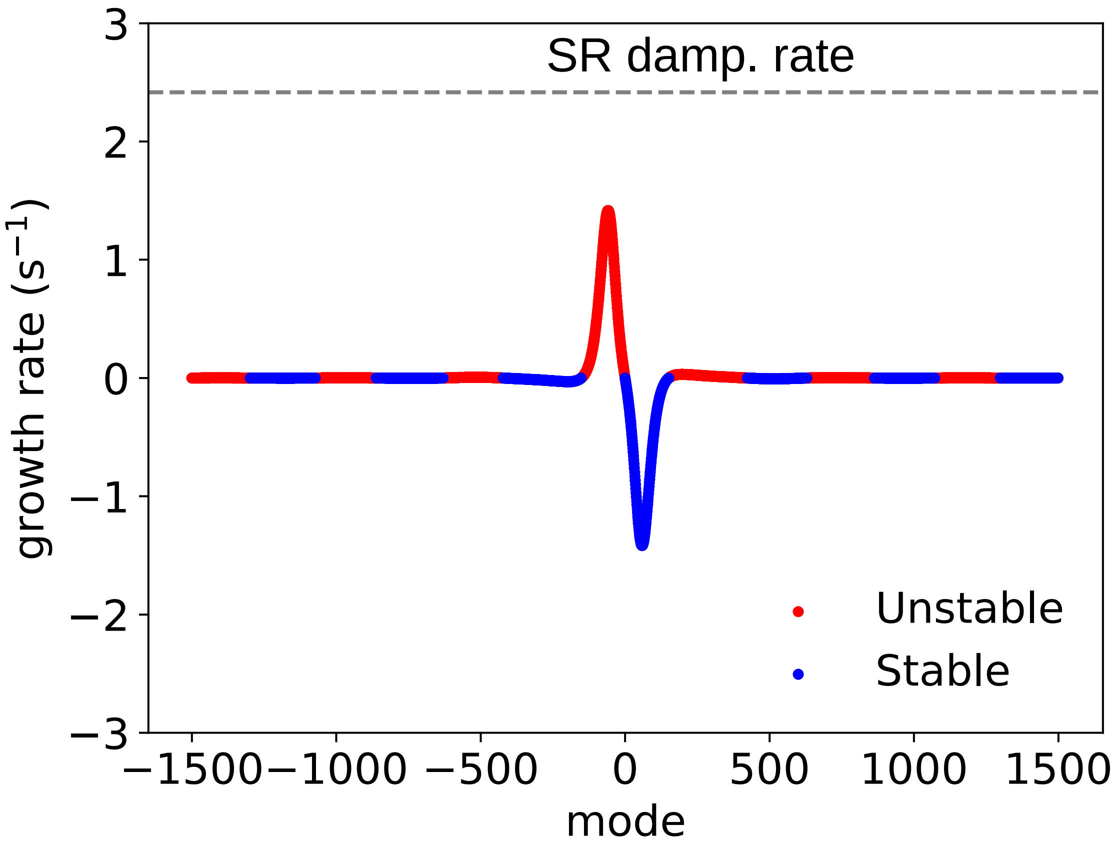
*** F. Pedersen, RF Cavity feedback, CERN/PS 92-59 (1992)*

Growth rates vs bunch mode number

→ Direct RF feedback reduces CBI growth rates below the threshold.

→ An additional feedback (1-turn delay, multi-harmonic?) could be implemented to provide additional margin.

Case of direct RF feedback only

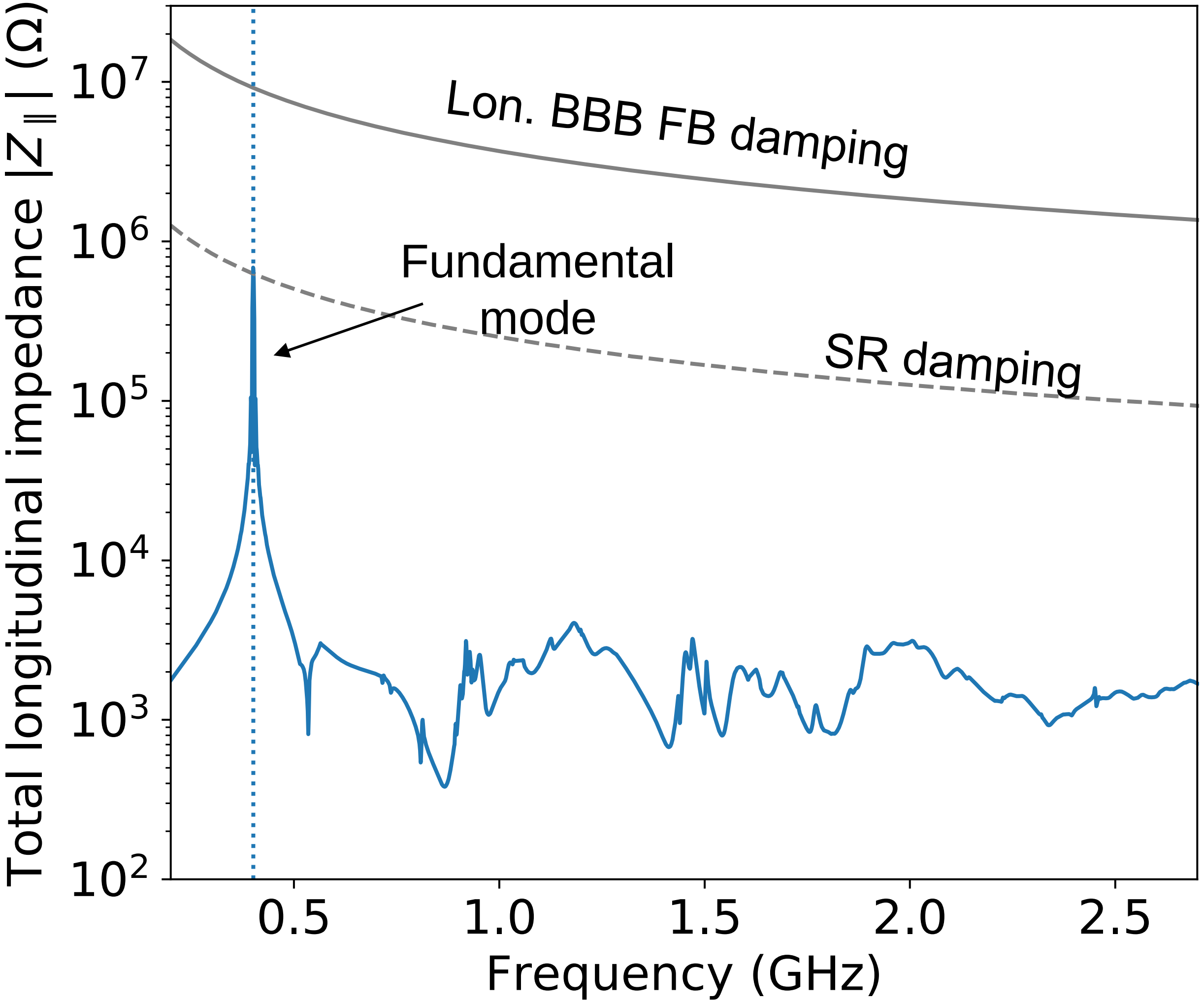


Longitudinal CBI due to HOMs at Z pole

A standard formula for threshold (only one sideband contributes)

$$Z_{\parallel}^{\mathrm{th}}(f) = \frac{2E_b Q_s}{e I_{b,\mathrm{DC}} \eta \tau_{\mathrm{SR}}} \frac{1}{f}$$

→ CBI instabilities due to HOMs will be suppressed by synchrotron radiation



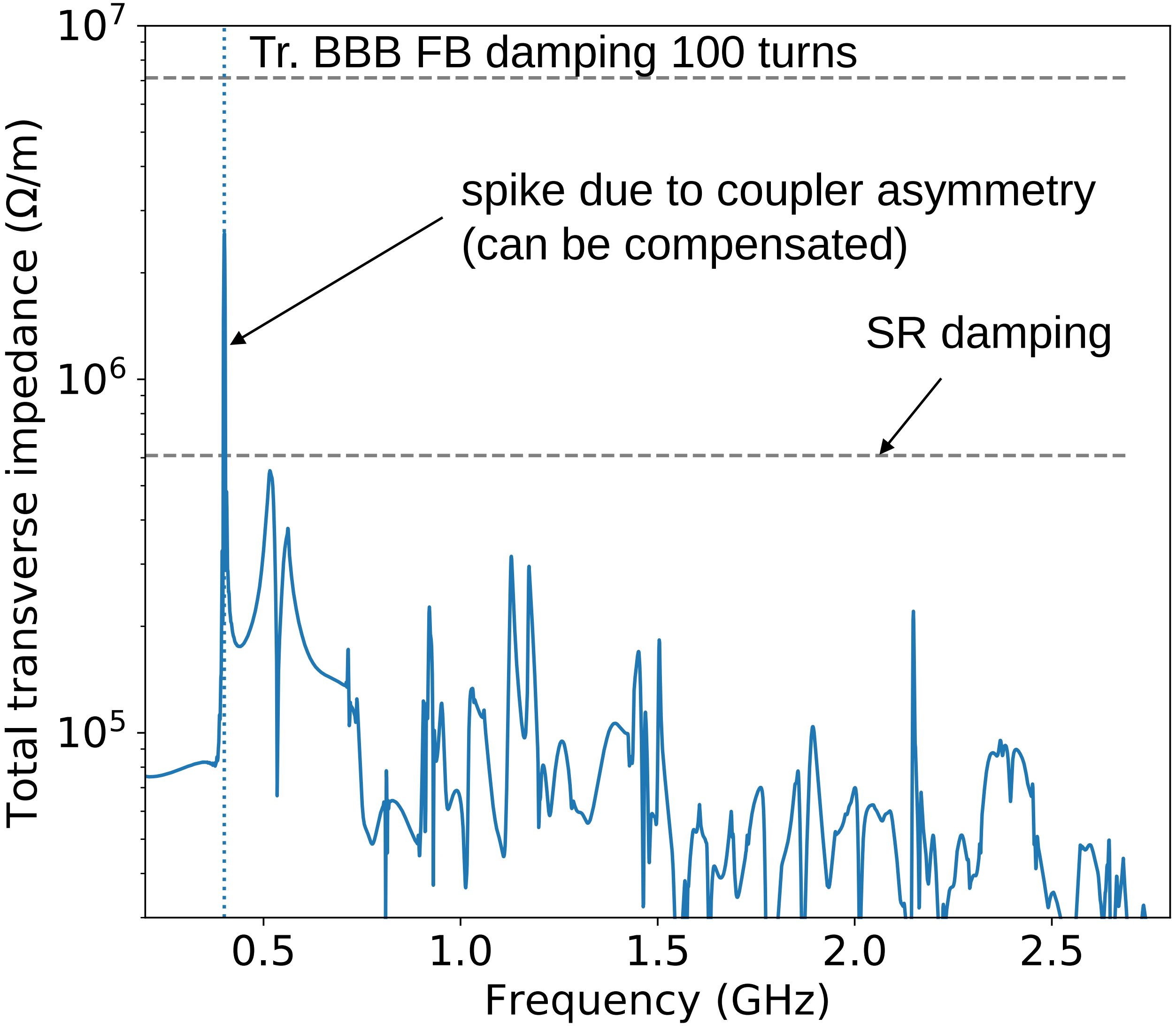
S. Gorgi Zadeh, PhD thesis, 2020

Transverse CBI due to HOMs

Similar expression for threshold

$$Z_{\perp}^{\mathrm{th}} = \frac{E_b}{e f_{\mathrm{rev}} I_{b,\mathrm{DC}} \beta_{xy} \tau_{\mathrm{SR}}}$$

→ HOM below the cut-off frequency is close to the CBI threshold
→ Bunch-by-bunch feedback system damping time of about 100 turns should be sufficient to suppress instabilities due to HOMs



S. Gorgi Zadeh, PhD thesis, 2020

Alternative scenario

In CDR 400 MHz 4-cell cavities are used from W + for ttbar 800 MHz, 5-cell cavities will be installed in addition

In 2018*, a "Hybrid scheme" was proposed to split RF systems for low energy (Z, W) and high energy (H,ttbar) operation points (additionally to replace 4-cell with 2-cell cavities to be below the threshold of transverse CBI)
→ The present scenario also assumes the same RF system for e- and e+ beams for the H pole (similar to ttbar)**

→ RF voltage for ttbar is dominated by 800 MHz (its contribution is optimized as suggested by T. Raubenheimer and K. Oide***)

Parameter	Unit	H (ZH)	ttbar
Total current, J_A	mA	26.7	5.0
Total RF voltage, V_{tot}	GV	2.1	2.1/8.2
SR energy loss/turn, U_0	GeV	1.9	10.0
RF frequency, f_{RF}	MHz	400	400/800

preliminary

* S. Gorgi Zadeh et al, IPAC, 2018
** F. Peauger, V. Parma, O. Brunner, 151st FCC-ee Optics Design Meeting & 22nd FCCIS WP2.2 Meeting, Mar. 17, 2022
*** K.Oide, FCC-ee parameter meeting, Nov. 16, 2021

Summary

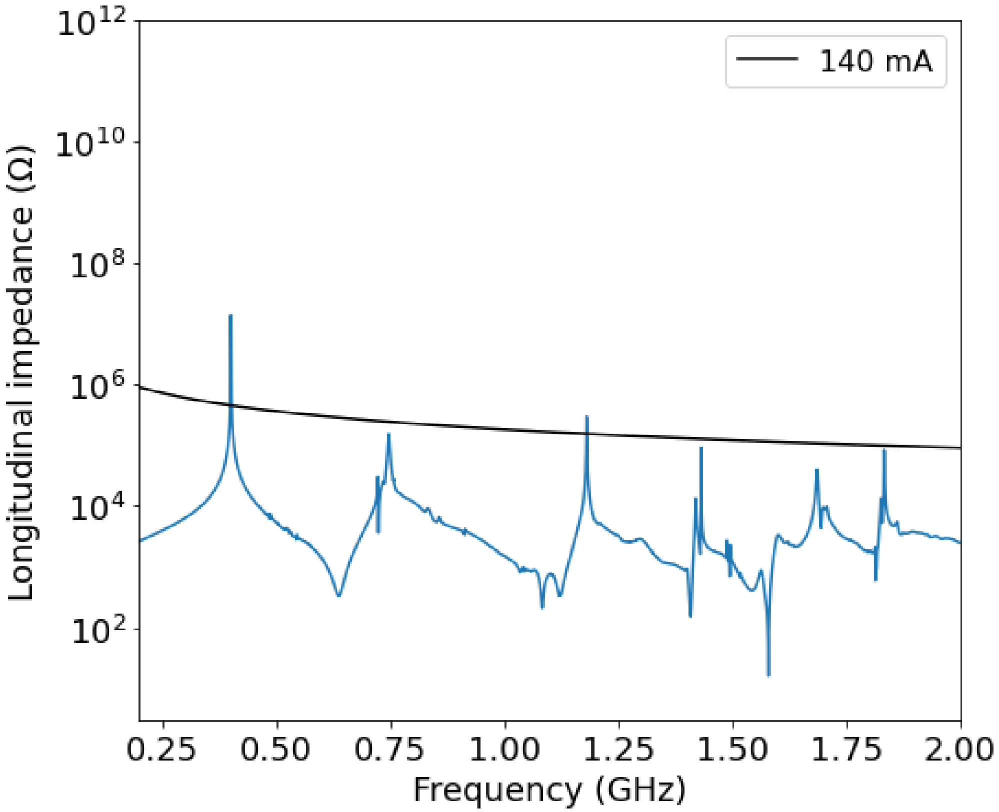
Beam-cavity interaction for FCC-ee operating at the Z pole is the most challenging (high beam current, a large number of bunches, etc).
They are re-evaluated for the latest parameter set:

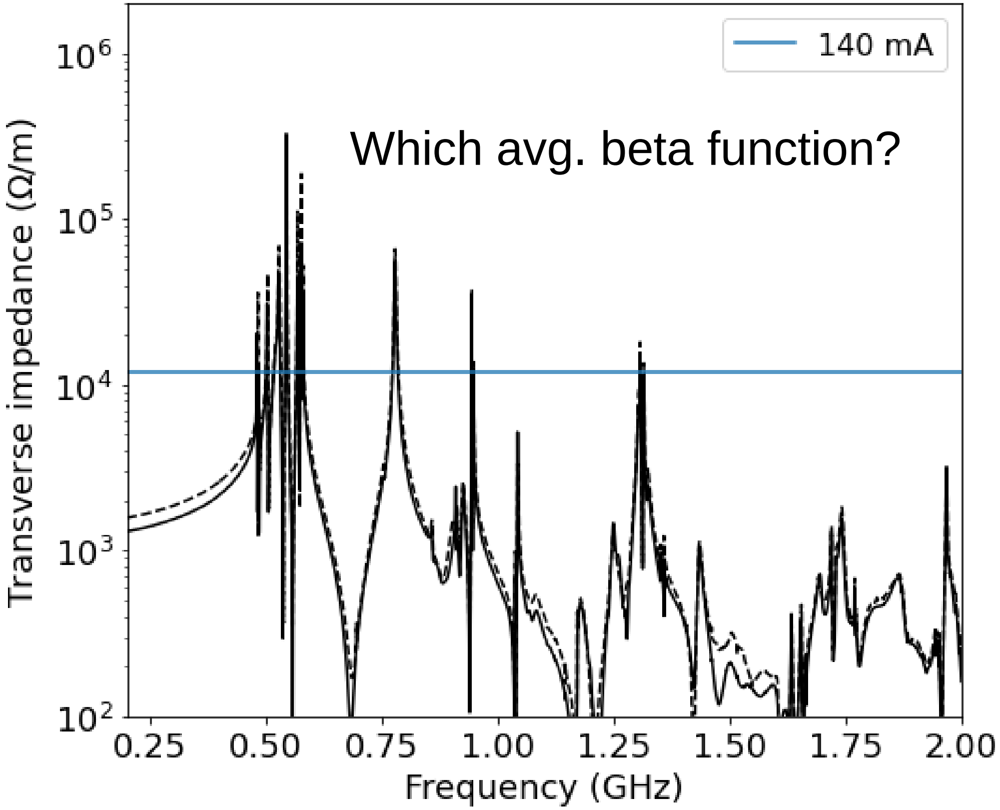
- HOM power losses weakly depend on single-bunch intensity.
- The impact of transient beam loading on the displacement of collision points is negligible.
- Longitudinal coupled-bunch instabilities are under control.
- To suppress transverse CBI due to HOMs bunch-by-bunch transverse feedback system is required.

Next steps:

- CBI and beam loading for W, H, ttbar calibration at Z energy
- HOM power and stability in the booster (24s at 20 GeV with the beam current of 140 mA)

Coupled-bunch instabilities in Booster





Which avg. beta function?

Longitudinal is very close to the threshold.

Thank you for your attention!

Steady-state beam loading

RF power per cavity in presence of beam loading $P = V_{\mathrm{cav}} I_{b,\mathrm{DC}} \cos\phi_s = 50\ \mathrm{MW}/N_{\mathrm{cav}}$ is minimized by using*

Optimal quality factor $$Q_L = \frac{V_{\mathrm{cav}}}{2(R/Q) I_{b,\mathrm{DC}} \cos\phi_s}$$

Red – fixed parameters

Optimal detuning $$\Delta\omega = \omega_0 - \omega_{RF} = -\frac{\omega_{\mathrm{RF}}(R/Q)\ I_{b,\mathrm{DC}} \sin\phi_s}{V_{\mathrm{cav}}}$$

Lower voltage requires less RF power but results in **larger detuning**.
→ Transient beam loading can potentially affect luminosity
→ Longitudinal coupled bunch instability (CBI) due to fundamental mode can be an issue

** D. Boussard, Control of cavities with high beam loading, IEEE Trans. Nucl. Sci. 32, 1852 (1985)*

- Next steps:
- HOM power and stability in Full energy booster (should be easy to get longitudinal CBI threshold curve at 20 GeV)

- CBI and beam loading for H calibration at Z energy