HOM power in FCC-ee cavities

Ivan Karpov, CERN

Acknowledgments: O. Brunner, A. Butterworth, R. Calaga, J. F. Esteban Müller, N. Schwerg, E. Shaposhnikova

FCC Week 2017, Berlin

FCC-ee options

	Z	W	H	$t\bar{t}$
Bunches / beam, M	71200	6000	740	62
Bunch spacing, t_{bb} [ns]	2.5	50	400	4000
Bunch population, N_b	0.4×10^{11}	0.5×10^{11}	0.8×10^{11}	2.1×10^{11}
Bunch length, σ_t [ps]	12	8.3	7.7	9.2
Beam current, J_A [mA]	1399	147	29	6.4

Harmonic number, h = 130680
Ring circumference, C = 97.75 km

HOM power loss in FCC cavities

Simulated cavity impedance

Normalized Fourier harmonics of beam current

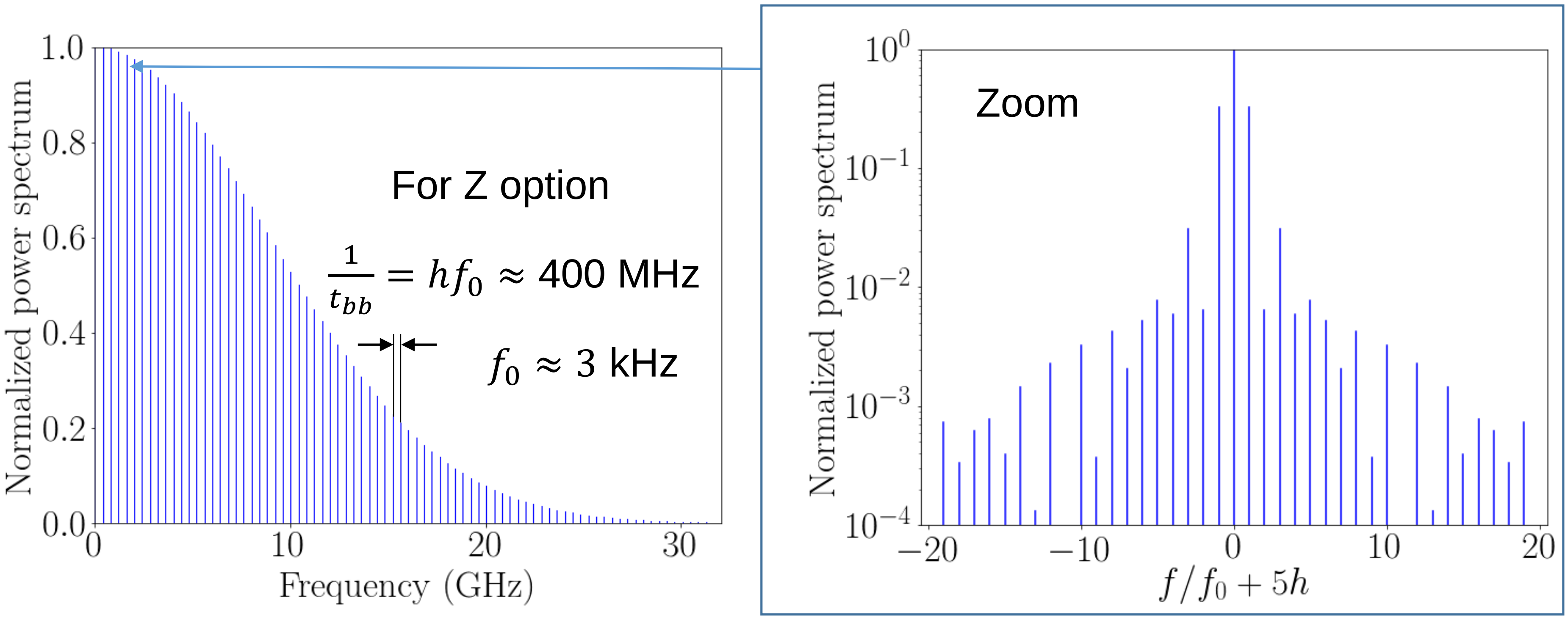
$$P = J_A^2 \sum_{k=-\infty}^{\infty} \mathrm{Re}\left[Z_{||}(kf_0)\right] |J_k|^2$$

f_0 - revolution frequency
J_A - average beam current

→ HOM power should be extracted (max 1 kW per coupler)

Beam power spectrum

Spectrum contains multiples of $1/t_{bb}$ and f_0 harmonics

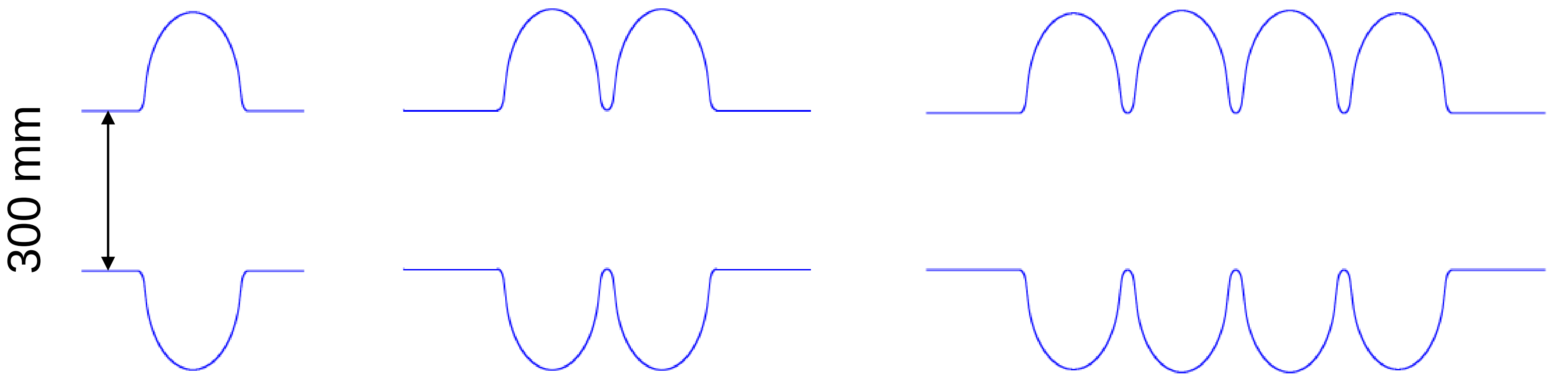


For Gaussian bunches $$|J_k|^2 = e^{-(2\pi k f_0 \sigma_t)^2} \frac{\sin^2(M\pi k f_0 t_{bb})}{M^2 \sin^2(\pi k f_0 t_{bb})}$$

M is number of bunches

Example of 400 MHz cavities

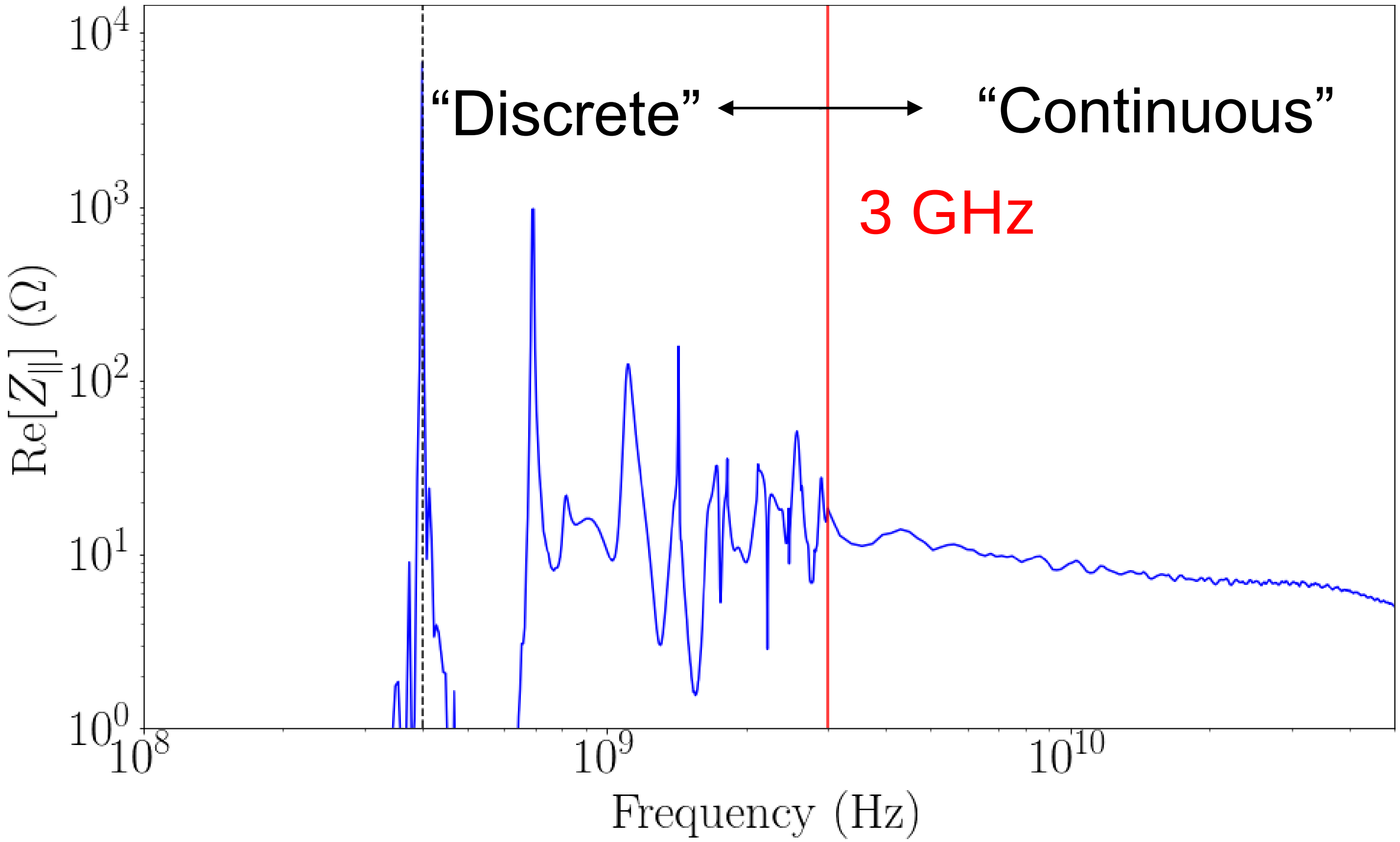
Cavity options for FCC-ee (Input from R. Calaga)



Impedance calculation using ABCI

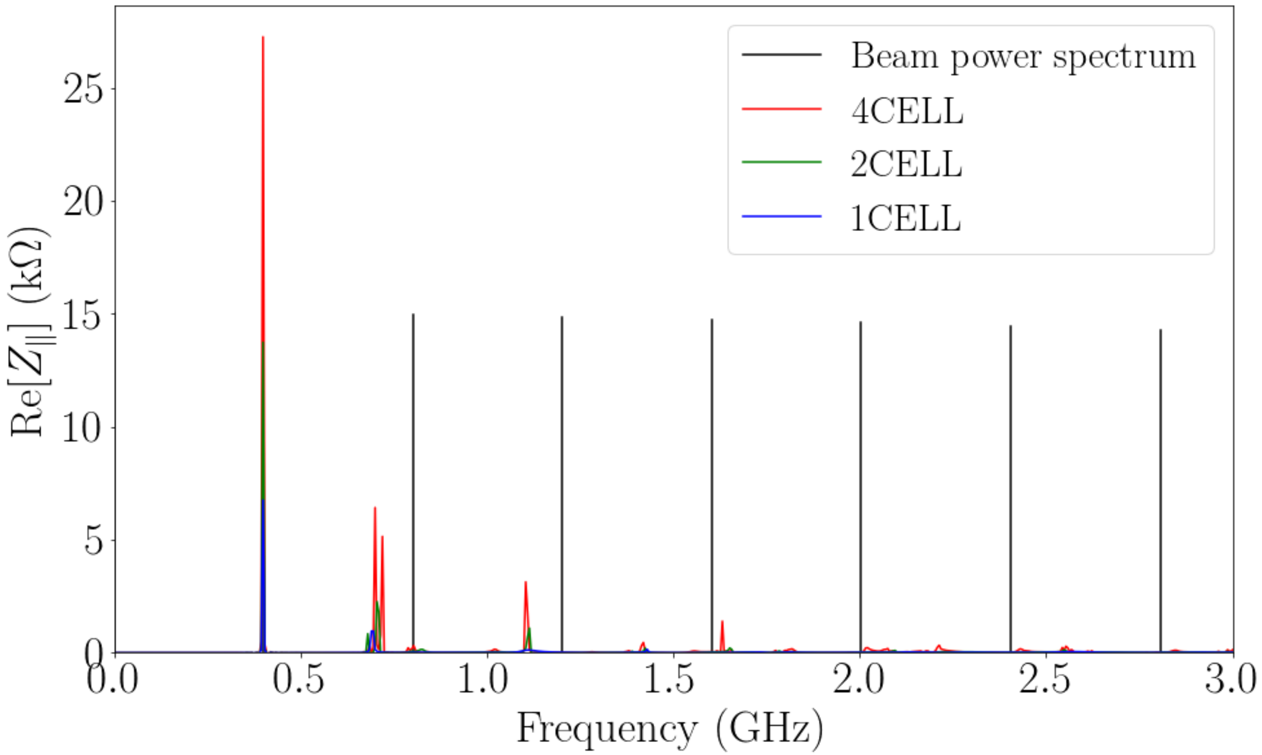
Axisymmetric structure + Gaussian bunch → Wake potential → Loss factor + Impedance

Example of 400 MHz single-cell cavity impedance



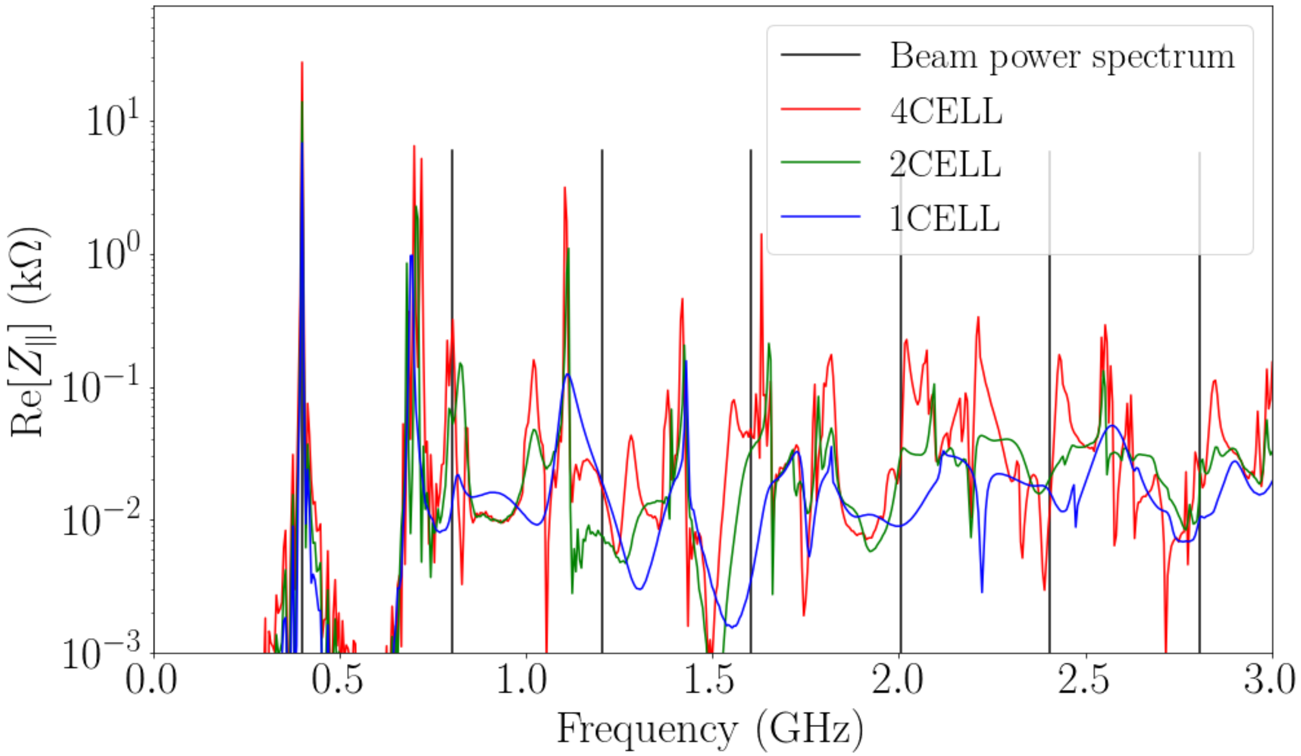
Cutoff for all trapped modes ≤ 3 GHz

Example of 400 MHz cavities. Impedance below 3 GHz



Resonant lines are far from the beam spectrum harmonics $k \times 400$ MHz (care should also be taken in any future design)
→ This impedance can be excluded from power loss calculations

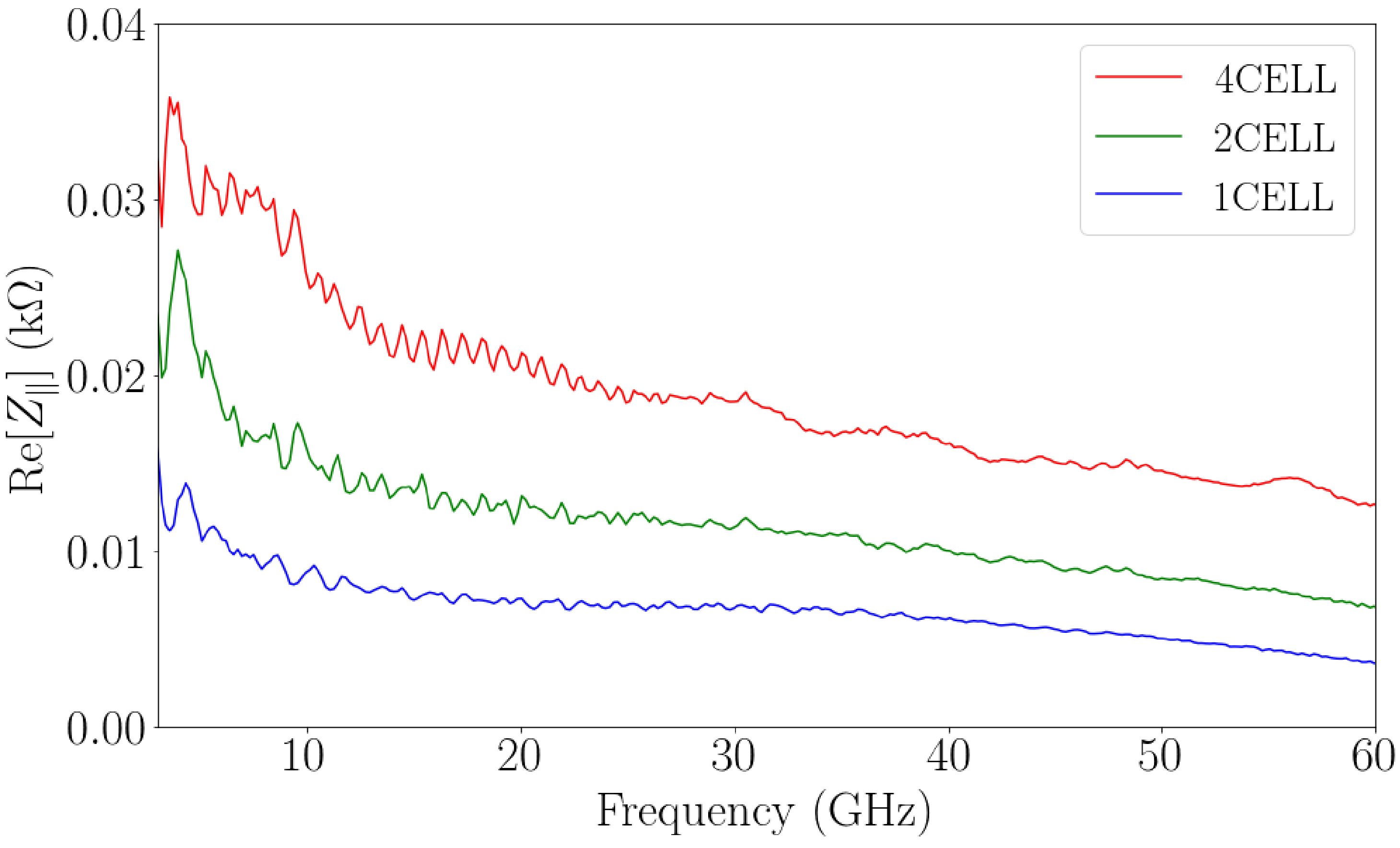
Example of 400 MHz cavities. Impedance below 3 GHz



Resonant lines are far from the beam spectrum harmonics $k \times 400$ MHz (care should also be taken in any future design)

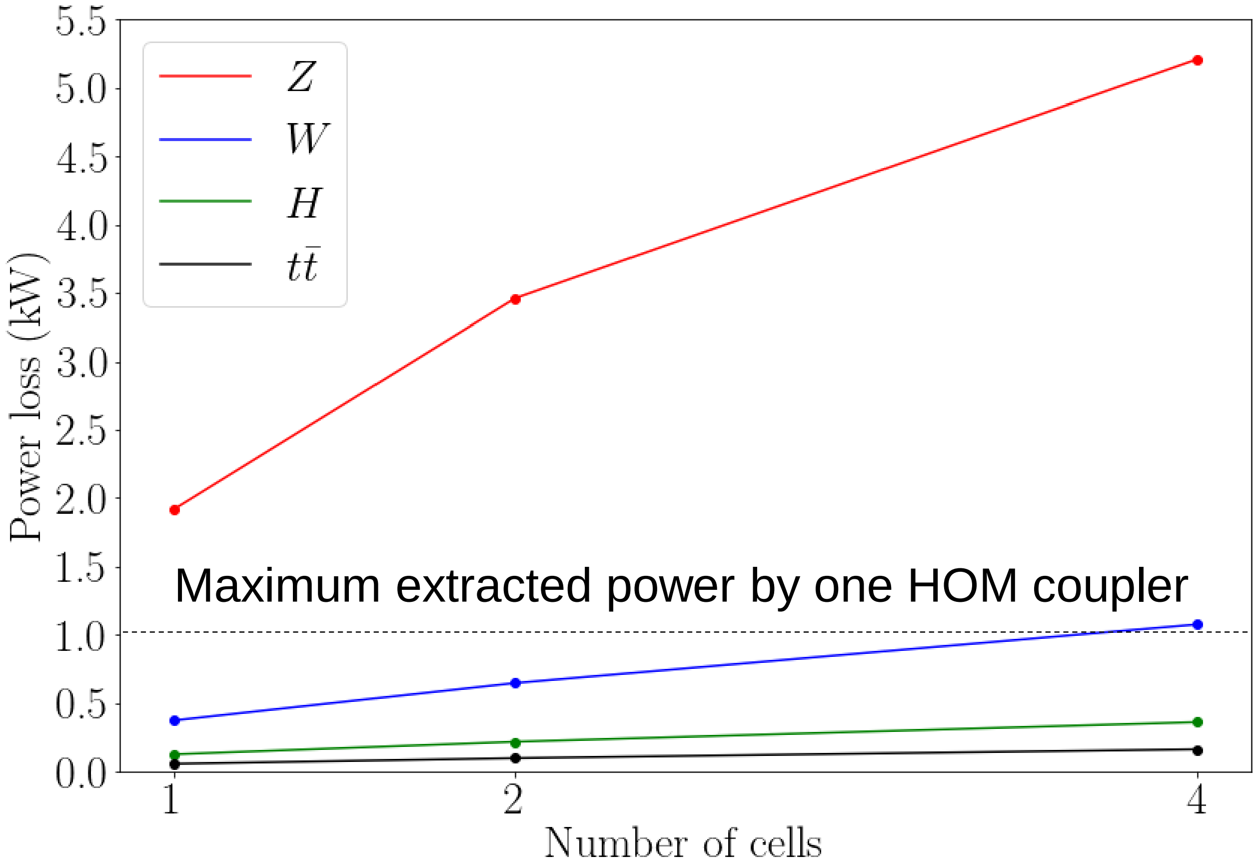
→ This impedance can be excluded from power loss calculations

Impedance above 3 GHz



→ Larger cavity impedance for larger number of cells (opposite per cell)

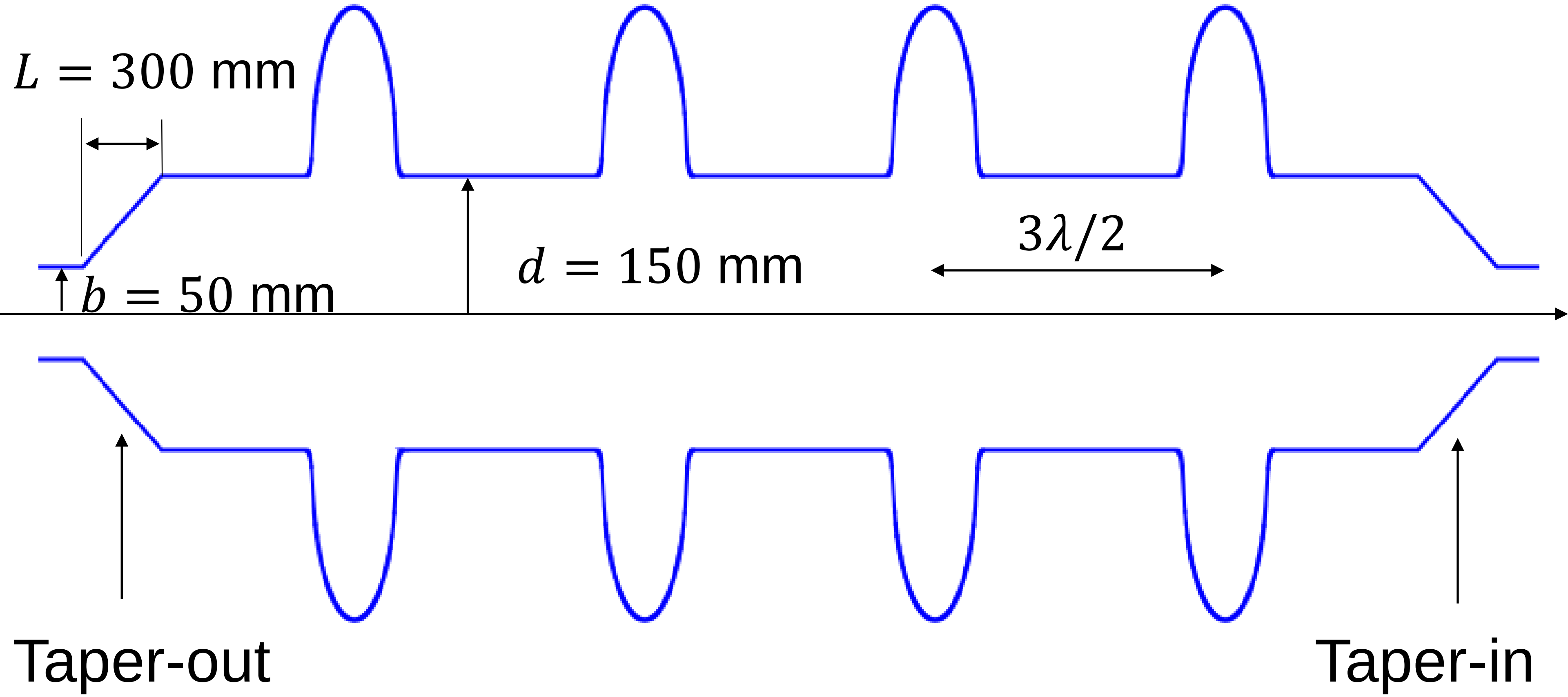
Power loss for different number of cells in FCC-ee machines



Discrete impedance lines are excluded.

Single-cell cavity design is feasible for Z machine

LHC-like layout of cryomodule



Loss factor of taper-out

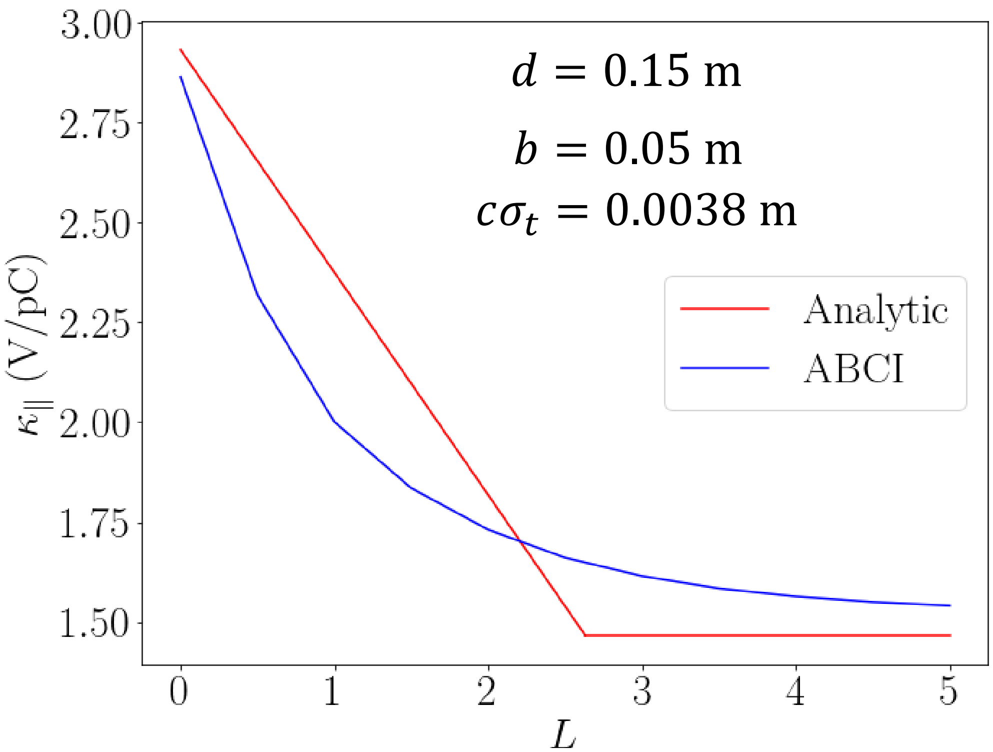
Analytic estimates*

$$c\sigma_t \ll b < d$$

$$\kappa_\parallel(\sigma) = \frac{1}{2\pi\varepsilon_0 c\sigma_t\sqrt{\pi}} \ln\left(\frac{d}{b}\right)\left[1 - \frac{\tilde{\eta}}{2}\right]$$

$$\tilde{\eta} = \min(1, \eta)$$

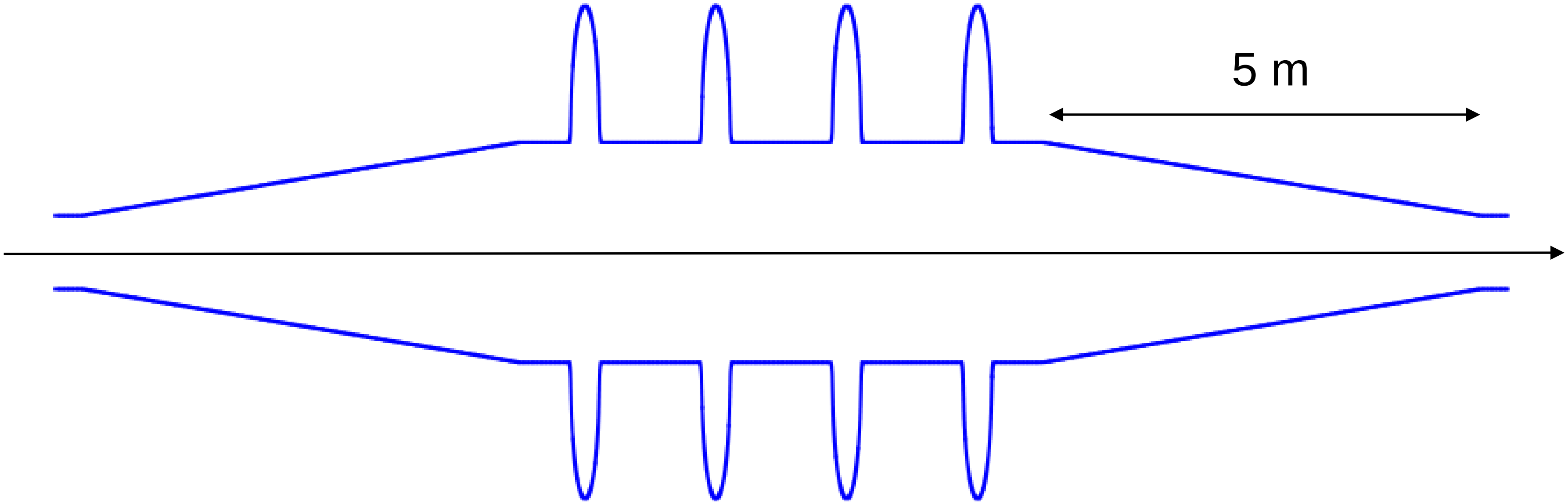
$$\eta = \frac{Lc\sigma_t}{(d-b)^2}$$



Short wake potentials are used in simulations

*S. A. Heifets and S. A. Kheifets Rev. Mod. Phys. **63**, 631 (1991)

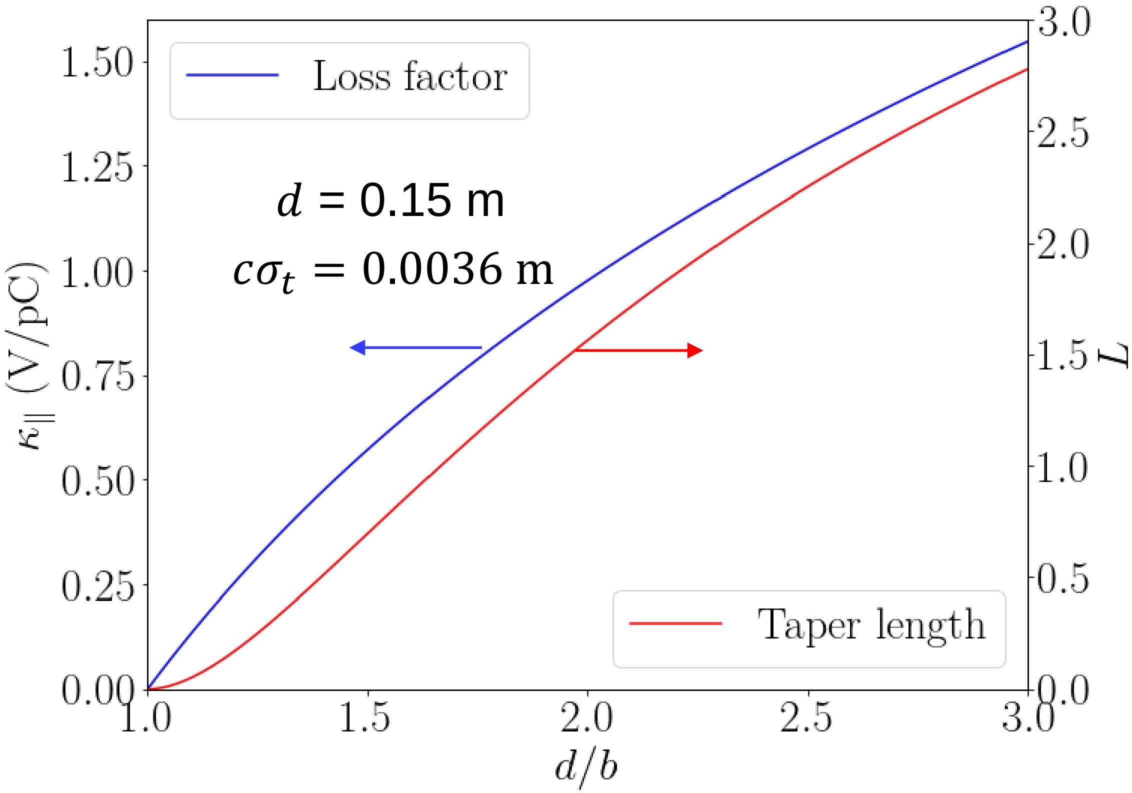
Loss factors of 4-cavity structure



Structure	Loss factor $\kappa_{\parallel}$ (V/pC)		
	Steps	Taper-out	Tapers
With cavities	3.82	2.78	1.41
Without cavities	3.23	1.54	0.13

Loss factor of 4 cavities is 1.21 V/pC

Optimization of transitions



Asymptotic value of loss factor for taper-out

$$\kappa_{\parallel}(\sigma) = \frac{1}{4\pi\varepsilon_0 c\sigma_t\sqrt{\pi}}\ln\left(\frac{d}{b}\right)$$

Minimum required length

$$L = \frac{(d-b)^2}{c\sigma_t}$$

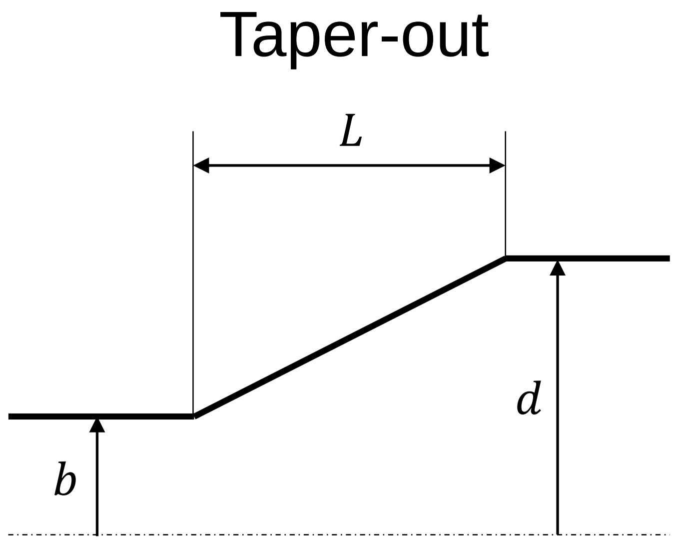
Conclusions

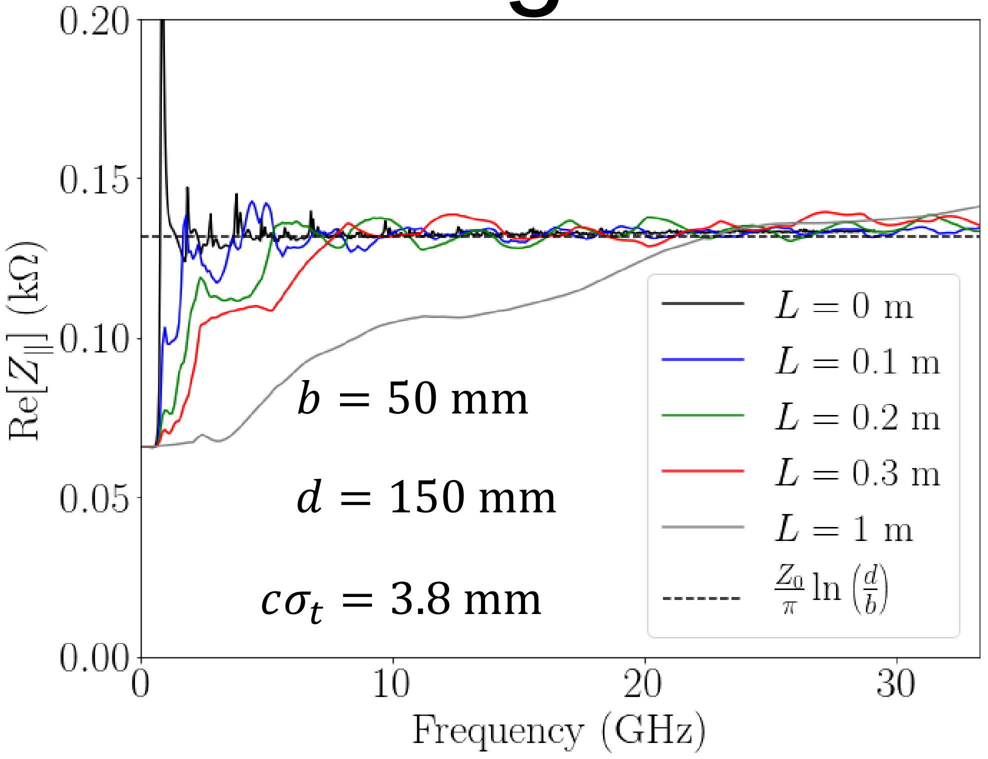
- Estimations of power loss for all FCC-ee machines (400 MHz cavities)
  - Maximum power losses are for Z machine: ~ 2 kW for single cell cavity, main contribution is given by impedance above 3 GHz
  - For higher energy machines power losses are below 1 kW

- Significant contribution to the total power loss from tapers for FCC-ee bunch length.
  - For transition from 150 mm to 50 mm loss factor of taper-out ~ 1.5 V/pC is achieved for 5 m length
  - Optimization of cold-warm transitions is ongoing

Thank you for your attention!

Impedance of tapers: dependence on length

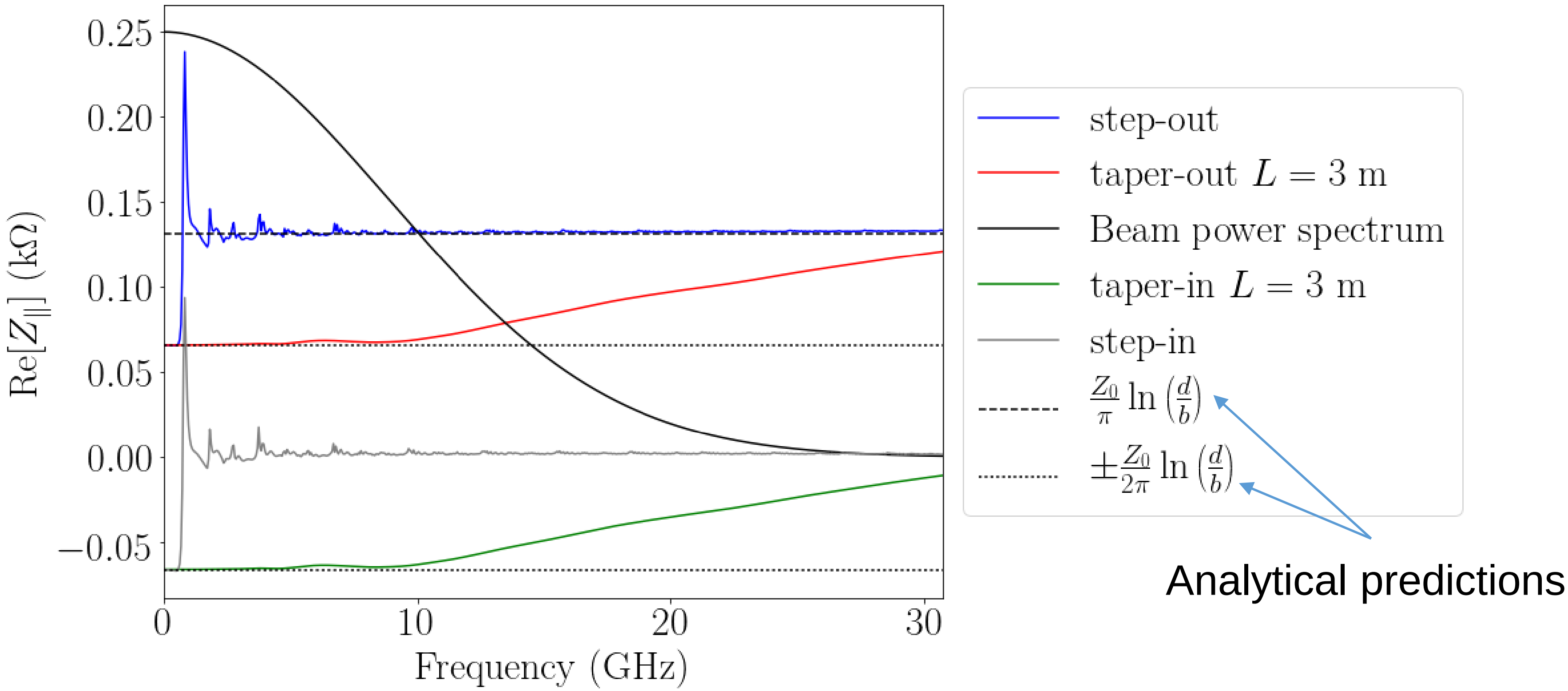




Asymptotic behavior at high frequencies

$$f \gg \frac{c}{2\pi b} \rightarrow Z_0^{\parallel} = \frac{Z_0}{\pi} \ln \frac{d}{b}$$

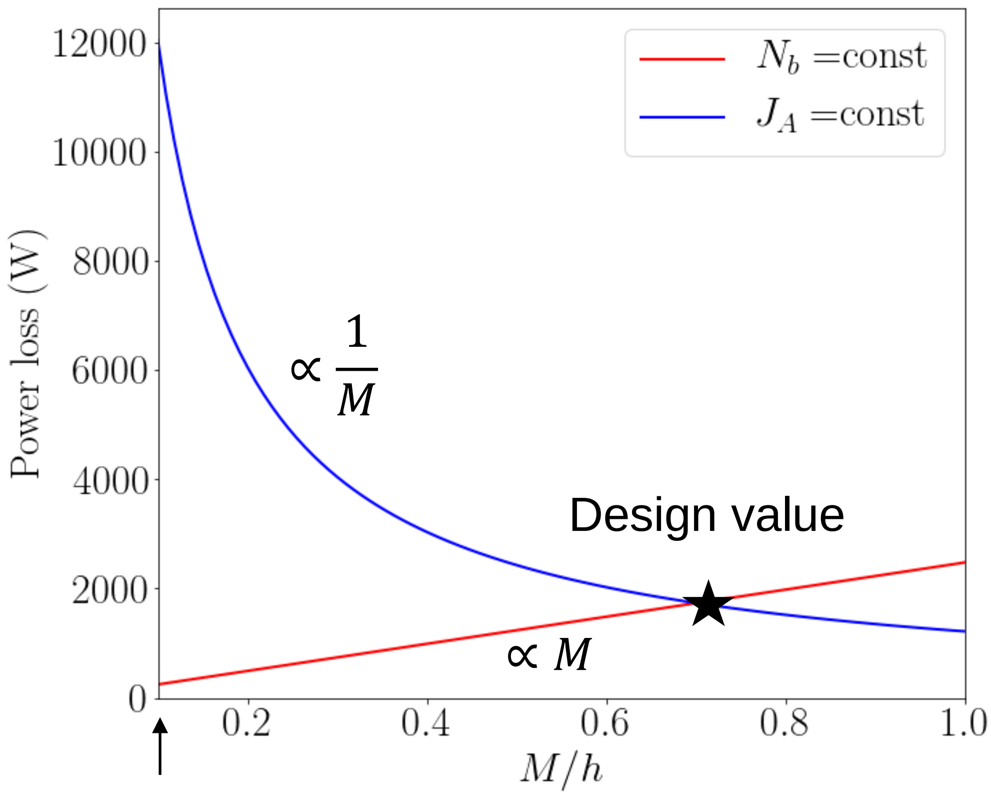
Comparison of impedances of steps and tapers



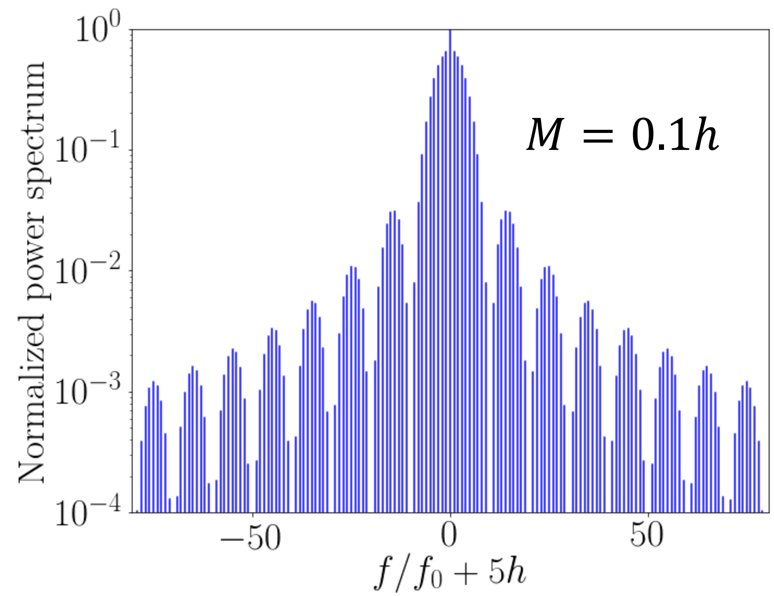
-> Reduction of loss factor due smaller impedance at frequencies below 20 GHz

Role of gap

Example for Z1 option (2.5 ns bunch spacing) and single-cell cavity



Minimum value is 0.1



- Scaling corresponds to the case of broadband impedance
- Only for very small *M* one can expect that resonances can hit revolution harmonics