HOM damping requirements for high-current option of FCCee

Ivan Karpov, Rama Calaga, Elena Shaposhnikova

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FCC-ee collider parameters

Parameters:

f_{rf} = 400 MHz, h = 130680, C = 97.75 km

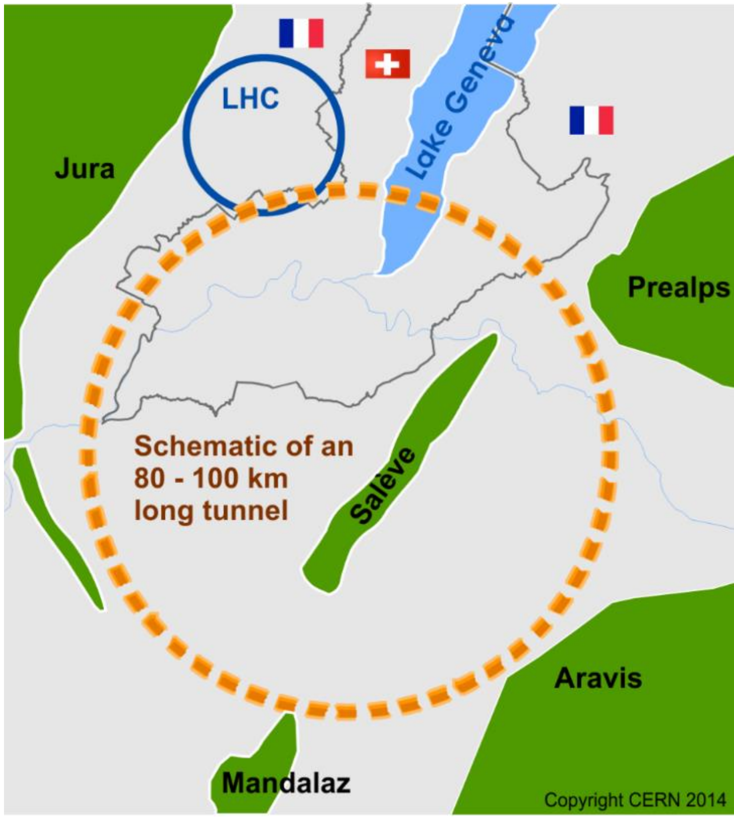
- 4 energies defined by experimental program

Machine	Z	W	Z	$t\bar{t}$
Energy (GeV)	45.6	80	120	182.5

- 50 MW power loss per beam due to synchrotron radiation
- Low-energy Z machine

  → highest current (≈ 1.4 A)

  → most challenging for high-order mode (HOM) power extraction (max power 1 kW per HOM coupler)



HOM power loss calculations

Normalized Fourier harmonics of beam current

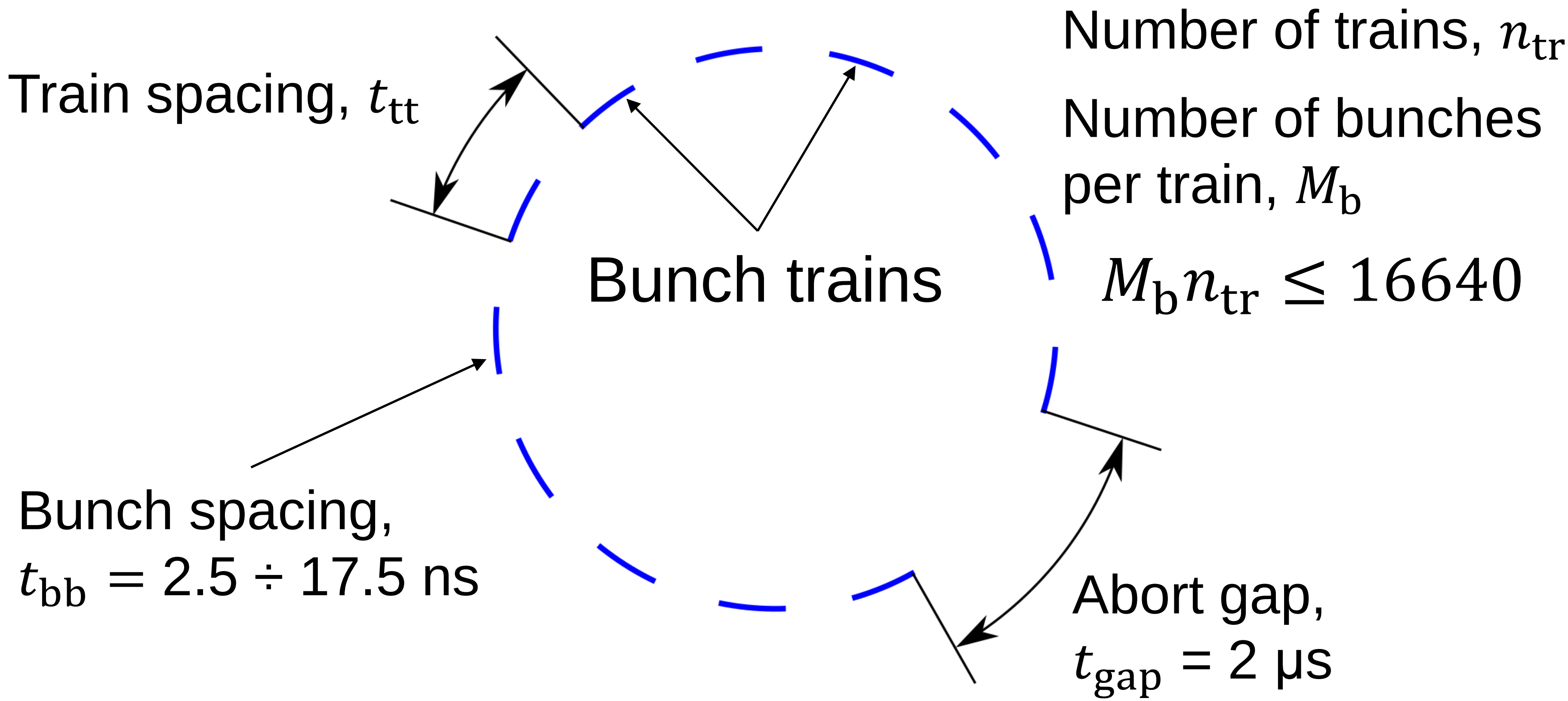
Longitudinal rf cavity impedance

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

J_A – average beam current
f_0 – revolution frequency
k – revolution harmonic number

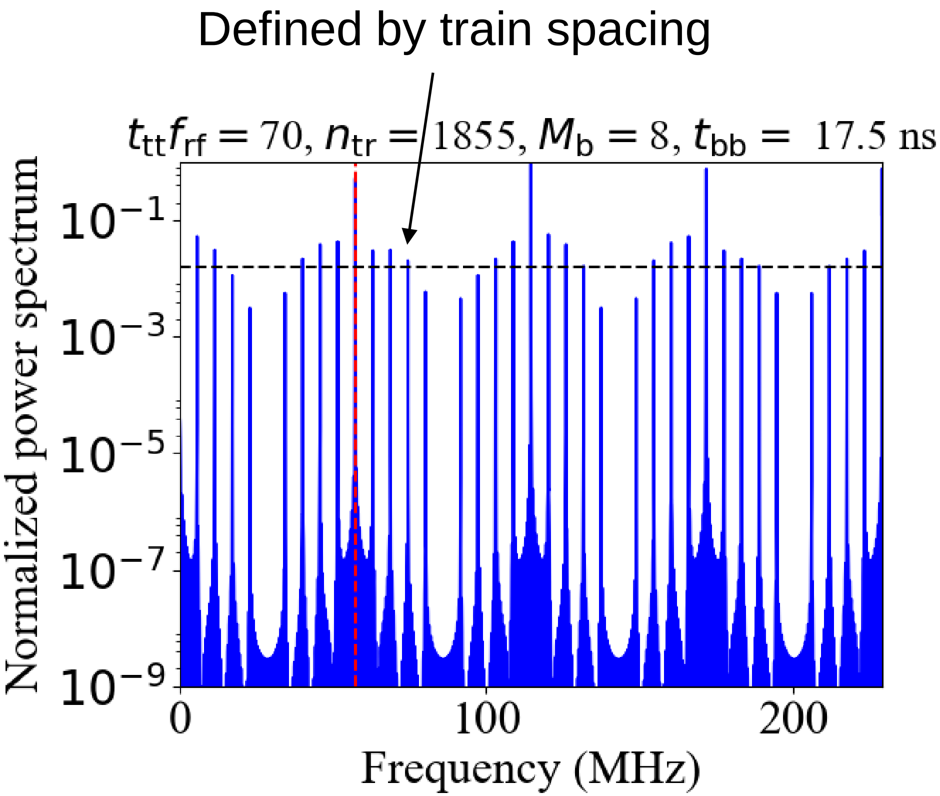
Estimations of the power loss are required to determine parameters for HOM absorbers.

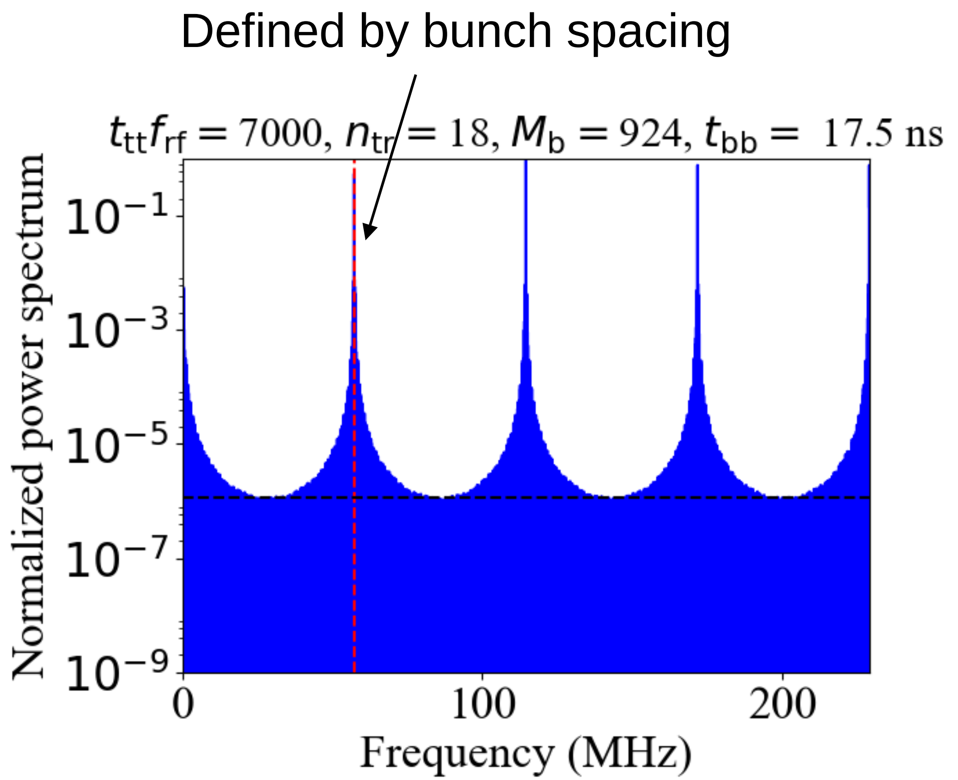
Beam spectrum for different filling schemes



Spectrum is dominated by:
$1/t_{bb}$ lines (always present)
+ $1/t_{tt}$ lines (depending on number of trains)

Beam spectrum for different filling schemes

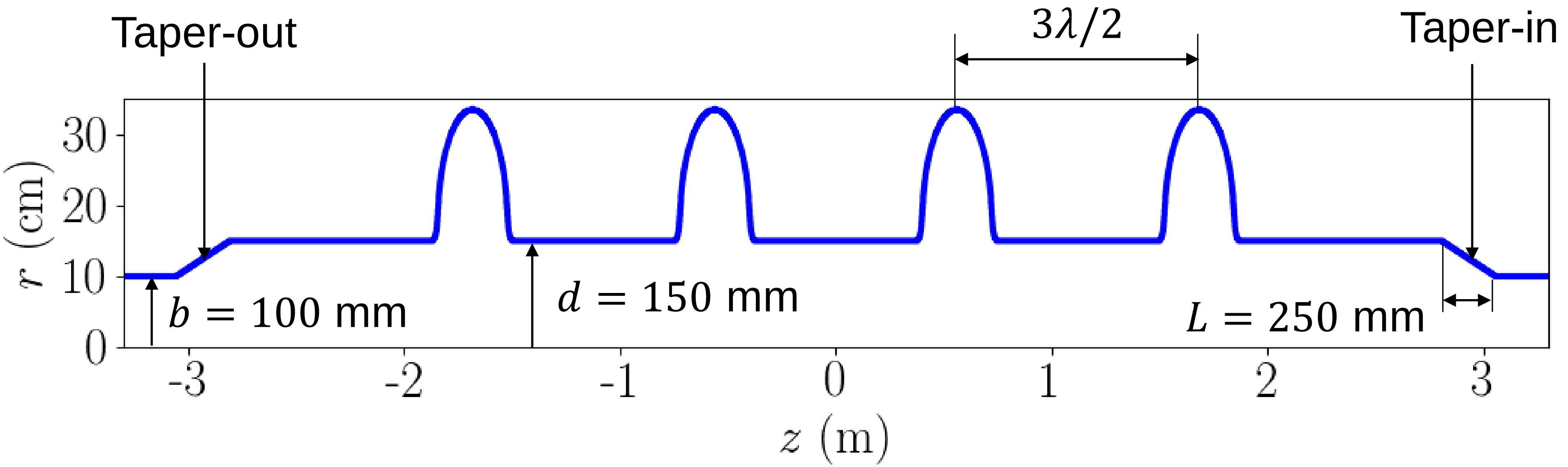




Spectrum is dominated by:
$1/t_{bb}$ lines (always present)
+ $1/t_{tt}$ lines (depending on number of trains)

rf system for FCC-ee Z machine

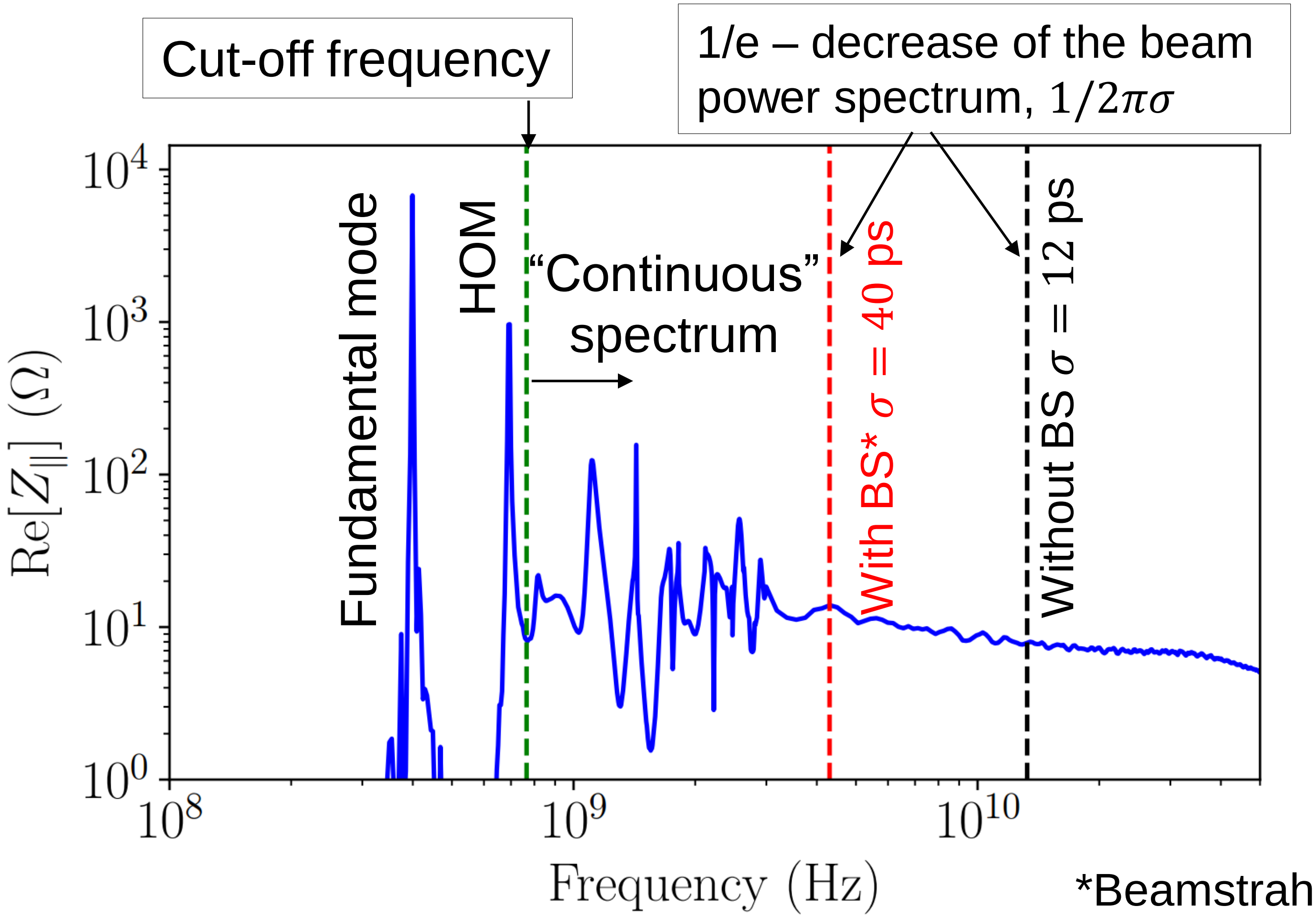
13 cryomodules with four 400 MHz single-cell LHC-like cavities



Impedance calculation using ABCI

Axisymmetric structure + Gaussian bunch → Wake potential → Impedance

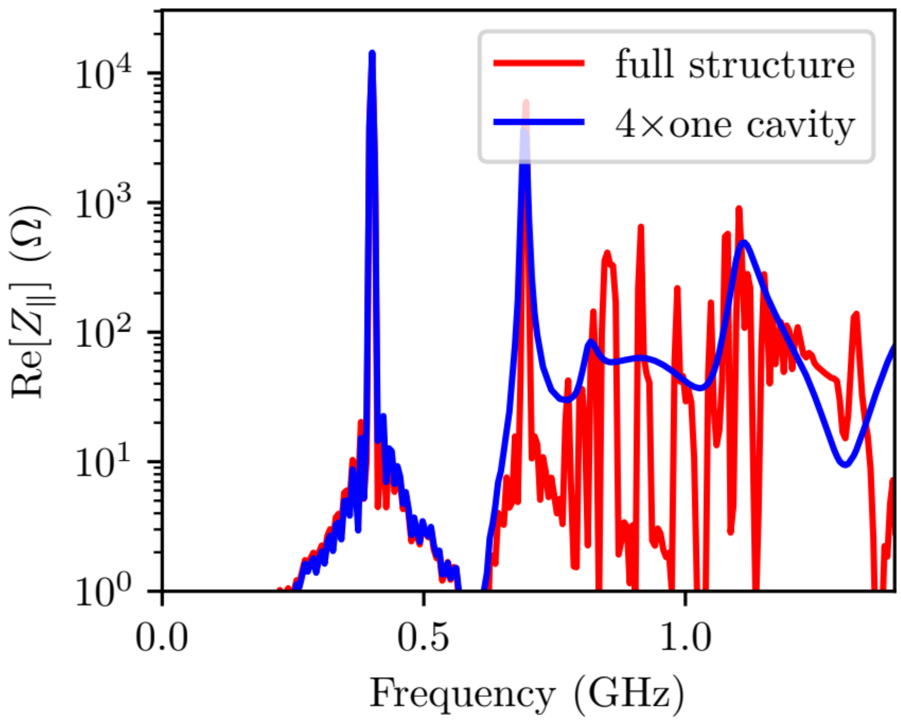
Single-cell cavity impedance

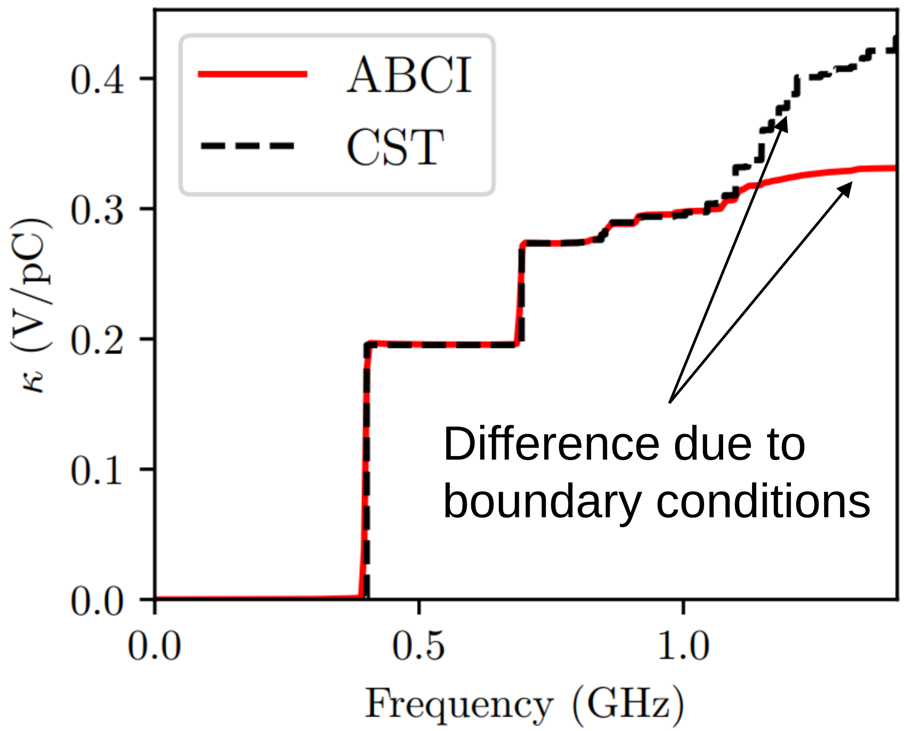


*Beamstrahlung

→ Only one mode below cut-off frequency with parameters:
$f_\mathrm{r} \approx 694$ MHz, $R/Q \approx 12\ \Omega$ (CST EMS simulations), quality factor Q = ?

Impedance of full structure





Four single-cell cavities displaced by 3λ/2
+ 25 cm long tapers from 15 cm to 10 cm

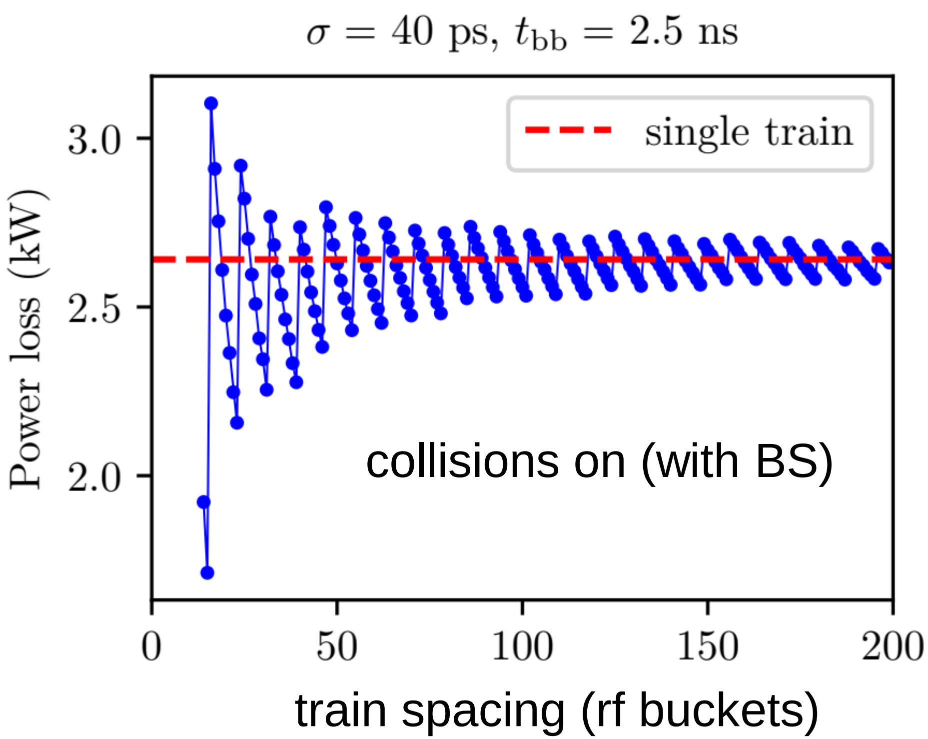
For CST $\kappa = \sum_n \pi f_n (R/Q)_n \mathrm{e}^{-(2\pi f_n \sigma)^2}$

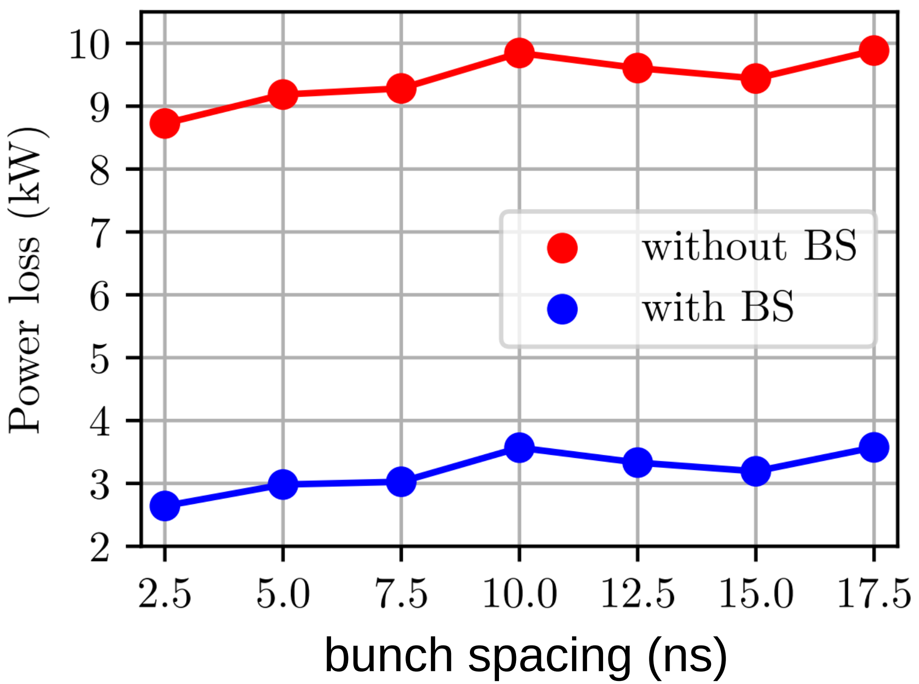
→ There are four modes with high (R/Q) below cut-off frequency of the beam pipe between cavities.

→ Higher frequency HOMs have small (R/Q) values

Power loss above cut-off frequency

Constant parameters: total current ≤ 1.4 A, abort gap 2 μs, bunch population 1.7e11
Variable parameters: number of bunches in the train, number of trains, train spacing

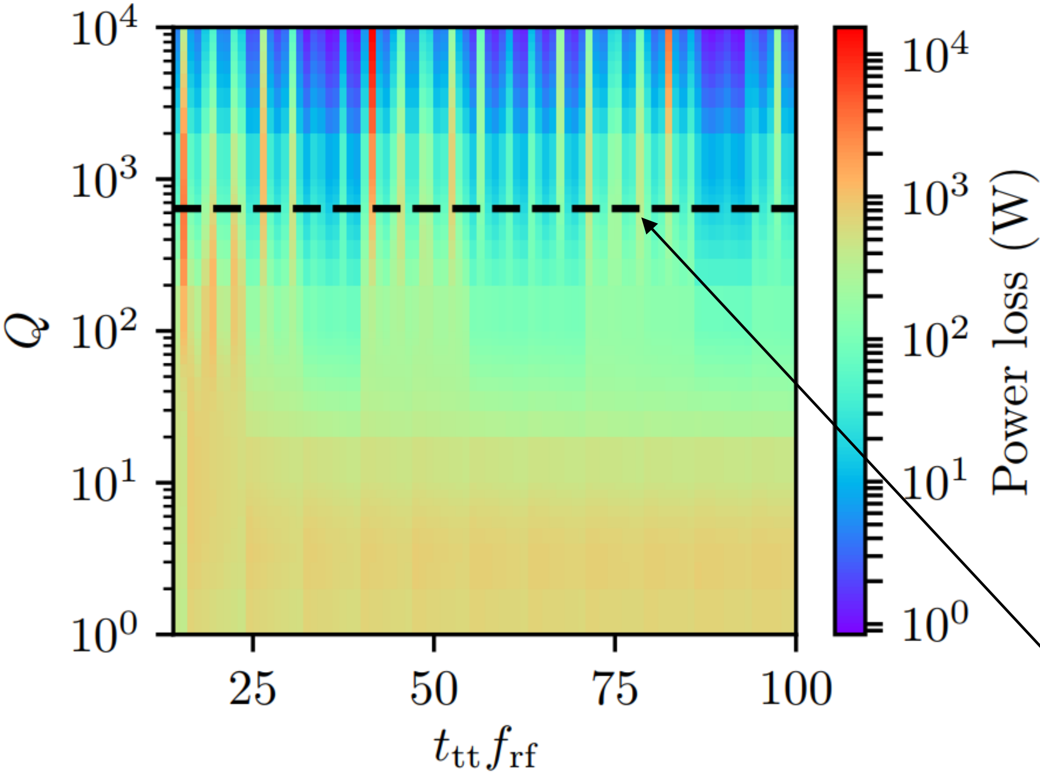




Power loss is moderate for the present cavity design for bunches in collisions
There is a weak dependence on train spacing and bunch spacing

Power loss for HOM below cut-off frequency

$f_r \approx 694$ MHz, $R/Q \approx 12\ \Omega$



Longitudinal coupled-bunch instability growth rate

$$\frac{1}{\tau} = \frac{e|\eta|J_A}{2EQ_s} f_r R$$

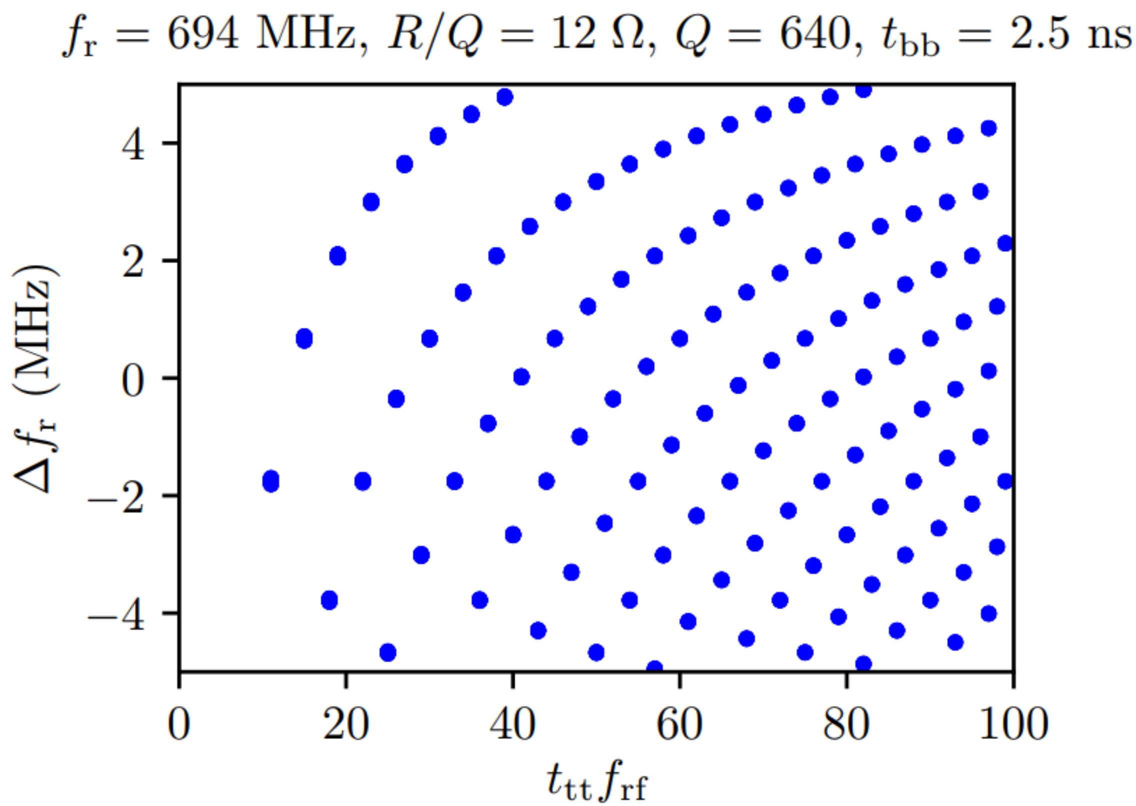
If $\tau > \tau_{SR} \rightarrow$ stability

τ – growth time
τ_{SR} – radiation damping time
η – slip factor
E – beam energy
Q_s – synchrotron tune

Stability threshold for 2 MV/cavity accelerating gradient

Power losses of few 100 W are for small Q + "resonant" cases with high Q
→ Damping of the mode for longitudinal stability should be moderate
→ Resonant cases should be identified

Shift of the resonant frequency



Rounded off value

Resonant case when beam spectral line overlaps with HOM* $\left|1 - \frac{[f_r t_{tt}]}{f_r t_{tt}}\right| < \frac{1}{Q}$

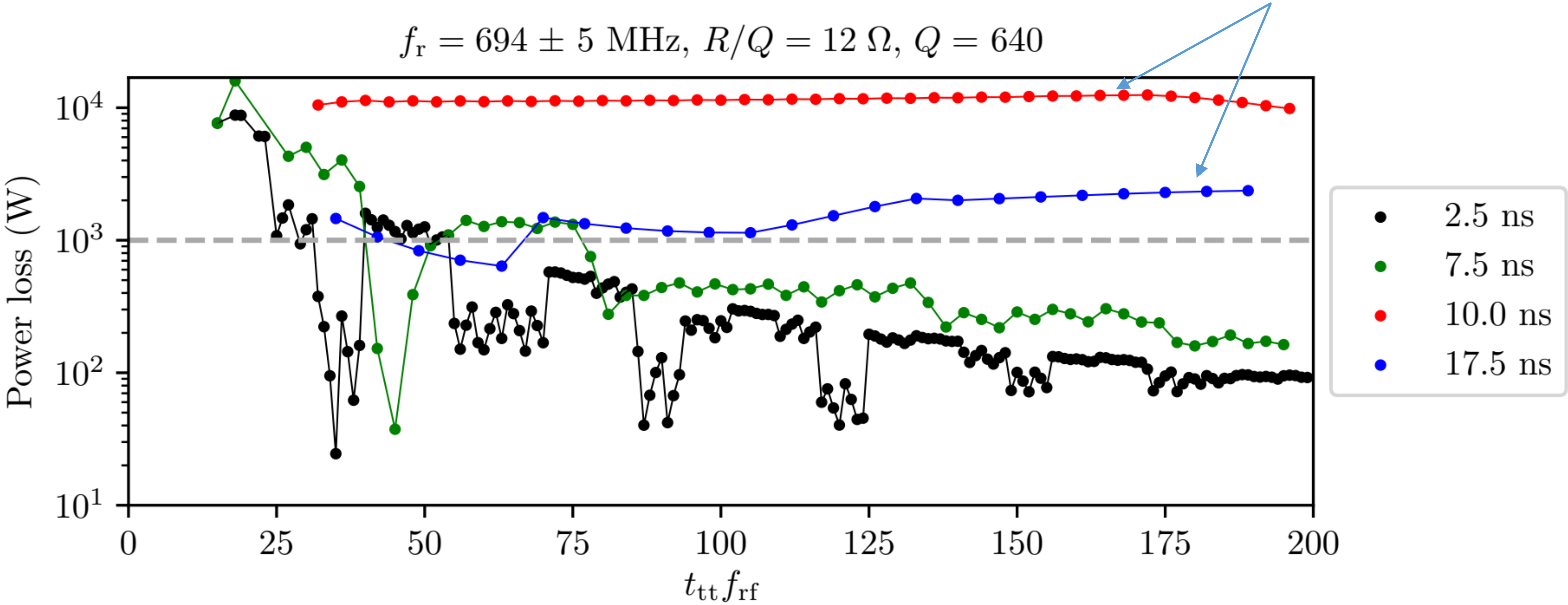
→ There are many resonant cases

→ Not all of them are dangerous

*I.Karpov et al., Phys. Rev. Accel. Beams 21, 071001 (2018)

Power losses for different filling schemes

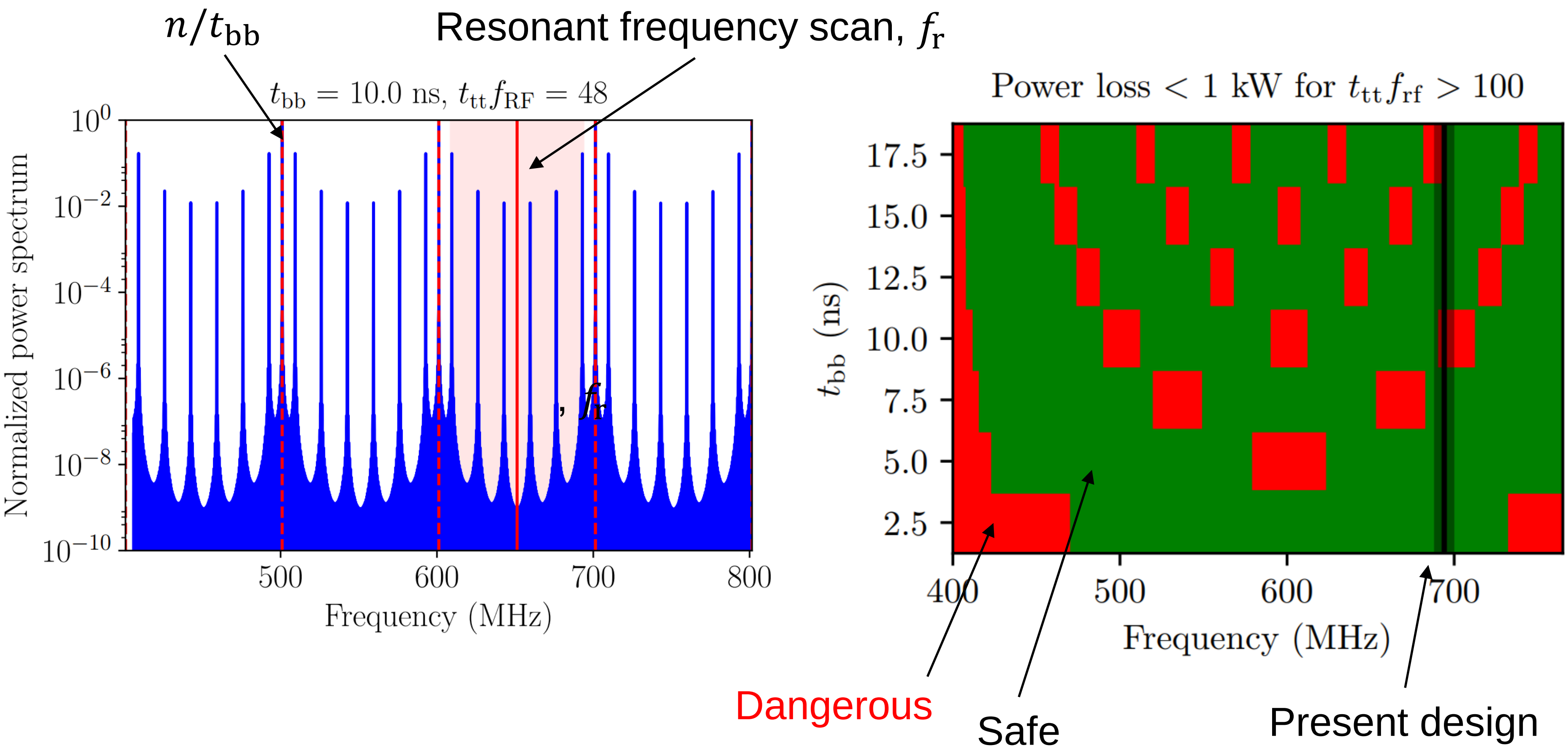
Overlap with spectral lines defined by bunch spacing



→ Some train spacings should be avoided in operation

→ Strong power losses for 10 ns and 17.5 ns bunch spacings

More “general” case



→ Operation settings define recommendations for the cavity design (position of HOMs)

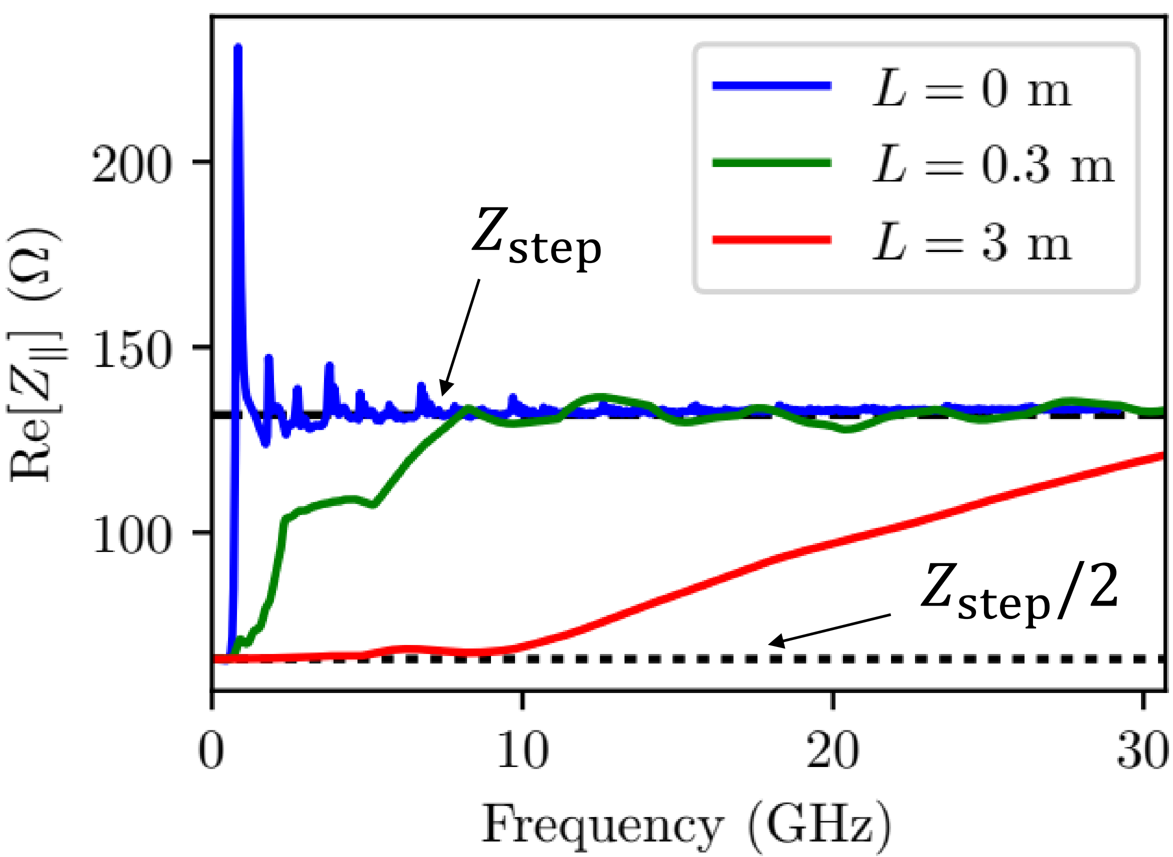
Summary

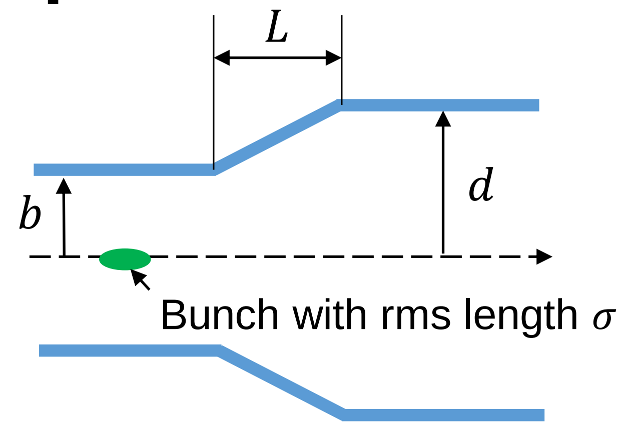
- Power losses in FCCee single-cell rf cavities were evaluated
- Contribution from continuous impedance spectrum is around 3 kW for bunches in collisions.
- Below cutoff frequency there is one HOM with high R/Q (it can split into 4 modes for the full structure) which can significantly contribute to power losses
- Critical filling schemes were identified and should be avoided in operation for the given cavity design:
    - 10 ns and 17.5 ns bunch spacings are not feasible
    - Other bunch spacings can be used with particular filling schemes (distance between trains > 100 rf buckets)
- HOM frequency ranges for new cavity designs which are “safe” for given bunch spacings were identified

Thank you for your attention!

Contribution of tapers

$b = 5$ cm, $d = 15$ cm



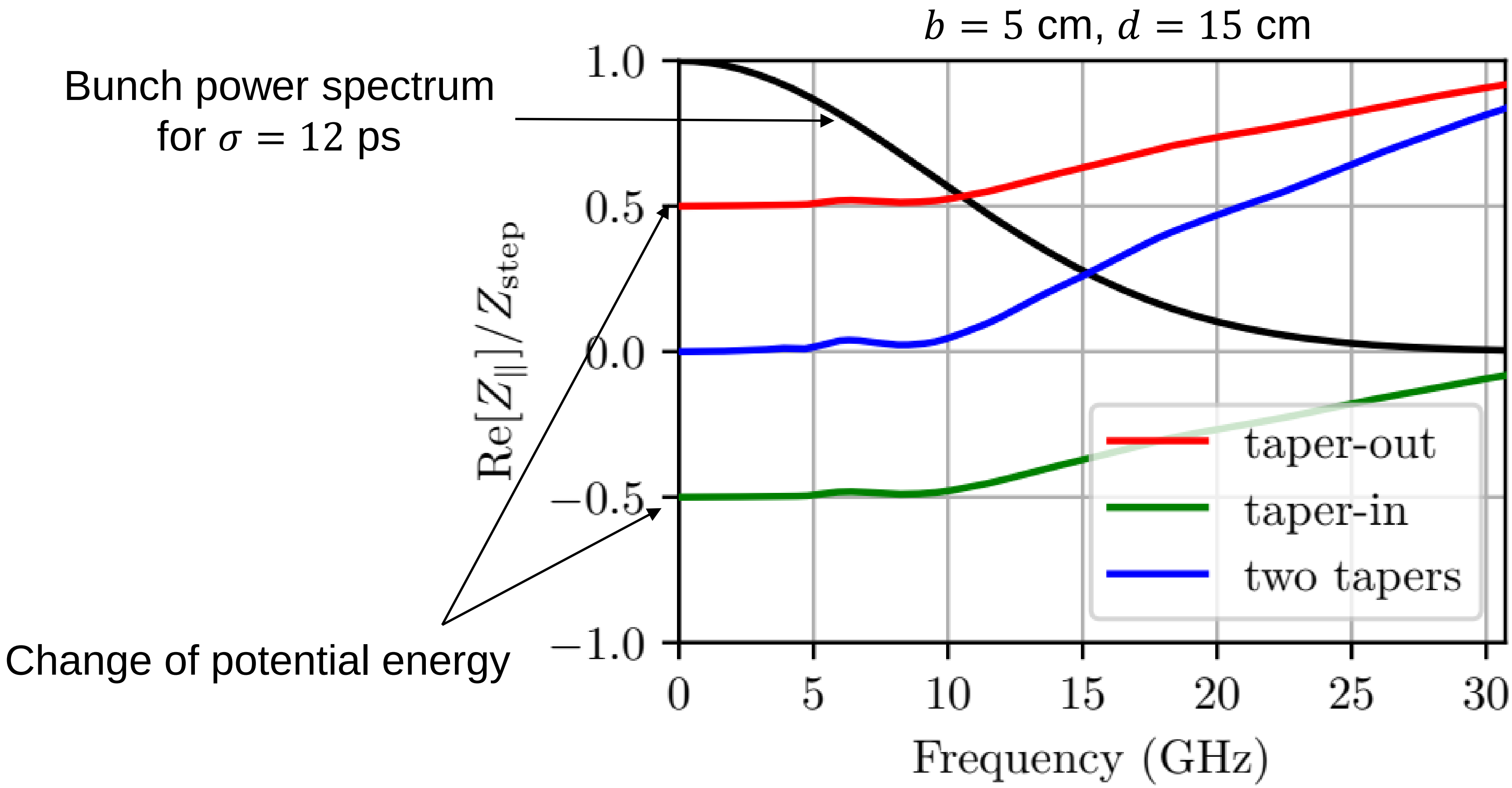


For $c\sigma \ll b < d$, impedance of step-out transition at high frequencies

$$Z_{\text{step}} = \frac{Z_0}{\pi} \ln \frac{d}{b}$$

Frequency range of transition from $Z_{\text{step}}/2$ to Z_{step} is defined by taper geometry

Optimal taper length*



If distance between tapers >> $d^2/c\sigma$, contributions of taper-in and taper-out are compensated for $L > L_{\text{opt}} = (d-b)^2/c\sigma$

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