Beam-cavity interaction challenges for FCC-ee cavities

Ivan Karpov, CERN

Acknowledgments: P. Baudrenghien, O. Brunner, A. Butterworth,
R. Calaga, J. F. Esteban Müller, R. Rimmer, E. Shaposhnikova, D. Teytelman

Overview of challenges in FCC-ee Z machine

Parameter	Value
Beam current, $I_{\mathrm{b,DC}}$	1.39 A
Number of bunches, M	16640
Minimum abort gap, τ_{gap}	2 µs
RF frequency, f_{RF}	400.79 MHz
R/Q of fundamental mode	42.3 Ω
Cavity voltage, V_{cav}	1.91 MV
Number of cavities, N_{cav}	52
Harmonic number, h	130680
Radiation damping time, τ_{SR}	414 ms

→ Power losses due to high order modes (HOM)

→ Transient beam loading

→ Longitudinal coupled-bunch instability

HOM power loss calculations

Simulated cavity impedance

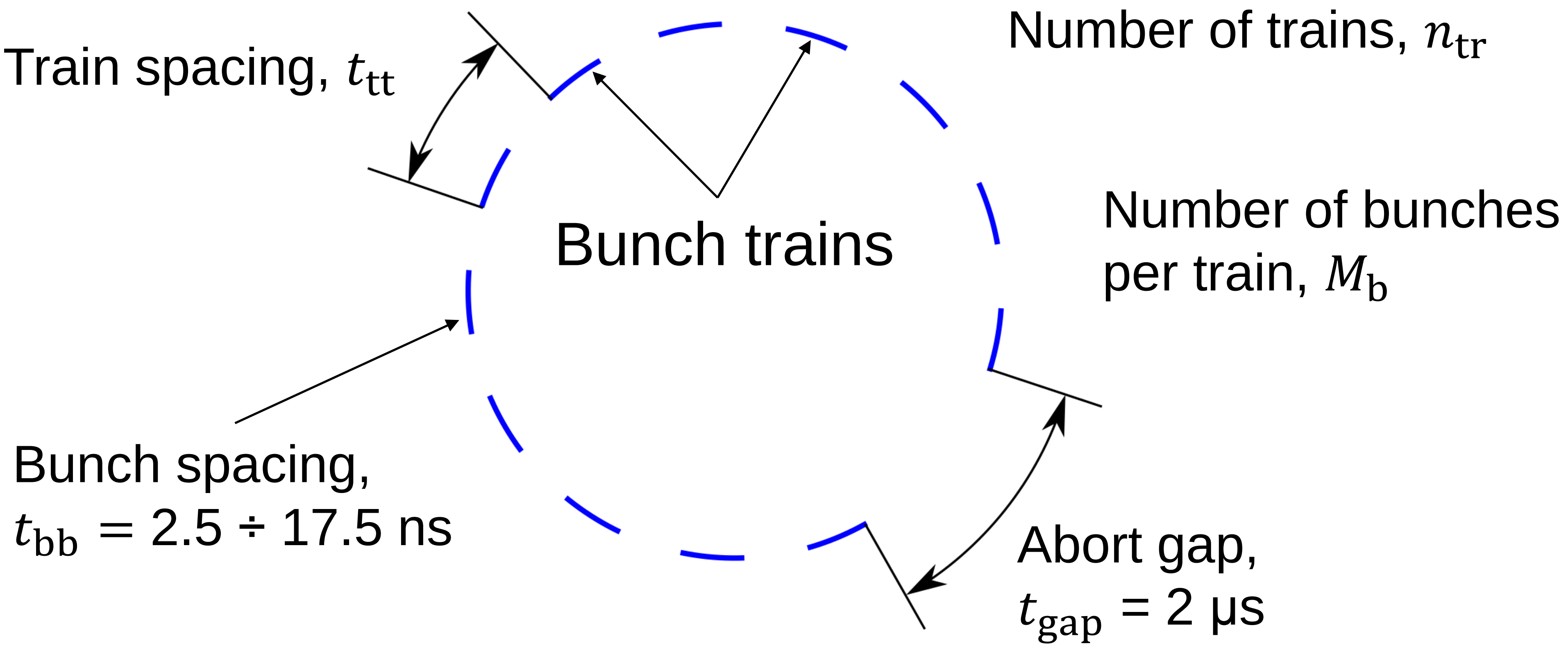
Normalized Fourier harmonics of beam current

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

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

Estimations of the power loss are required to determine parameters for HOM absorbers (max 1 kW per coupler).

Beam spectrum for different filling schemes



Train spacing, t_{tt}

Number of trains, n_{tr}

Bunch trains

Number of bunches per train, M_{b}

Bunch spacing, $t_{\mathrm{bb}} = 2.5 \div 17.5$ ns

Abort gap, $t_{\mathrm{gap}} = 2$ μs

Spectrum is dominated by:

$1/t_{\mathrm{bb}}$ lines (always present)

$1/t_{\mathrm{tt}}$ lines (depending on number of trains)

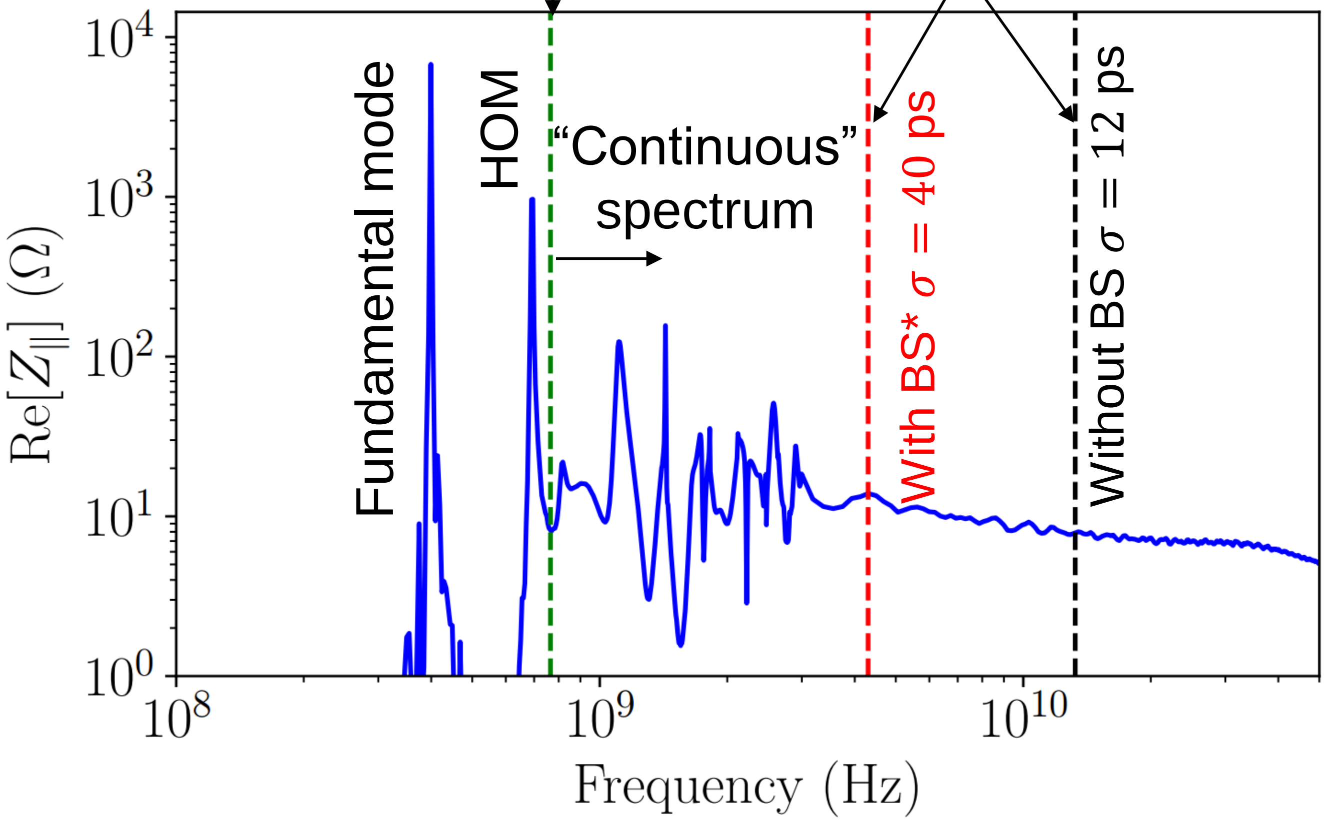
Impedance of LHC-like single-cell cavity

Impedance calculation using ABCI

Axisymmetric structure
+
Gaussian bunch
↓
Wake potential
↓
Impedance

Cut-off frequency

1/e – decrease of the beam power spectrum, $1/2\pi\sigma$

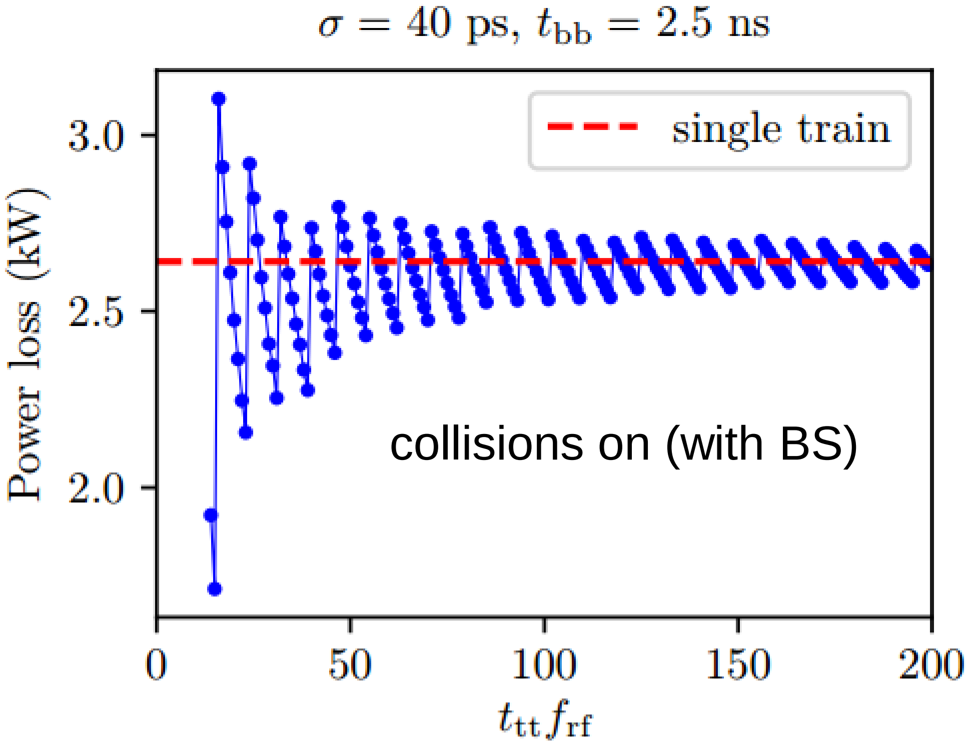


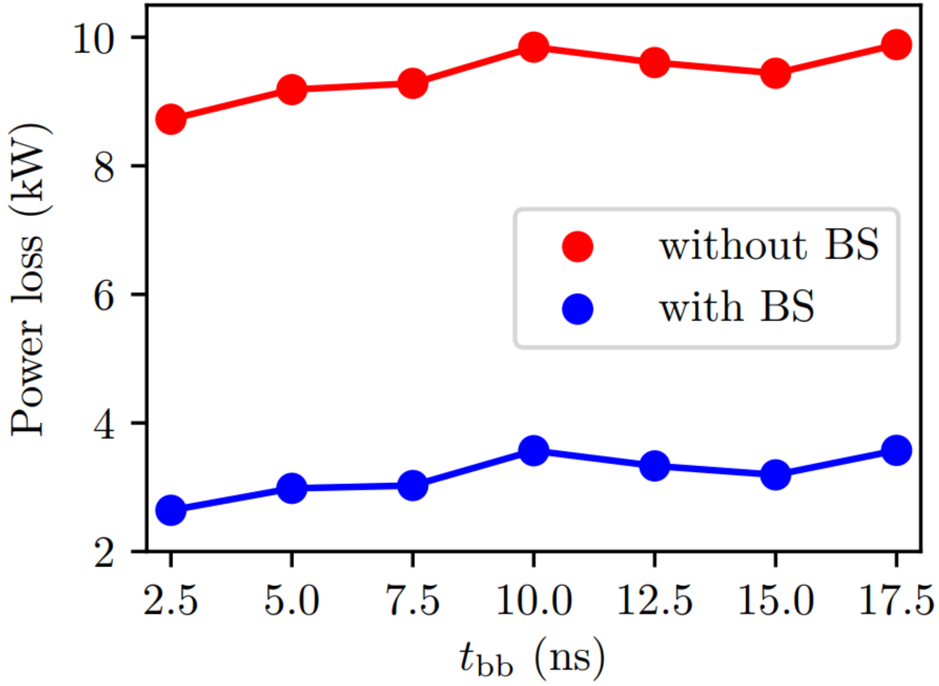
*Beamstrahlung effect

→ 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 = ?

Power loss above cut-off frequency

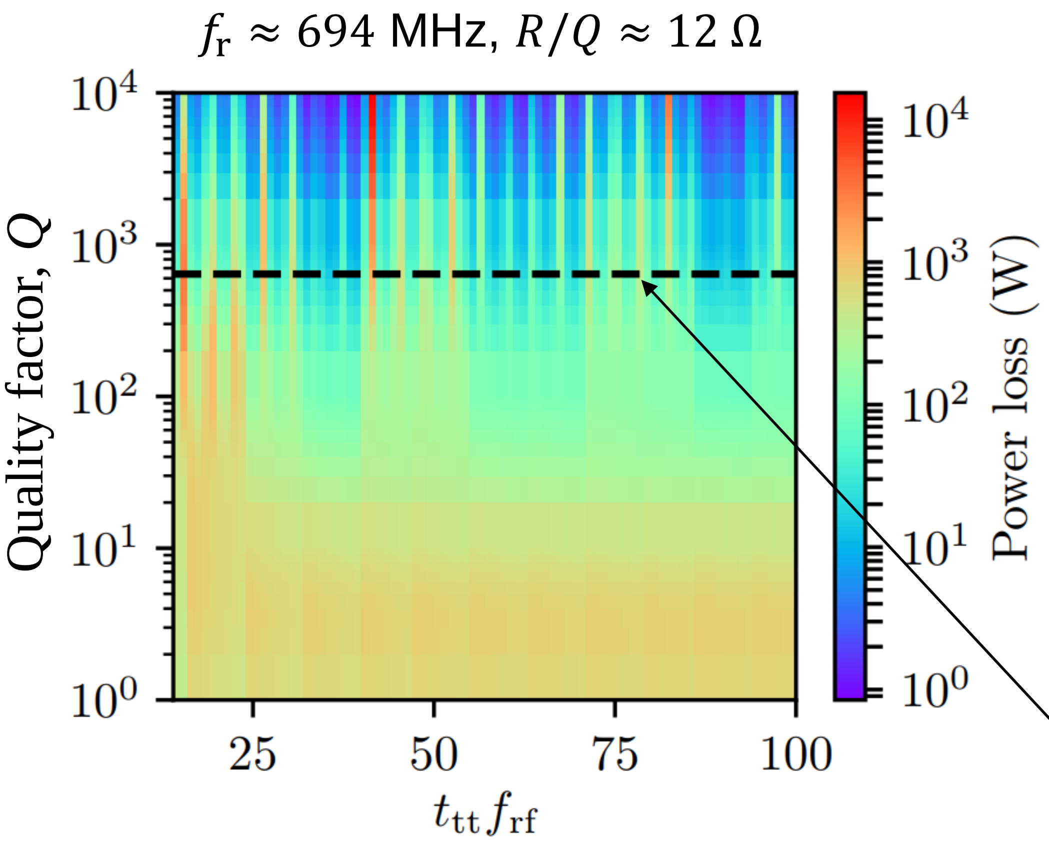
Constant parameters: total current ≤ 1.4 A, abort gap 2 μs, bunch population 1.7e11
Variable parameters: number of bunches in the train, number of trains, train spacing





→ Power loss is moderate for the present cavity design for bunches in collisions (≈ 3 kW)
→ There is a weak dependence on train spacing and bunch spacing

Power loss for HOM below cut-off frequency



Stability threshold

Longitudinal coupled-bunch instability growth rate due to HOM

$$\frac{1}{\tau} = \frac{e|\eta| I_{\mathrm{b,DC}}}{2 E Q_s} f_\mathrm{r} R$$

If $\tau > \tau_\mathrm{SR}$ → stability

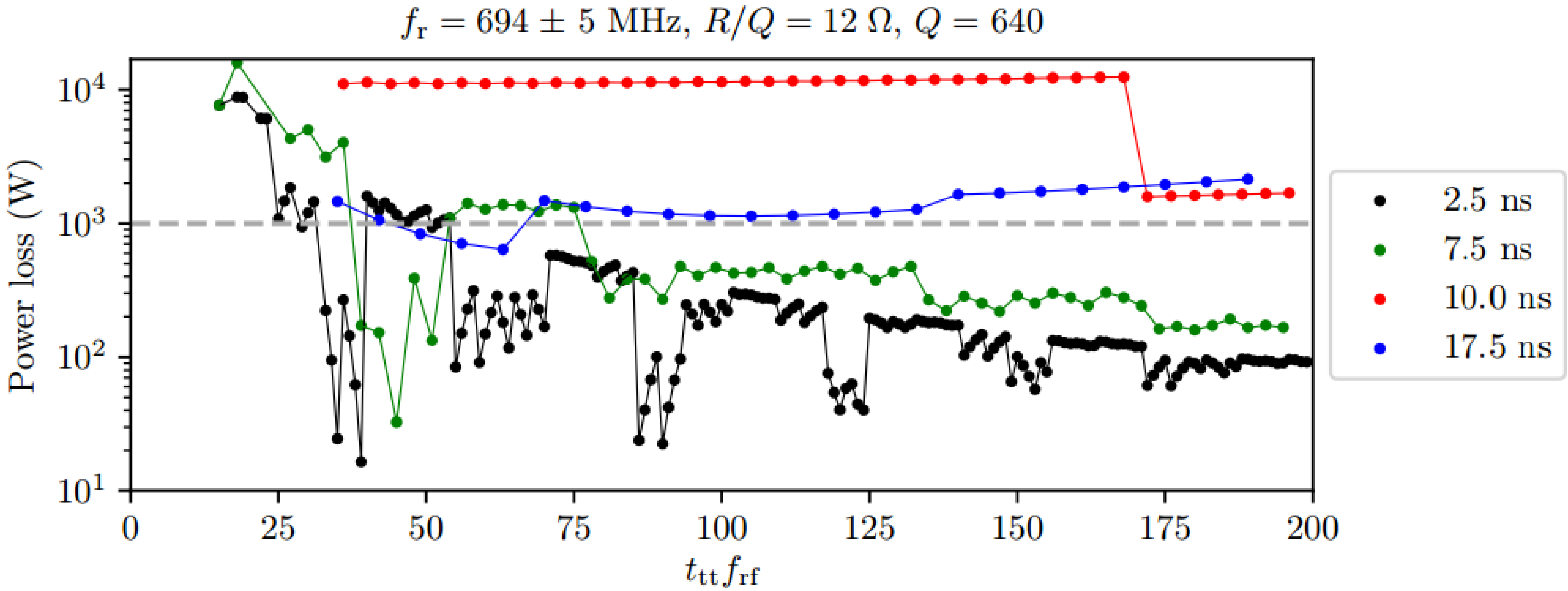
τ – growth time
τ_SR – radiation damping time
η – slip factor
E – beam energy
Q_s – synchrotron tune

Power losses of about 1 kW are for small Q + “resonant” cases with high Q
→ Damping of the mode for longitudinal stability should be moderate
→ Resonant cases should be identified

Power losses for different filling schemes

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

Rounded off value



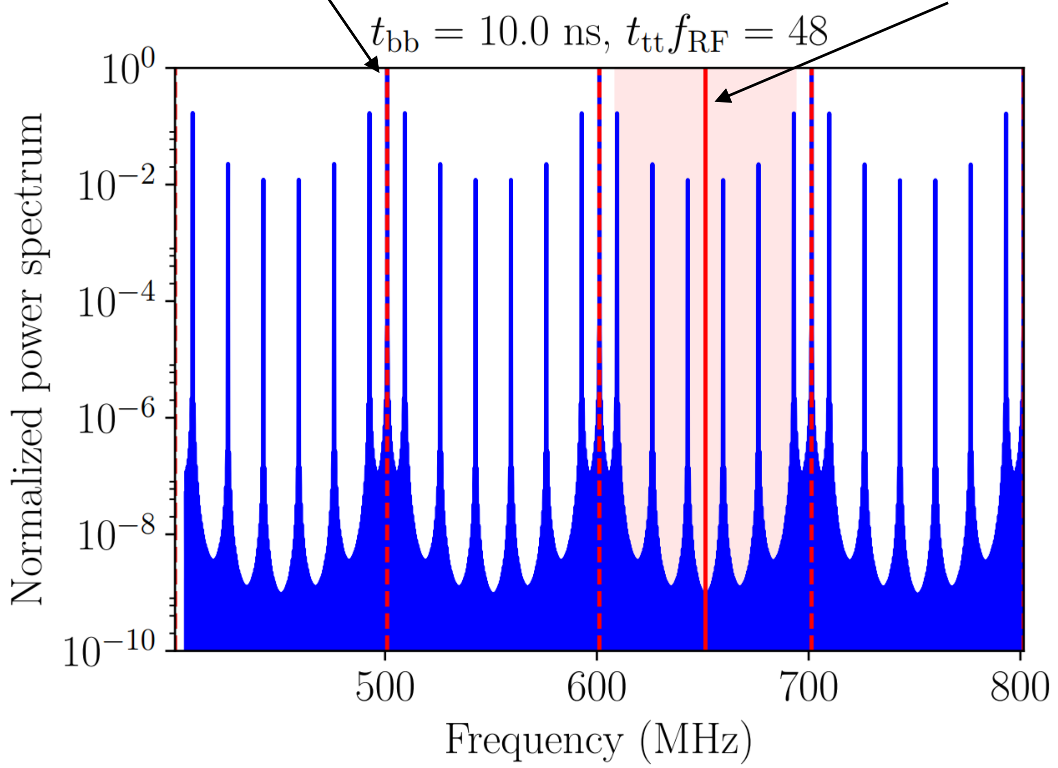
→ Some filling schemes should be avoided in machine operation (restrictions for train and bunch spacings)

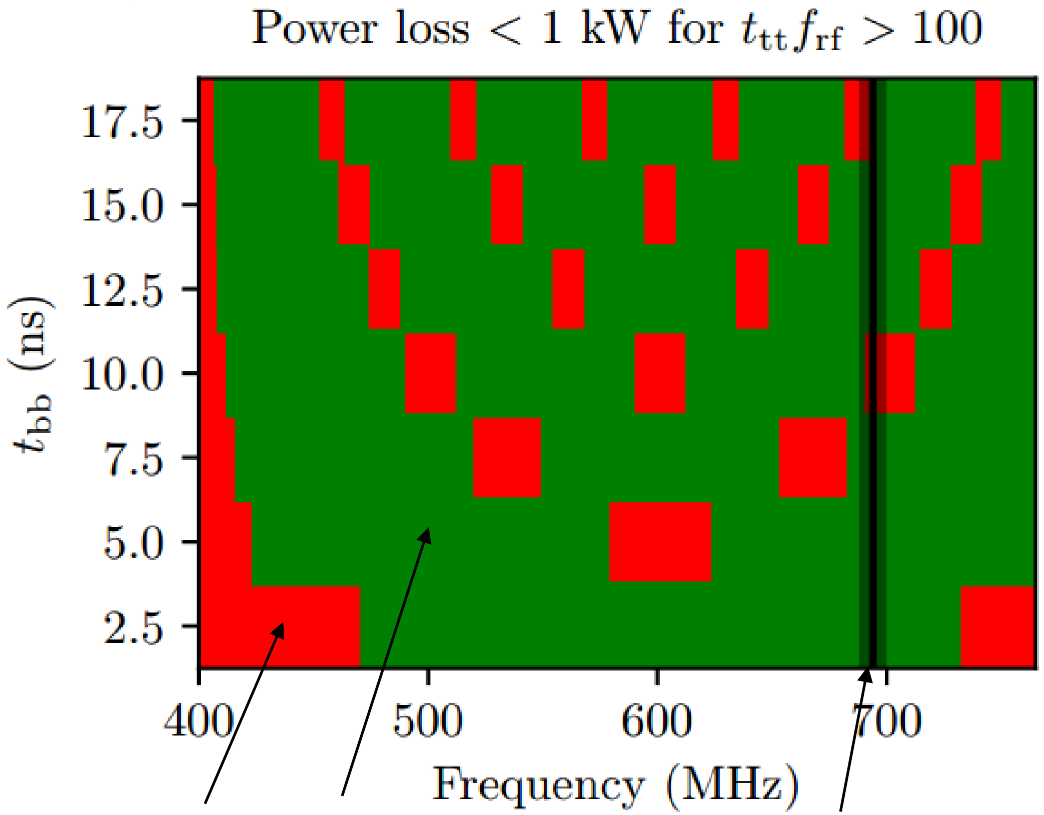
*I.Karpov et al., CERN-ACC-NOTE-2018-0005 (2018)

More “general” case

n/t_{bb}

Resonant frequency scan, f_{r}



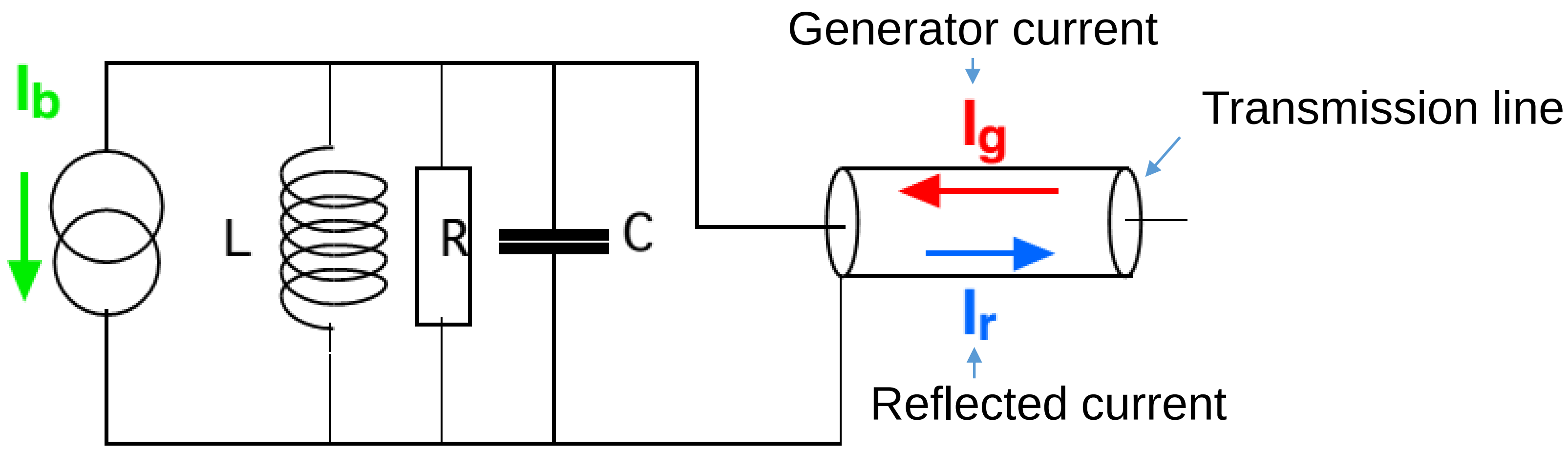


Dangerous **Safe** Present design

→ Operation settings define recommendations for the cavity geometry

Transient beam loading

Lumped circuit model for superconducting RF cavity*



$$I_g(t) = \frac{V(t)}{2R/Q}\left(\frac{1}{Q_0} + \frac{1}{Q_{\text{ext}}} - \frac{2i\Delta\omega}{\omega_{\text{RF}}}\right) + \frac{dV(t)}{dt}\frac{1}{\omega_{\text{RF}}R/Q} + \frac{I_{\text{b,RF}}(t)}{2}$$

For FCC-ee Z machine

Optimum detuning $$\Delta\omega_{\text{opt}} = \omega_0 - \omega_{\text{RF}} = -\omega_{\text{RF}}\frac{\langle I_{\text{b,RF}}\rangle R/Q\,\sin(\phi_s)}{2V_{\text{cav}}}$$ (11.4 kHz)

Optimum loaded quality factor $$Q_{L,\text{opt}} = \left(\frac{1}{Q_0} + \frac{1}{Q_{ext}}\right)^{-1} \approx \frac{V_{\text{cav}}}{\langle I_{\text{b,RF}}\rangle R/Q\,\cos(\phi_s)}$$ (44000)

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*For example in J. Tückmantel, CERN-ATS-Note-2011-002, 2011

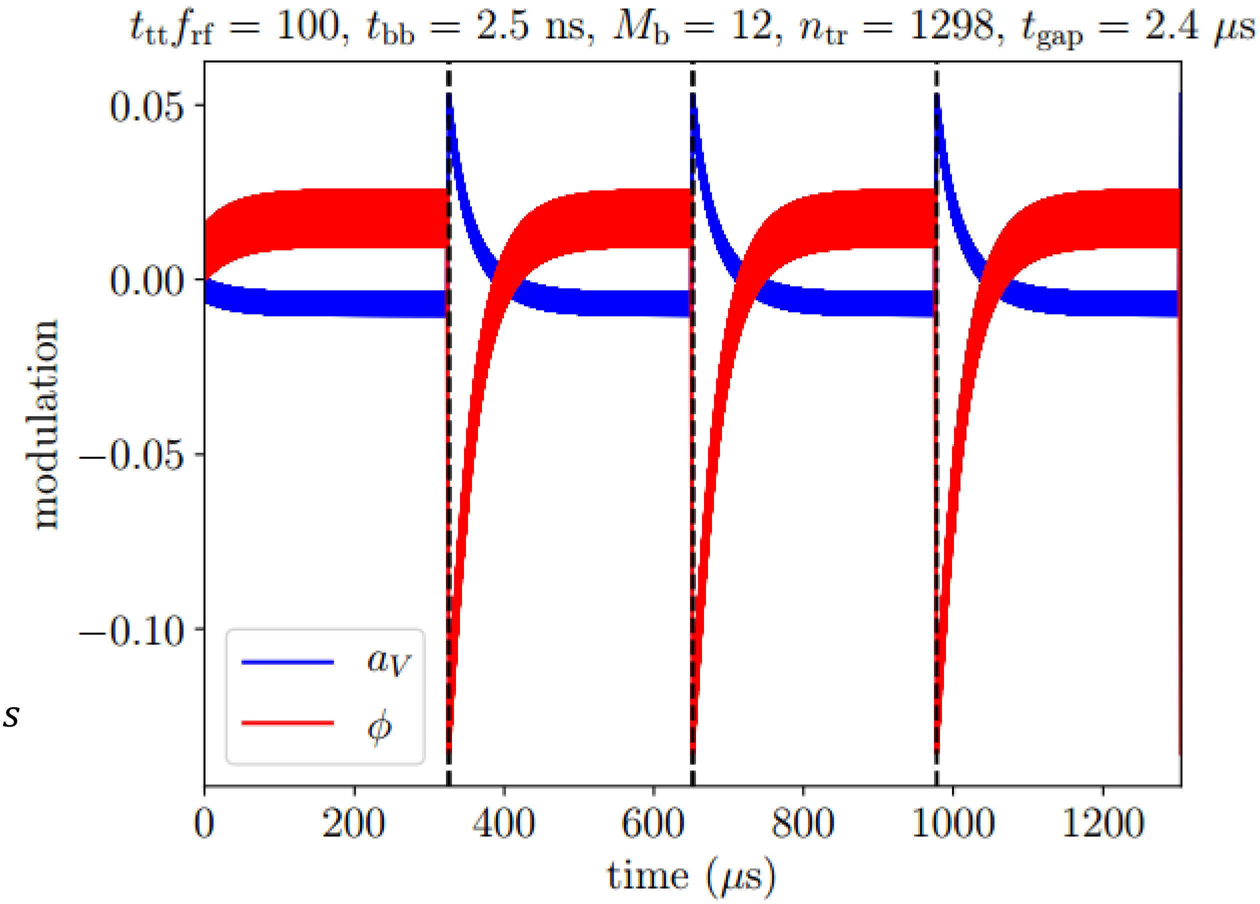
Numerical calculations of transients

Assuming optimum detuning and

$$I_{\mathrm{b,RF}}(t) = 2I_{\mathrm{b,DC}}[1 + a_{\mathrm{b}}(t)]e^{i[\phi(t)-\phi_s]}$$

$$V(t) = V_{\mathrm{cav}}[1 + a_V(t)]e^{i\phi(t)}$$

a_b – beam current modulation



We get:

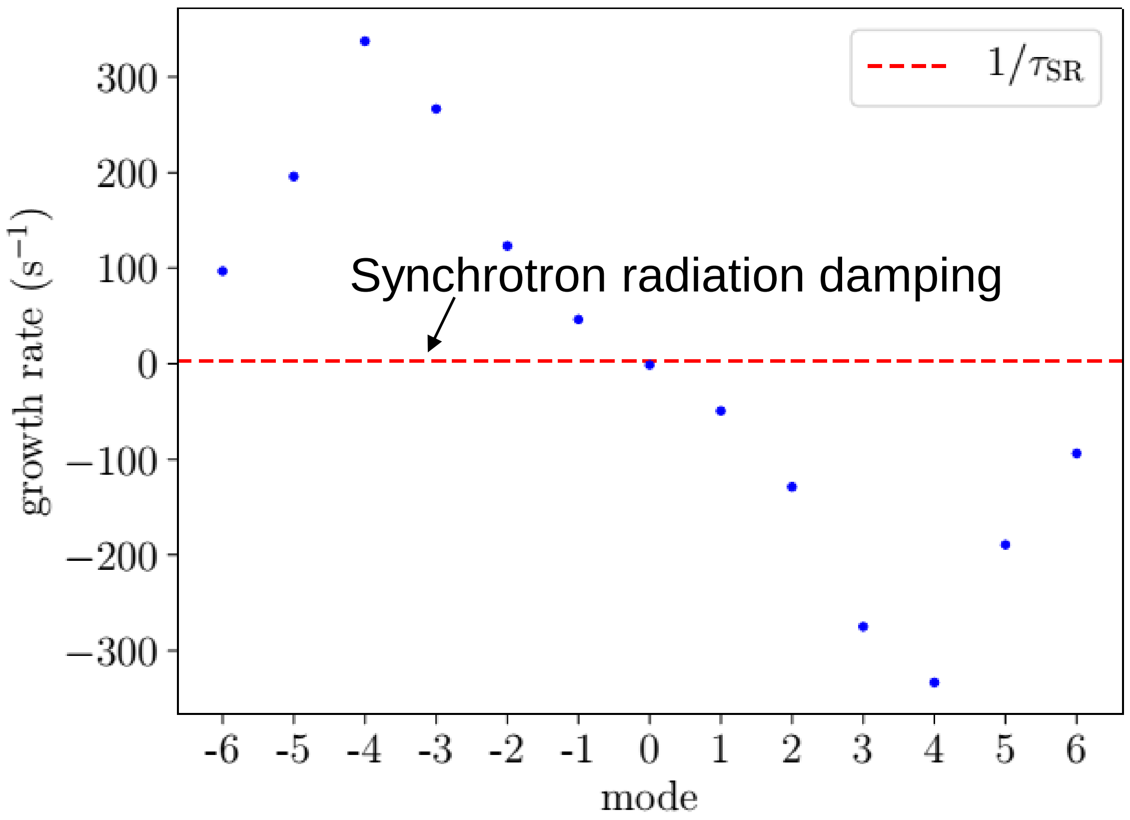
$a_V(t)$ – amplitude modulation → spread of σ and Q_s
$\phi(t)$ – phase modulation → collision point shift

Modulation is dominated by abort gap
→ For $t_{\mathrm{gap}} > 2$ μs, peak-to-peak $a_V >$ 6%, and peak-to-peak ϕ > 60 ps
→ Collision point shift can be eliminated, if gap transients are matched (PEP-II, LHC)

Longitudinal coupled-bunch instability driven by the fundamental impedance

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

$$\frac{1}{\tau_m} \approx \frac{e\eta\omega_{\mathrm{RF}}}{4\pi E Q_s} I_{\mathrm{b,DC}} N_{cav} \left(\mathrm{Re}\{Z_\parallel[\omega_{\mathrm{RF}} + (m+Q_s)\omega_{\mathrm{rev}}]\} - \mathrm{Re}\{Z_\parallel[\omega_{\mathrm{RF}} - (m+Q_s)\omega_{\mathrm{rev}}]\}\right)$$



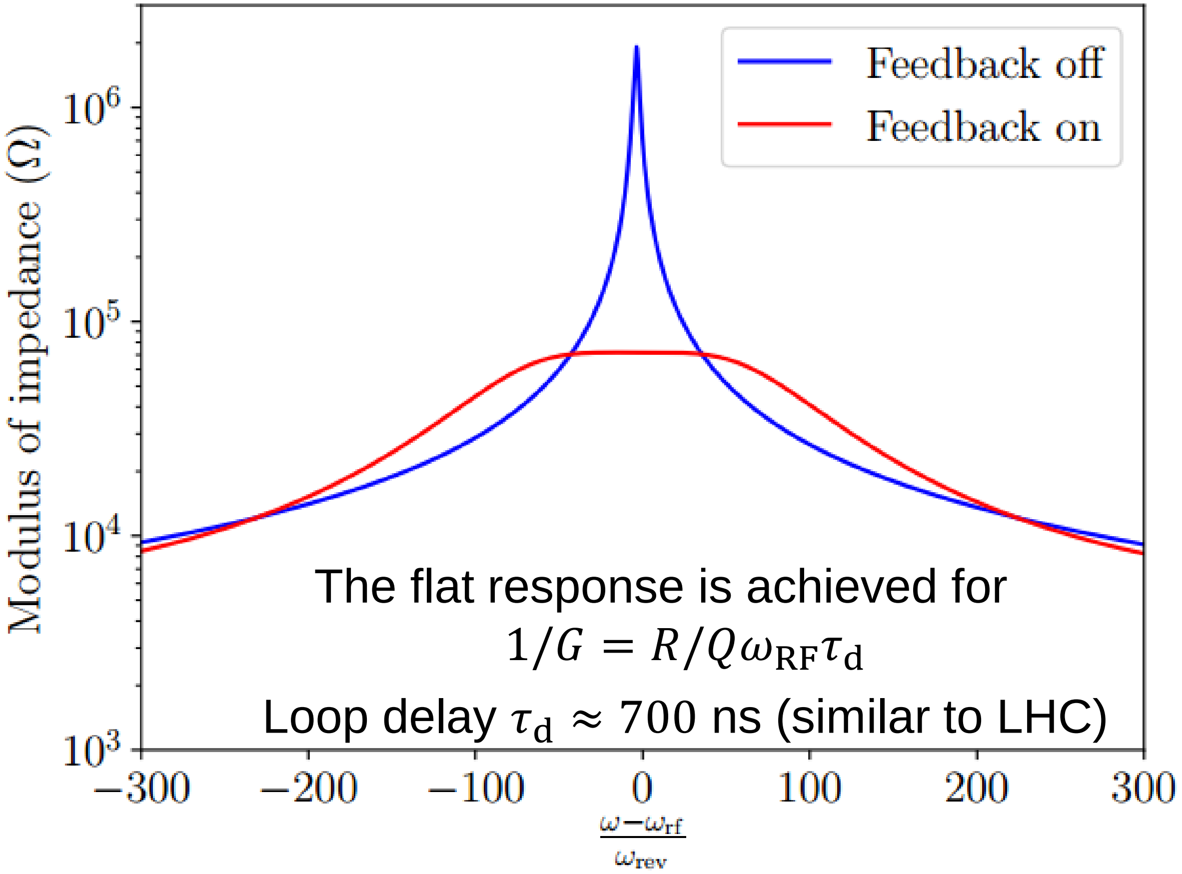
Fundamental cavity impedance

$$Z_\parallel(\omega) = \frac{R/Q Q_L}{1 + iQ_L\left[\frac{\omega_{\mathrm{RF}}}{\omega_0} - \frac{\omega_0}{\omega_{\mathrm{RF}}}\right]}$$

→ For optimum detuning (about $4 \times f_{\mathrm{rev}}$) the most unstable mode is $m =$ -4

*For example in A. Chao, Physics of Collective Beam Instabilities in High Energy Accelerators, 1993

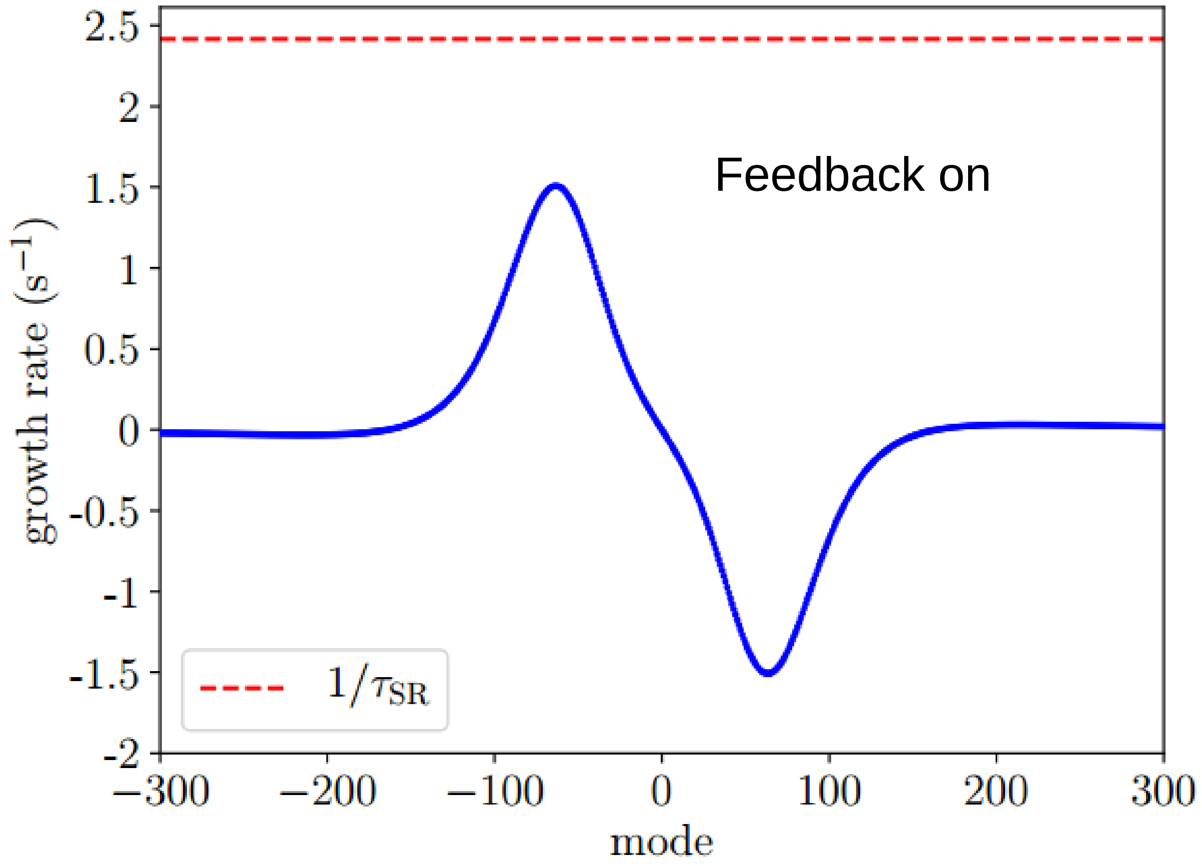
Mitigation by direct RF feedback*



The flat response is achieved for

$$1/G = R/Q\,\omega_{\rm RF}\tau_{\rm d}$$

Loop delay $\tau_{\rm d} \approx 700$ ns (similar to LHC)



→ growth rates of all unstable modes are smaller than synchrotron radiation damping rate

→ To increase stability margins one-turn delay feedback (similar to SPS, LHC) or more sophisticated double peaked comb filter (PEP II) can be used

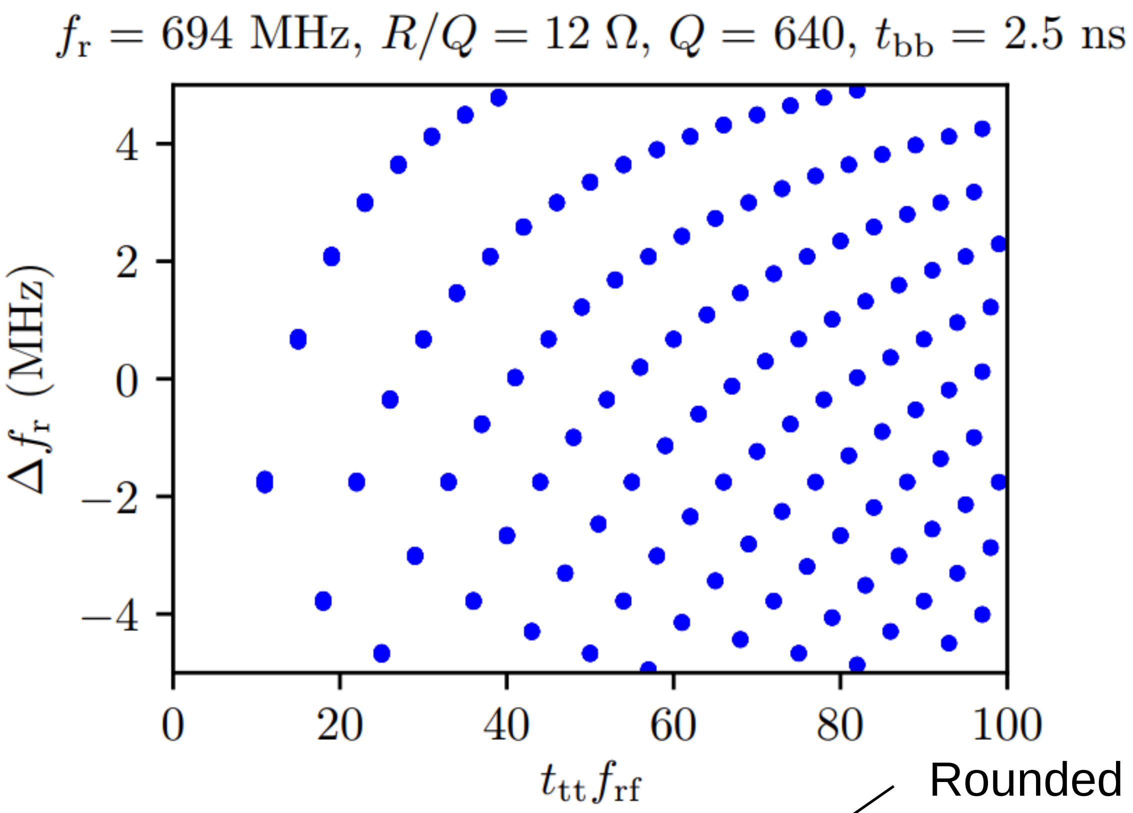
*D. Boussard, Control of Cavities with High Beam Loading, IEEE NS-32 (1985)

Conclusions

- HOM power loss contributions:
  - From impedance above cutoff frequency is about 3 kW,
  - From overlap of HOM below cutoff frequency with beam spectral line is below 1 kW for train spacing larger than 100 RF buckets, if 10 ns and 17.5 ns bunch spacing are excluded from operation.
- HOM frequency ranges for new cavity designs which are “safe” for given bunch spacings were identified.
- Transient beam loading is dominated by abort gap. For t_{gap}> 2 μs:
  - peak-to-peak cavity amplitude modulation > 6%,
  - peak-to-peak cavity phase modulation >60 ps, but collision point shift still can be eliminated by matching abort gap transients.
- Longitudinal coupled-bunch instability due to fundamental cavity impedance can be mitigated using direct RF feedback with loop delay of 700 ns.

Thank you for your attention!

Shift of the resonant frequency



Rounded off value

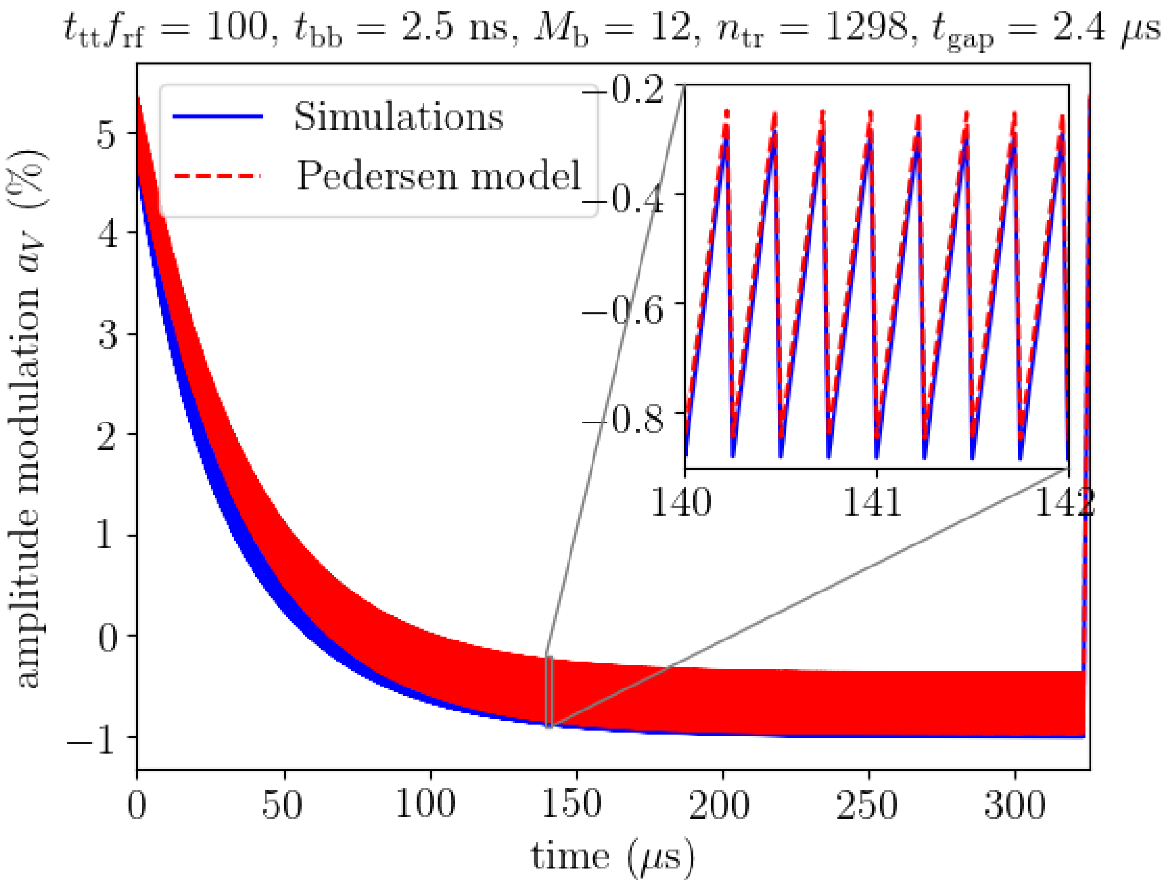
"Resonant" condition* $\left|1-\frac{[f_r t_{tt}]}{f_r t_{tt}}\right| < \frac{1}{Q}$

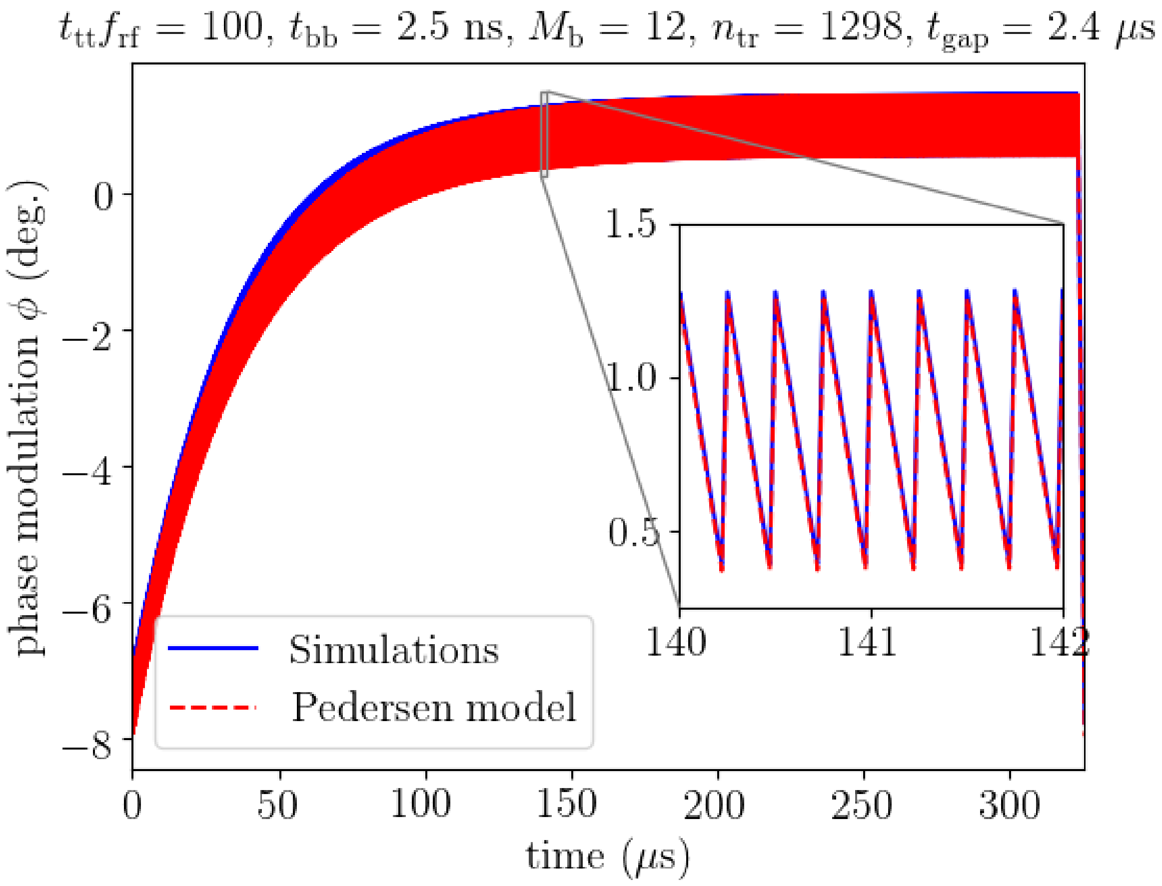
→ There are many cases when the spectrum line hits the resonant line

→ Not all of them are dangerous

*I.Karpov et al., CERN-ACC-NOTE-2018-0005 (2018)

Comparison with Pedersen model


$t_{\mathrm{tt}} f_{\mathrm{rf}} = 100$, $t_{\mathrm{bb}} = 2.5$ ns, $M_{\mathrm{b}} = 12$, $n_{\mathrm{tr}} = 1298$, $t_{\mathrm{gap}} = 2.4\ \mu$s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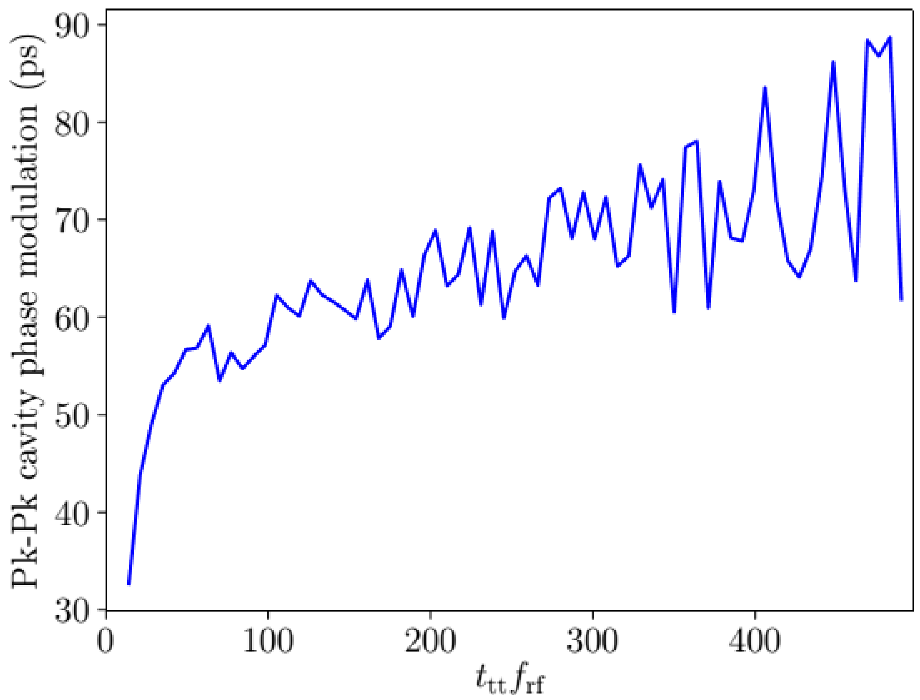

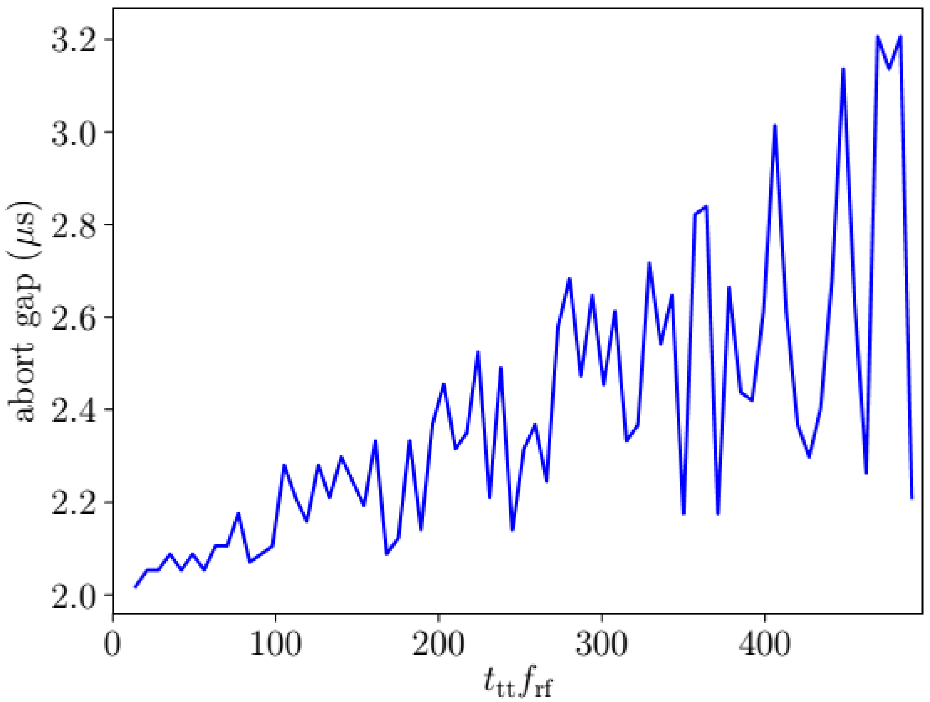

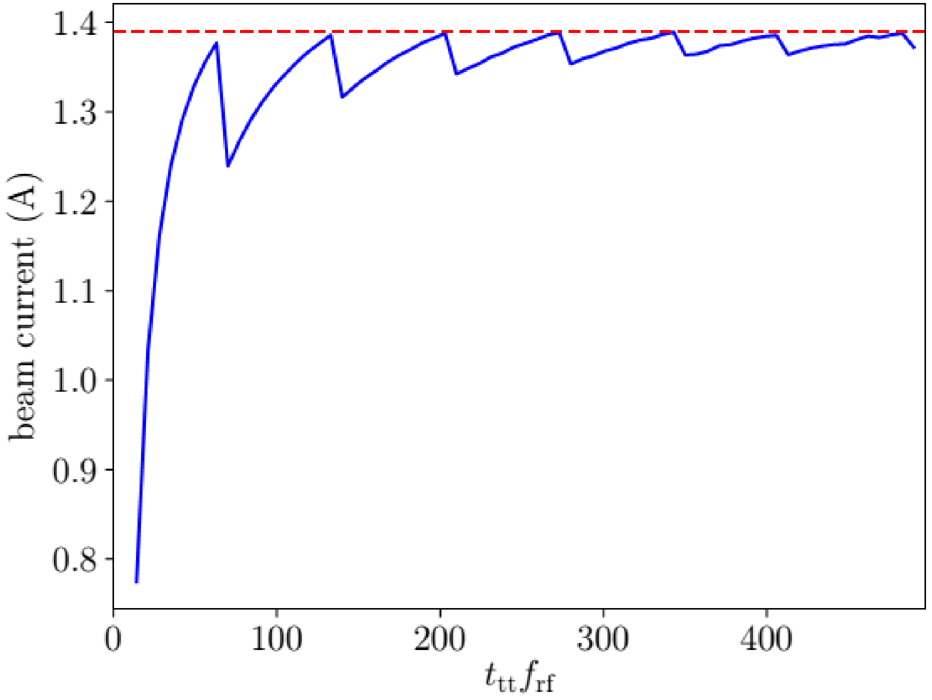

Dependence on the train spacing for bunch spacing of 17.5 ns

Beam current for different filling schemes