Beam-cavity interaction challenges for FCC-ee cavities

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Overview of challenges in FCC-ee Z machine

Parameter	Value	
Beam current, I _{b,DC}	1.39 A	
Number of bunches, M	16640	_
Minimum abort gap, $ au_{ m gap}$	2 µs	
RF frequency, $f_{\rm RF}$	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, $\tau_{\rm SR}$	414 ms	

→ Power losses due to high order modes (HOM)

 \rightarrow Transient beam loading

→ Longitudinal coupled-bunch instability

HOM power loss calculations



 $I_{b,DC}$ – 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



Spectrum is dominated by:

 $1/t_{bb}$ lines (always present) $1/t_{tt}$ lines (depending on number of trains)

Impedance of LHC-like single-cell cavity



*Beamstrahlung effect

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

Power loss above cut-off frequency

Constant parameters: total current \leq 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 (\approx 3 kW) → There is a weak dependence on train spacing and bunch spacing

Power loss for HOM below cut-off frequency



Power losses of about 1 kW are for small *Q* + "resonant" cases with high *Q*

- \rightarrow Damping of the mode for longitudinal stability should be moderate
- \rightarrow Resonant cases should be identified

Power losses for different filling schemes

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



 \rightarrow 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



 \rightarrow Operation settings define recommendations for the cavity geometry

Transient beam loading

Lumped circu superconduct

Lumped circuit model for
superconducting RF cavity*

$$I_{g}(t) = \frac{V(t)}{2R/Q} \left(\frac{1}{Q_{0}} + \frac{1}{Q_{ext}} - \frac{2i\Delta\omega}{\omega_{RF}}\right) + \frac{dV(t)}{dt} \frac{1}{\omega_{RF}R/Q} + \frac{I_{b,RF}(t)}{2}$$
For FCC-ee Z machine
Optimum detuning

$$\Delta\omega_{opt} = \omega_{0} - \omega_{RF} = -\omega_{RF} \frac{\langle I_{b,RF} \rangle R/Q \sin(\phi_{s})}{2V_{cav}}$$
(11.4 kHz)
Optimum loaded quality factor

$$Q_{L,opt} = \left(\frac{1}{Q_{0}} + \frac{1}{Q_{ext}}\right)^{-1} \approx \frac{V_{cav}}{\langle I_{b,RF} \rangle R/Q \cos(\phi_{s})}$$
(44000)

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

Numerical calculations of transients



 \rightarrow For $t_{\text{gap}} > 2 \,\mu\text{s}$, peak-to-peak $a_V > 6\%$, and peak-to-peak $\phi > 60 \,\mu\text{s}$

→ 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*

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



Fundamental cavity impedance

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

→ For optimum detuning (about $4 \times f_{rev}$) 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*



→ 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



 \rightarrow There are many cases when the spectrum line hits the resonant line \rightarrow Not all of them are dangerous

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

Comparison with Pedersen model





Beam current for different filling schemes

