Beam-cavity interactions for FCC-ee

Ivan Karpov, SY-RF-BR, CERN

Acknowledgements: Franck Peauger, Olivier Brunner,
Igor Syratchev, Rama Calaga, Shahnam Gorgi Zadeh,
Elena Shaposhnikova, Philippe Baudrenghien

138th FCC-ee Optics Design Meeting & 9th FCCIS WP2.2 Meeting, 07.05.2021

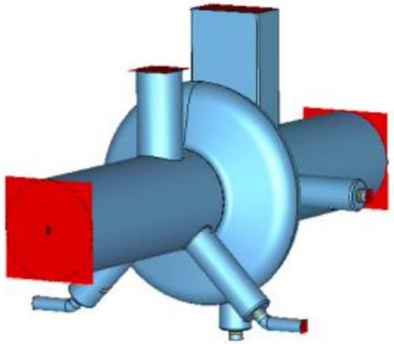
Interaction of beam with cavity impedance

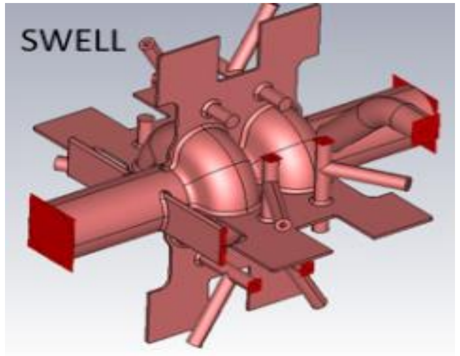
Main effects that need to be considered:

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

Most challenging FCC-ee operating at Z pole due to large beam current (1.4 A) and large number of bunches (16400).

In this talk 1-cell UROS$_1$ (modified LHC cavity) and 2-cell SWELL cavity types are discussed





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

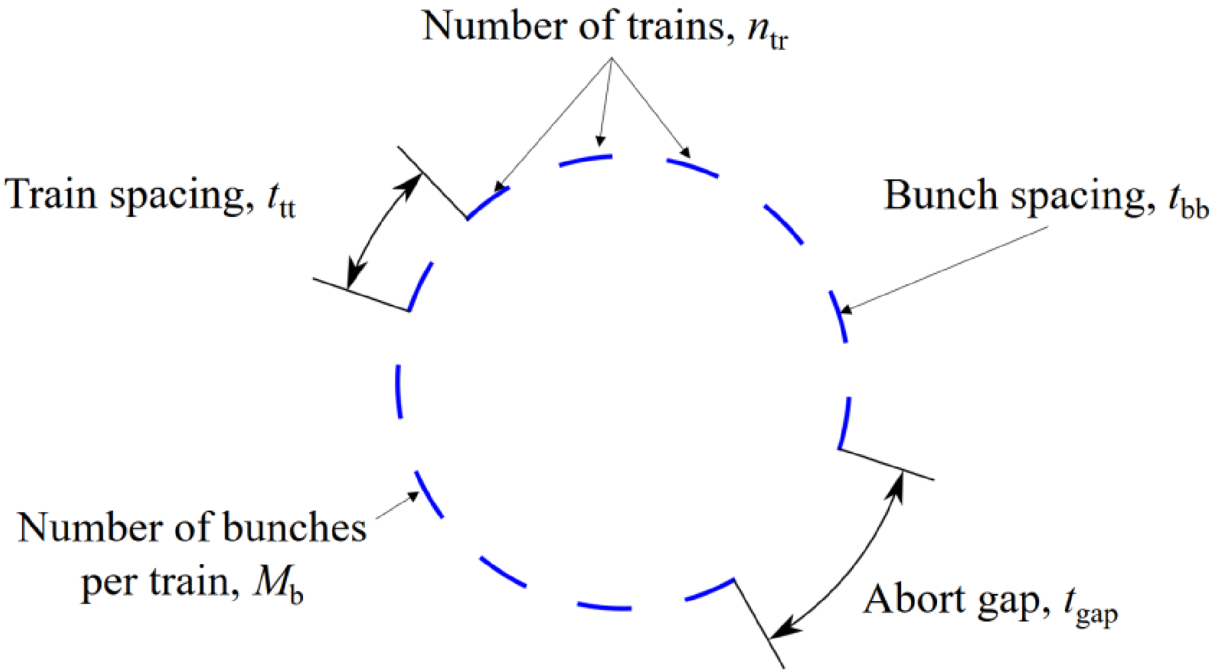
Optimal detuning $$\Delta\omega = \omega_0 - \omega_{RF} = -\frac{\omega_{\mathrm{RF}} (R/Q)\ I_{b,\mathrm{DC}} \sin\phi_s}{V_{\mathrm{cav}}}$$

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

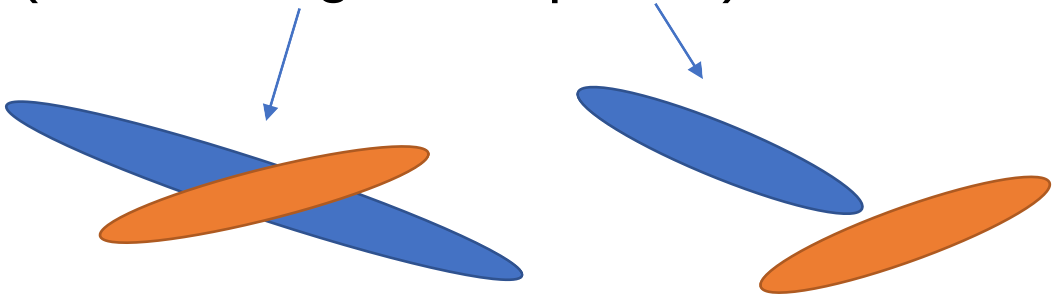
For maximum V_{cav} (P = 1 MW at 400 MHz and $P \approx 660$ kW at 600 MHz**) the minimum detuning for 1-cell UROS$_1$ is 10.7 kHz ($P \approx 1$ MW at 400 MHz), while about 57 kHz for 2-cell SWELL

** D. Boussard, Control of cavities with high beam loading, IEEE Trans. Nucl. Sci. 32, 1852 (1985)*
*** E. Montesinos, FCC week 2017*

Transient beam loading



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



→ Might have impact on luminosity

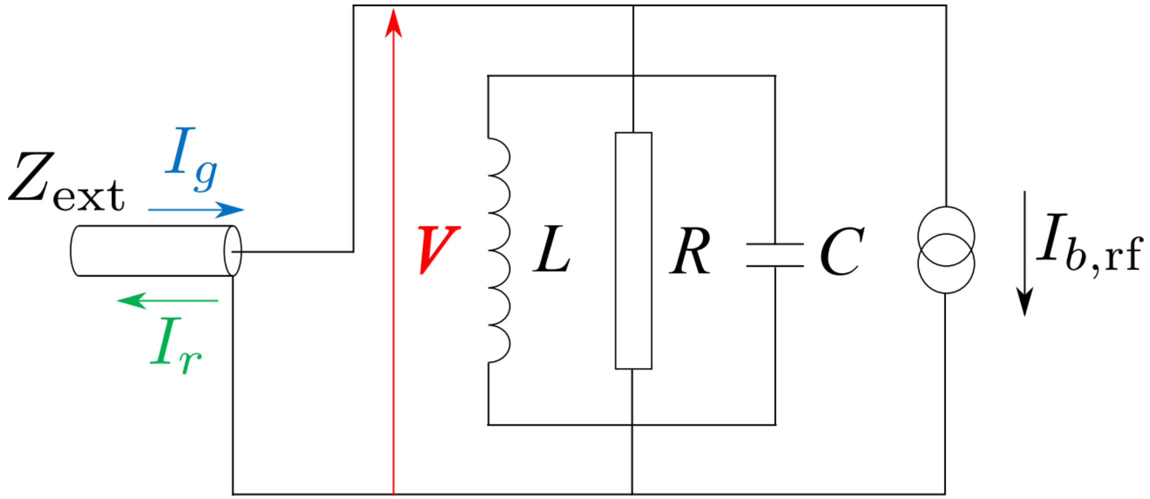
Conventional approaches:

- Small-signal model in frequency domain*, which assumes small modulations (but we have 100% modulation of beam current!)
- Particle tracking simulations (difficult for 16640 bunches in FCC-ee Z)

→ We use steady-state time domain method

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

Model for transient beam loading*



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

To calculate beam induced modulation we use:

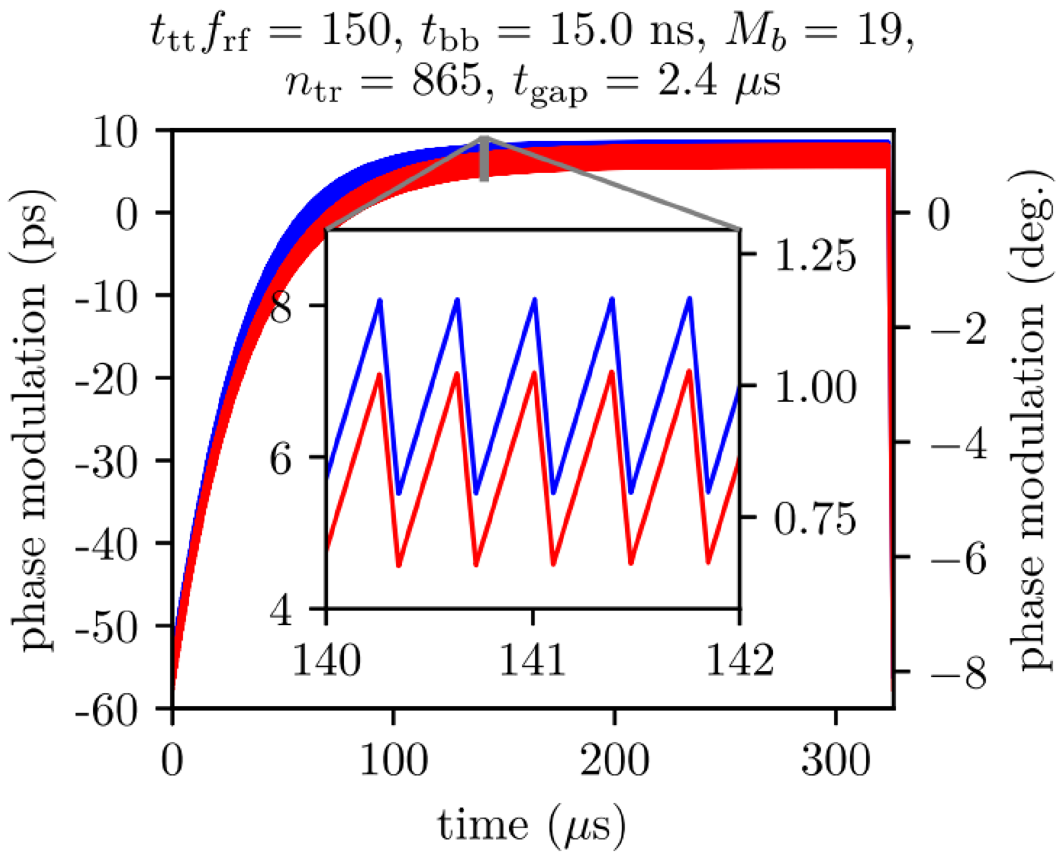
- $I_{\rm g}(t) =$ constant – no beam loading compensation
- $V(t) = A(t)e^{i\phi(t)}$, $I_{b,\rm RF}(t) = A_b(t)e^{-i\phi_s + i\phi_{\rm b}(t)}$
- relation for the synchronous phase $eN_{\rm cav}A(t)\cos[\phi_s - \phi_b(t) + \phi(t)] = \underset{\substack{\uparrow \\ \text{Energy loss per turn}}}{U_0}$

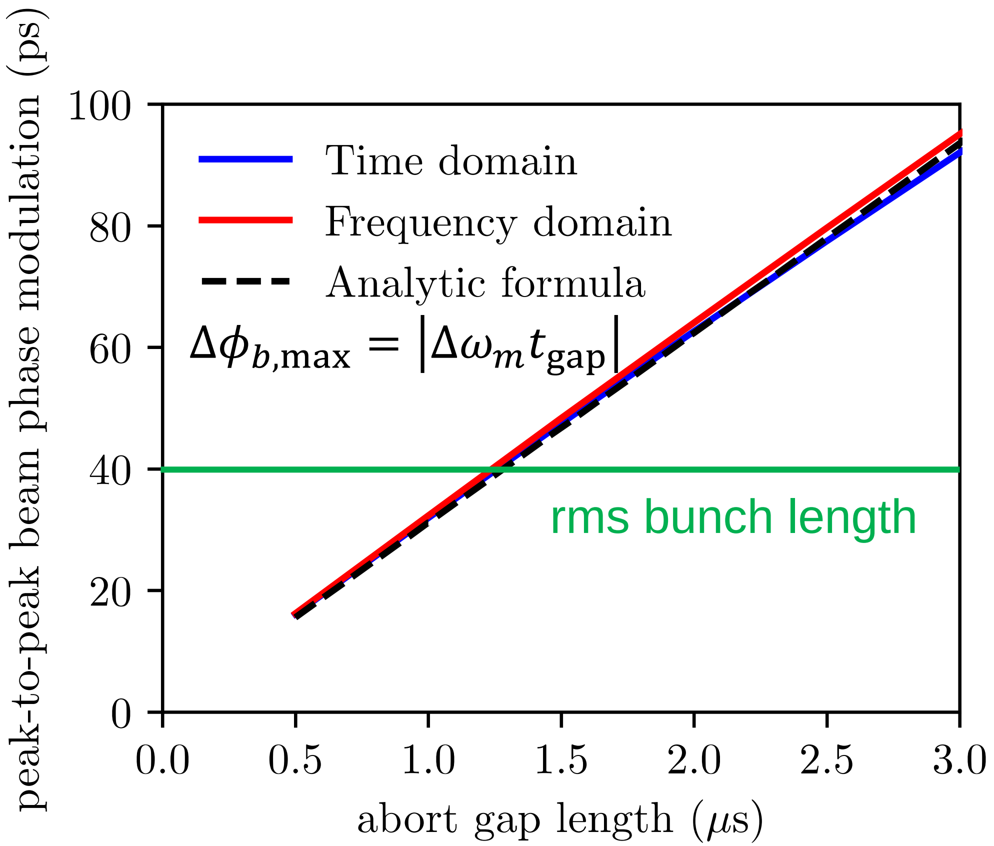
→ System of equations for $A(t), \phi(t),$ and $\phi_b(t)$ can be obtained and solved numerically**

** J. Tückmantel, CERN-ATS-Note-2011-002, 2011*

*** I. Karpov, P. Baudrenghien, PRAB 22, 081002 (2019)*

Results for single-cell cavity in FCC Z

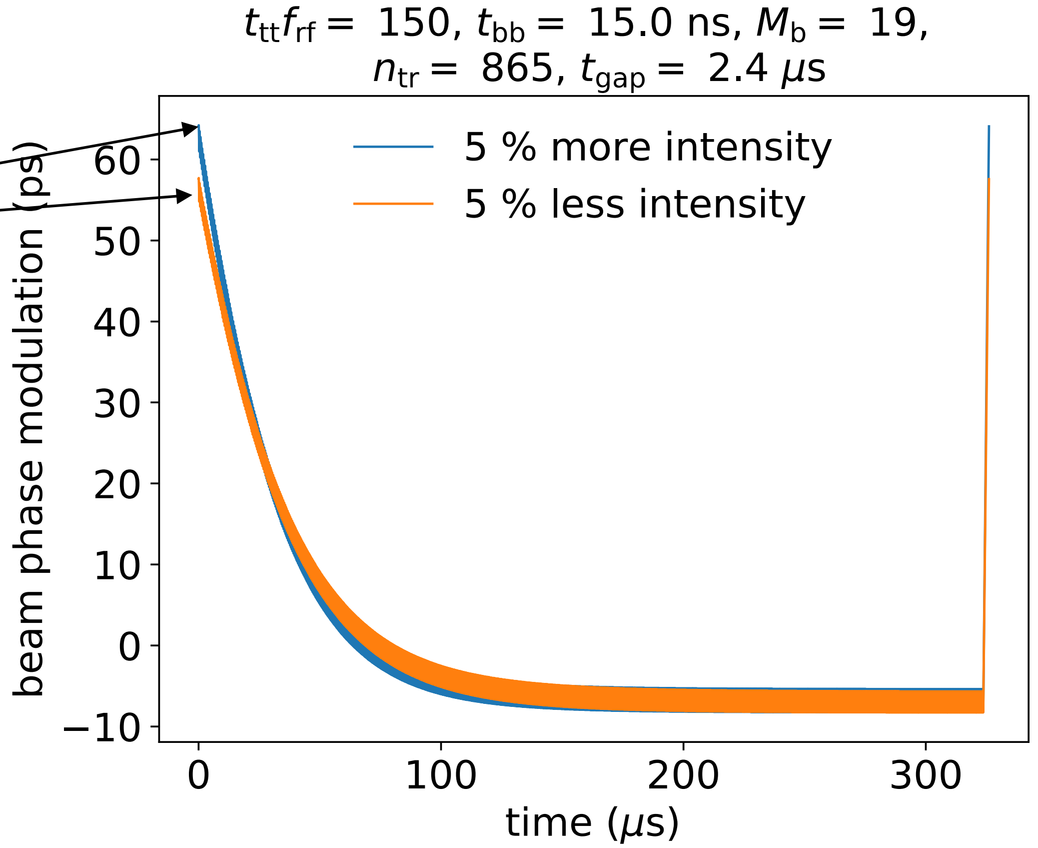




→ Reasonable agreement between time-domain and frequency-domain calculations
→ There is a strong modulation due to the abort gap and a fine structure due to the gaps between trains
→ For identical rings transients can be compensated by matching abort gaps (e.g., in PEPII, LHC,…)

Residual offset due to charge asymmetry

Imbalance of charge results in different detuning for electron and positron beams
→ slightly different transients



Assuming $\pm 5\ \%$ asymmetry, the maximum error is $0.1\ \Delta\phi_{b,\max}$ to be compared with 40 ps rms bunch length.

For abort gaps longer than 2.5 μs, the collision point shift is $> 0.2\ \sigma$ for UROS$_1$, while $> \sigma$ for SWELL.

→ Possible impact on luminosity and compensation schemes need to be evaluated.
→ Maximum abort gap length needs to be reconsidered.
→ Transients can be reduced by the expense of additional RF power.

Longitudinal CBI due to fundamental mode

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

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

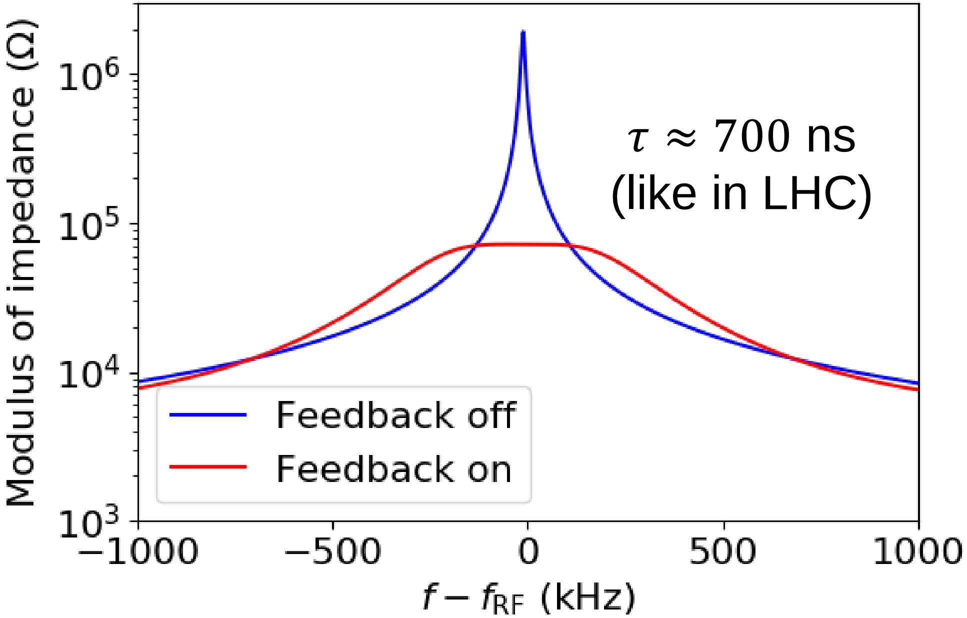
with $\omega_\pm = \omega_{\mathrm{RF}} \pm (m + Q_s)\omega_{\mathrm{rev}}$

Closed loop impedance with direct RF feedback**

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

τ – overall delay
G – feedback gain
ϕ – phase adjustment

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



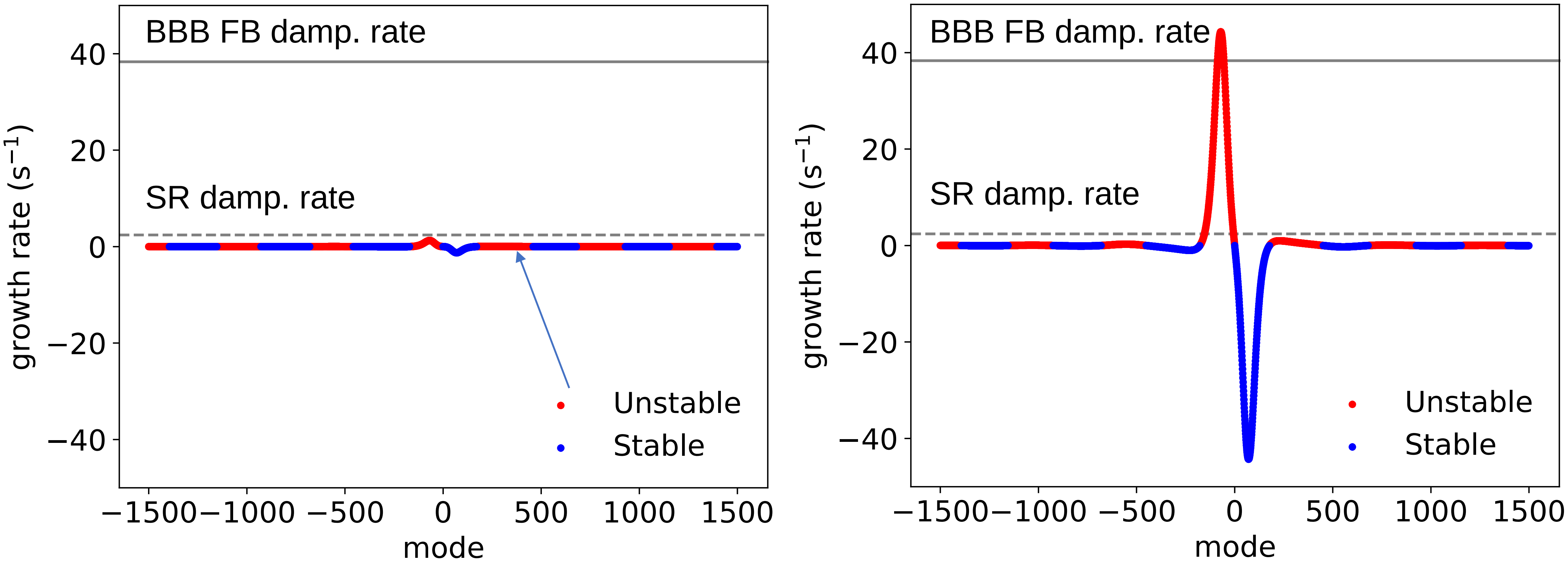
Passive damping if $\tau_m > \tau_{\mathrm{SR}}$ synchrotron radiation damping time (1273 turns),
Active damping if $\tau_m > \tau_{\mathrm{damp}}$ - damping time of longitudinal bunch-by-bunch feedback system ($2/Q_s = 80$ turns)

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

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

Longitudinal CBI due to fundamental mode

Growth rates vs bunch mode number (case of direct RF feedback only)



1-cell UROS_1, V_{cav} = 1.92 MV

2-cell SWELL, V_{cav}= 1.32 MV

→ Additional damping by RF feedback is required for SWELL cavity

Addition of one turn delay feedback

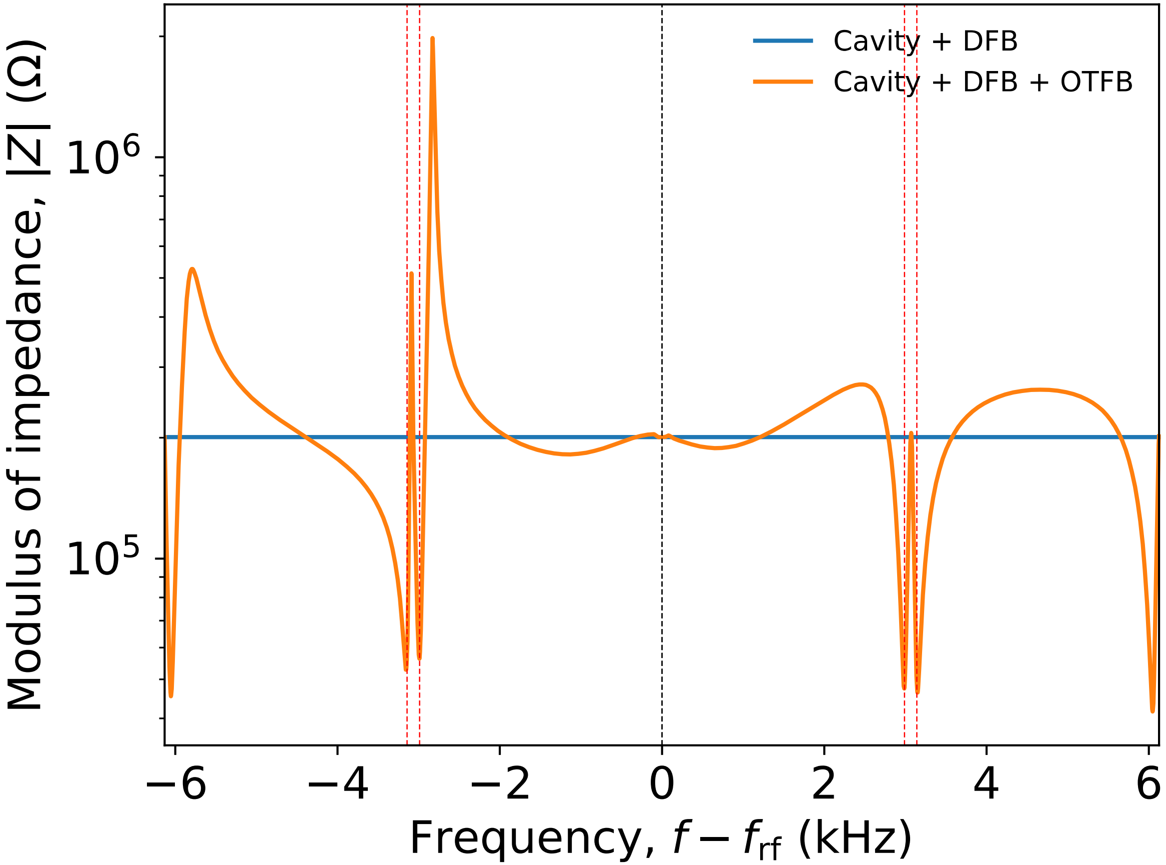
Closed loop impedance with direct RF feedback and one turn delay dual comb filter feedback*

$$Z_{\mathrm{cl}}(\omega) = \frac{Z(\omega)}{1 + e^{-i\tau\omega} G e^{i\phi} Z(\omega)[1 + H_{\mathrm{dcomb}}(\omega)]}$$

$$H^{*}_{\mathrm{dcomb}}(\omega) = \frac{G_{\mathrm{dcomb}}\left(1 - e^{-i\omega T_{\mathrm{rev}}}\right) e^{-i\omega(T_{\mathrm{rev}} - T_G)}}{[1 - K e^{-i(\omega T_{\mathrm{rev}} - Q_s)}][1 - K e^{-i(\omega T_{\mathrm{rev}} + Q_s)}]}$$

$$G_{\mathrm{dcomb}} = 10, K = 15/16$$

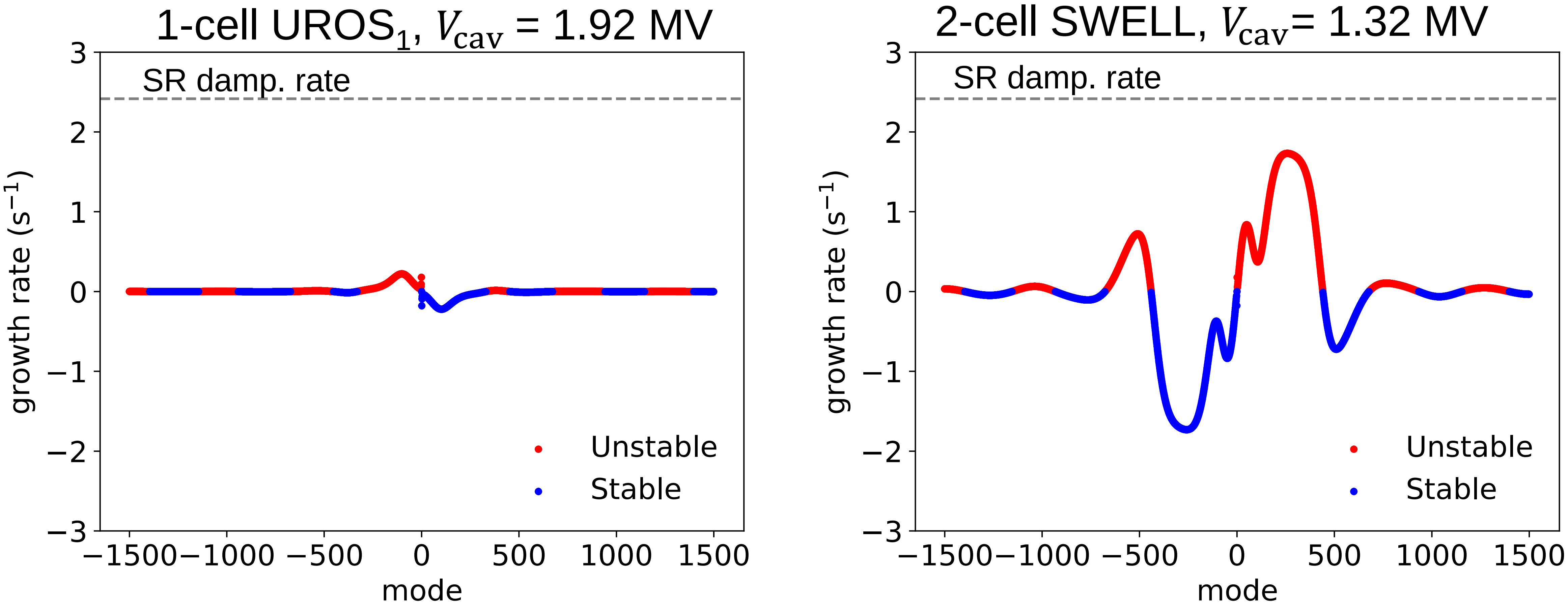
→ Further reduction of Z_{cl} at synchrotron side-bands



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

Longitudinal CBI due to fundamental mode

Growth rates vs bunch mode number (case of direct RF + one turn delay feedback)



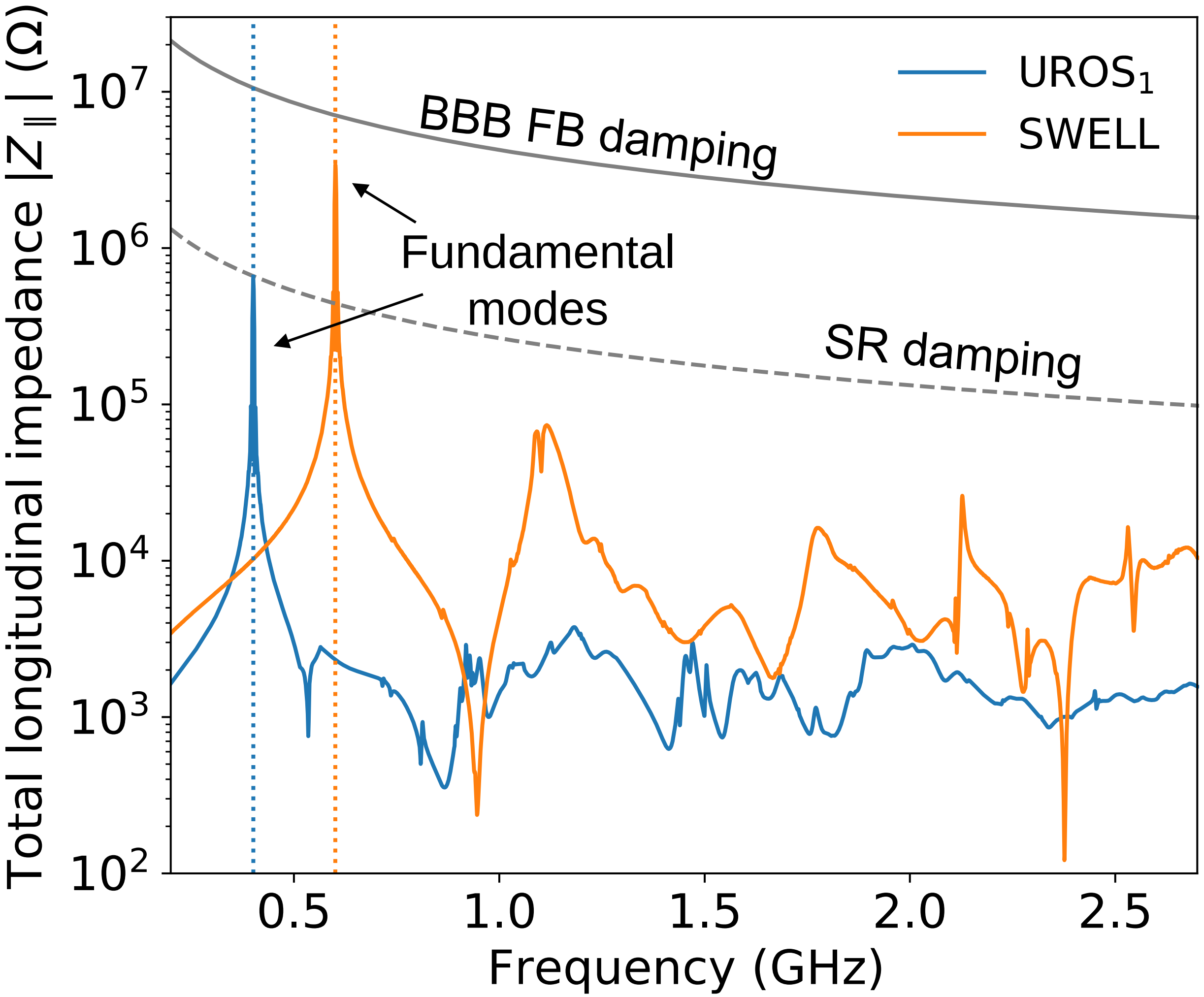
→ Direct RF and one turn delay feedback systems should be sufficient to reduce growth rates in SWELL below natural damping

Longitudinal CBI due to HOMs at Z pole

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



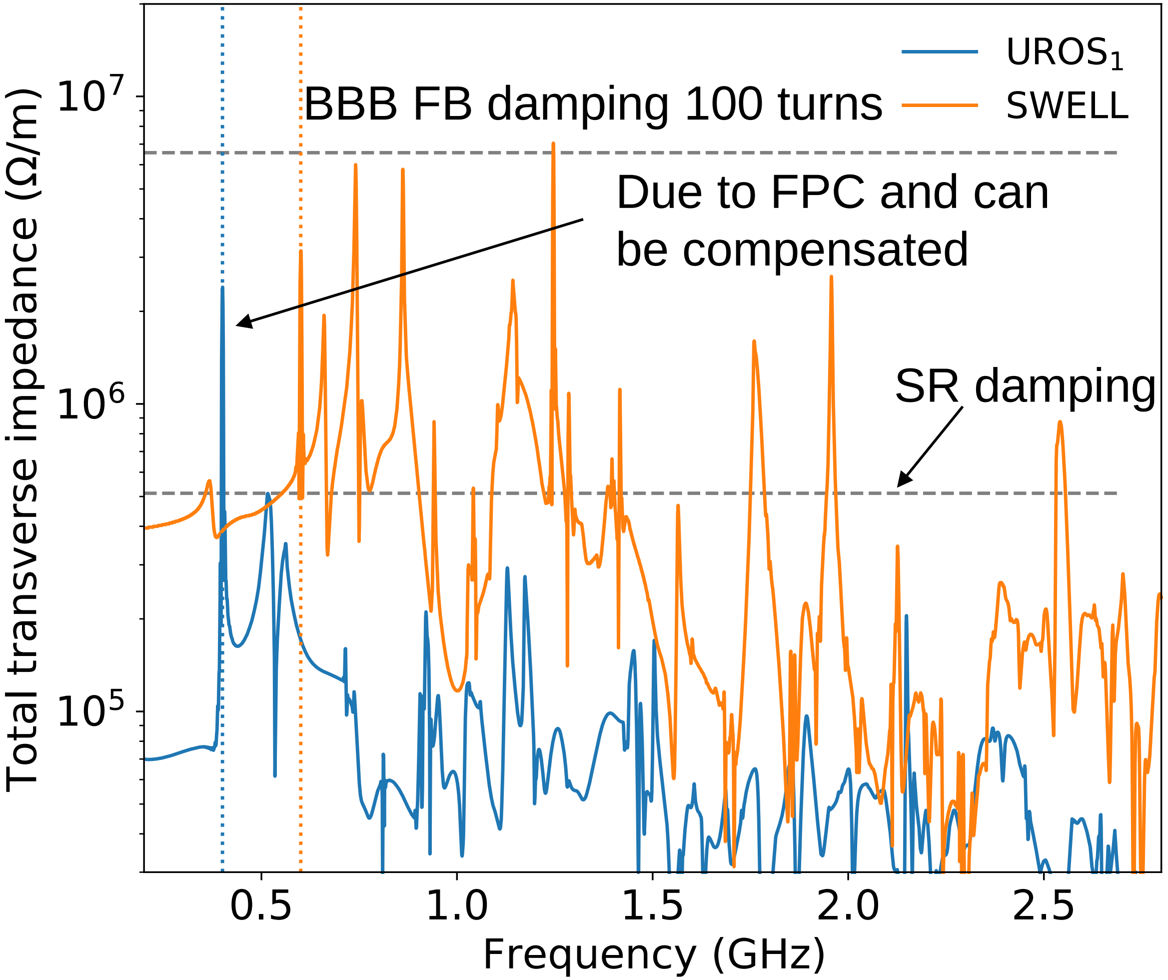
Transverse CBI due to HOMs

Similar expression for threshold

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

→ Bunch-by-bunch feedback system is required

→ Damping time of about 100 turns should be sufficient to suppress instabilities due to HOMs



HOM power losses

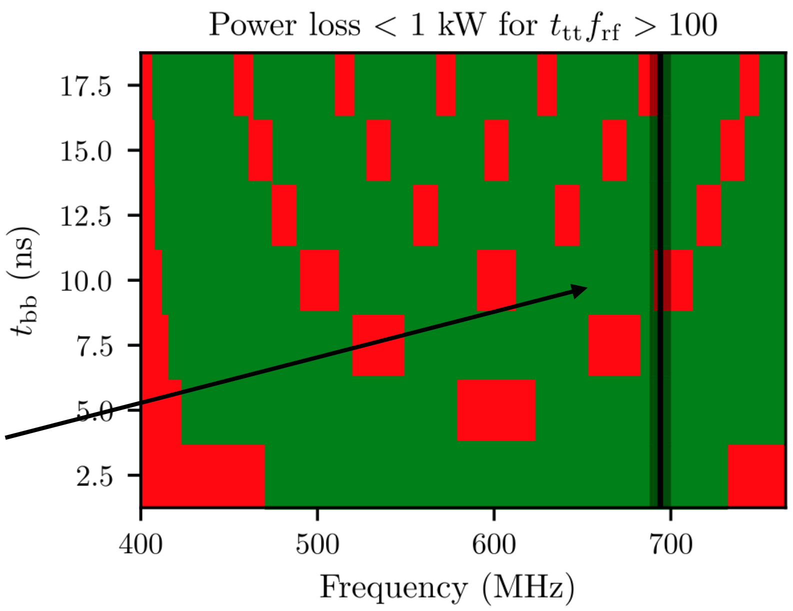
Simulated cavity impedance

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
→ Acceptable filling schemes were defined for operation


Power loss < 1 kW for $t_{\mathrm{tt}} f_{\mathrm{rf}} > 100$

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

HOM power losses: trapped modes

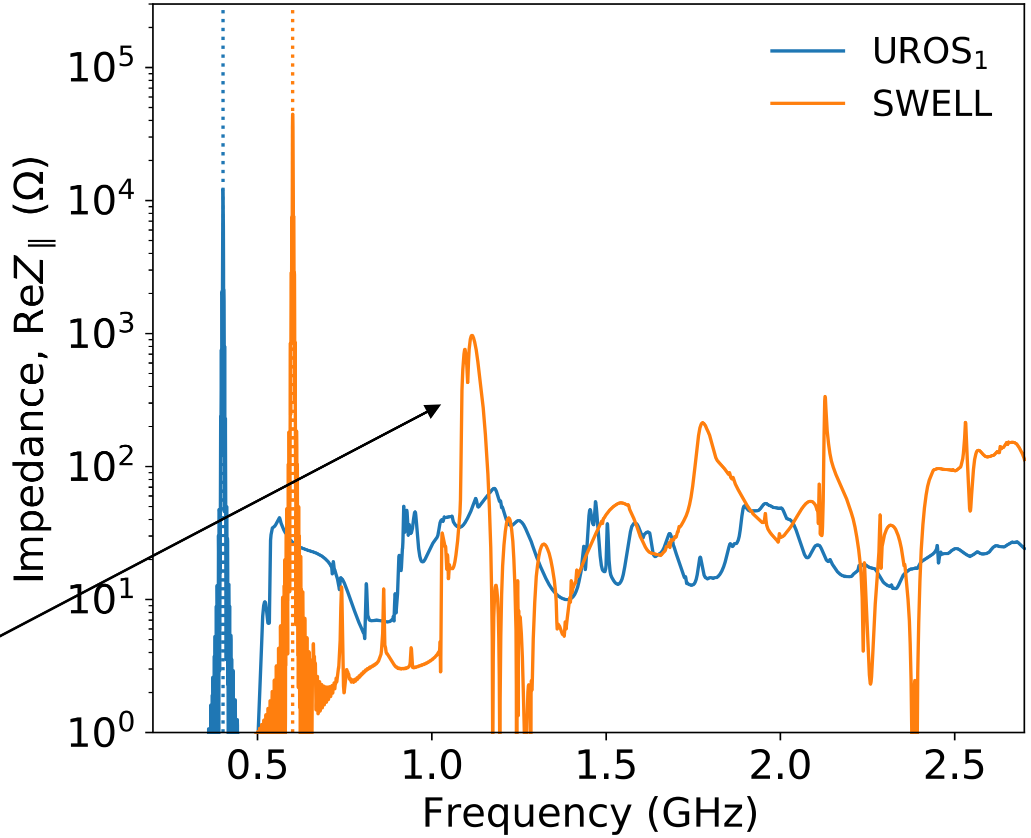
Resonant excitation:

$$P_{\text{res}} = I_{b,\text{DC}}^2 \,(R/Q)_{\text{HOM}} Q_{\text{ext}}$$

For UROS$_1$ cavity the first HOM sits above cut-off frequency as natural and passive way of damping

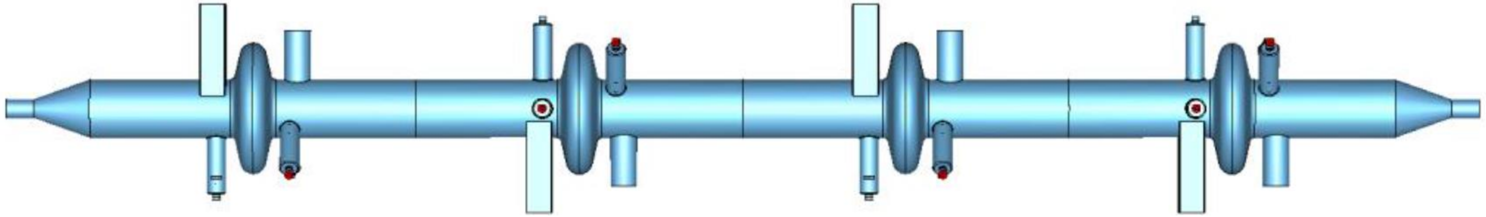
There are two trapped modes (heavily damped) for SWELL cavities:

Freq. (MHz)	R/Q **(Ω) linac. def.**	Q_{ext}	P_{res} **(kW) worst case**
1085.4	4.2	196	**0.8**
1097.1	20.3	59	**1.2**



→ Moderate HOM power loss even for the worst-case scenario of resonant excitation in SWELL

HOM power losses: above cut-off



Power loss can be estimated as
$P_{\mathrm{HOM}} = k_{\parallel,\mathrm{HOM}} I_{b,\mathrm{DC}} Q_b$

$P_{\mathrm{HOM}} \approx$ 7 kW for SWELL (preliminary)

Configuration	P_{HOM}	**BP**	**RWG**
UROS$_1$ cavity	6.3 kW	60 %	30 %
Four UROS$_1$ cavities	26.3 kW	33 %	48 %
Four UROS$_1$ cavities + tapers	45.9 kW	15 %	54 %

BP – beam pipe
RWG – rectangular waveguide

← Worst-case scenario of short tapers

Additional modes can appear in multi-cavity structures with tapers
→ Optimization of taper geometry is necessary

Large amount of HOM power propagates through beam pipes
→ Absorbers might be needed

Summary

Beam-cavity interaction for FCC-ee operating at Z pole is the most challenging.

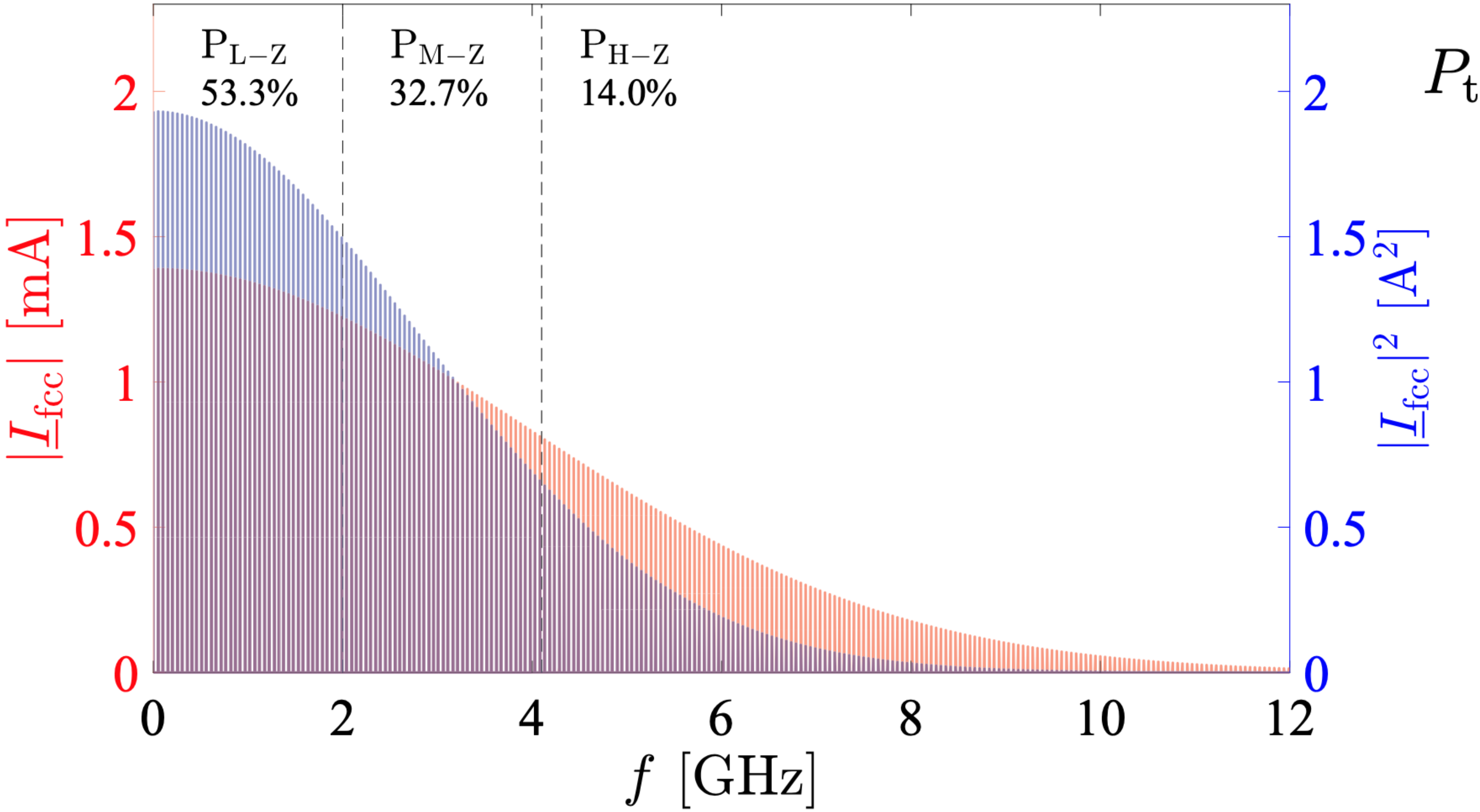
Comparison of 1-cell UROS$_1$ and 2-cell SWELL cavity types gives:

- Longitudinal CBI are under control for both designs.
- Transverse CBI due to HOMs should be suppressed by bunch-by-bunch transverse feedback system.
- HOM power losses are feasible (below 2 kW in resonant case). Calculations for multi-cavity case are still required.
- Impact of transient beam loading on displacement of collision point needs to be further evaluated.

Thank you for your attention!

Spare slides

HOM power calculations



$$P_{\mathrm{tot-W}} \approx P_{\mathrm{L-W}} + P_{\mathrm{M-W}} + \frac{46.7}{25.4} P_{\mathrm{M-W}}$$