HOM power in RF cavities of FCC-ee rings (old and new parameters)

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HOM power loss calculations

Simulated cavity impedance

Normalized Fourier harmonics of beam current

$$P = J_A^2 \sum_{k=-\infty}^{\infty} \mathrm{Re}\left[Z_{||}(k f_0)\right] |J_k|^2$$

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

Estimations of the power loss are required to determine parameters for high order mode (HOM) absorbers.

Recap on the progress

- Power losses were evaluated for all FCC-ee machines (Z, W, H, $t\bar{t}$) and different cavity designs (single cell, two cells and four cells)
  - The highest power loss from continuous cavity impedance spectrum P_{cont} is for the Z machine → a single-cell design is preferable. P_{cont} around 2kW can be extracted using several HOM couples (max 1kW/coupler);
  - For other machines it is below 1kW
- Contribution of taper impedance can be reduced using proper taper dimensions (length of 3m for 12 ps bunches and transitions for beam pipe radii from 15 cm to 5 cm)
- Different filling schemes were analyzed for the Z machine
  - Critical cases were identified for the single-cell cavity design (a spectral line hits HOM below cut-off frequency) → filling schemes which should be avoided in operation were determined
- Calculations for new parameters were performed

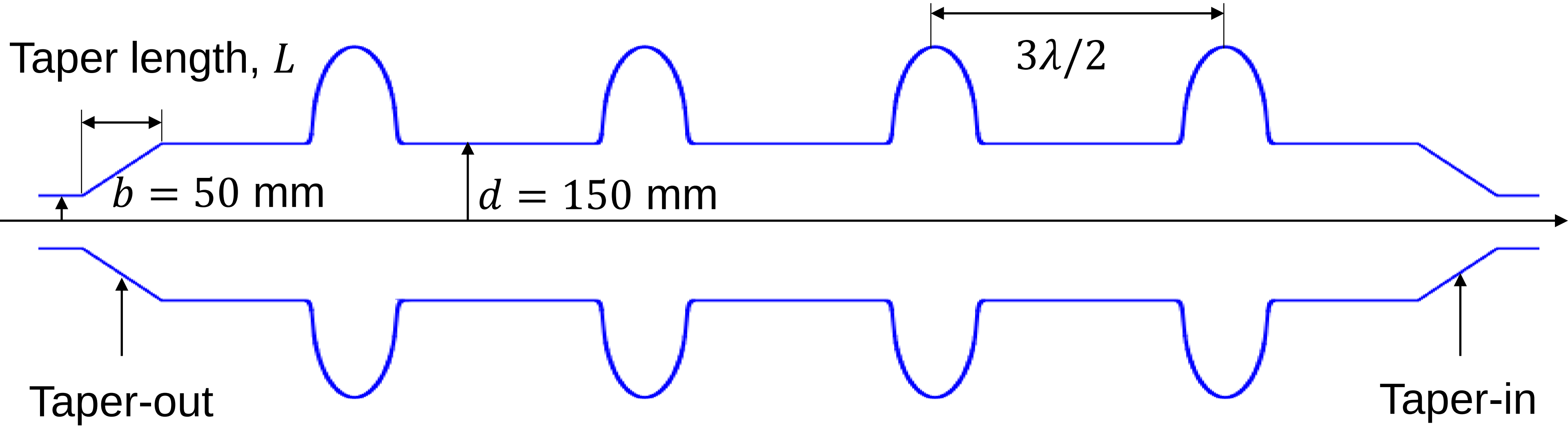
Parameters for Z machine

Parameter	Old	New
Beam current, J_A [A]	1.4	1.385
Bunch population, N_p	0.4×10^{11}	1.5×10^{11}
Bunch length (in collision), σ_t [ps]	7 (12)	12 (37)
Number of bunches, M	71200	18800
Total RF voltage, V_tot [MV]	255	100 (?)
RF frequency, f_RF [MHz]	400.79	
Harmonic number, h	130680	

→ For new parameters the bunch spacing can be different due to a smaller number of bunches (t_bb = 2.5 ÷ 15 ns)
→ Smaller RF voltage – to be studied

LHC-like layout of cryomodule

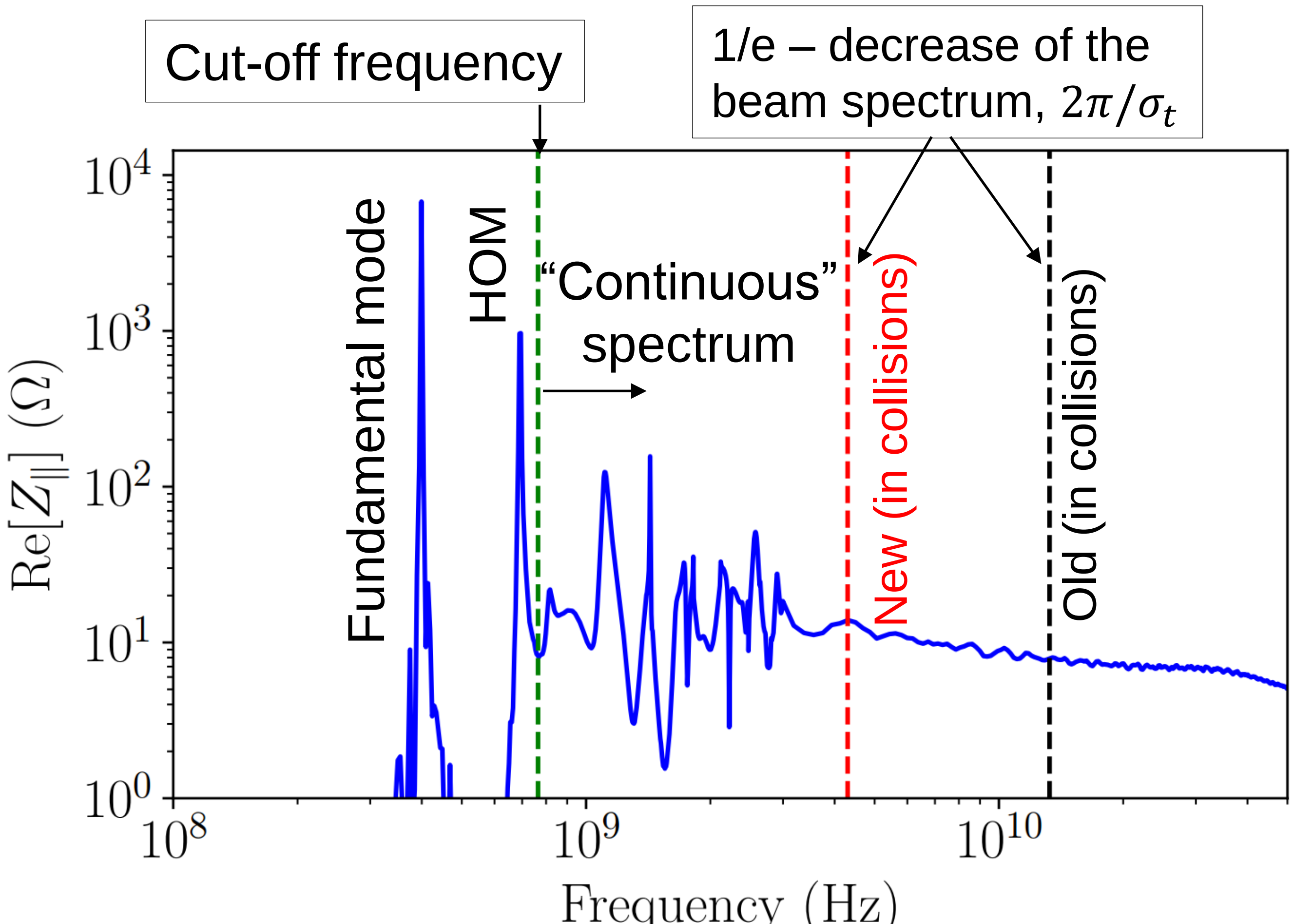
400 MHz LHC cavities with modified shape (input from R. Calaga)



Impedance calculation using ABCI

Axisymmetric structure + Gaussian bunch → Wake potential → Impedance

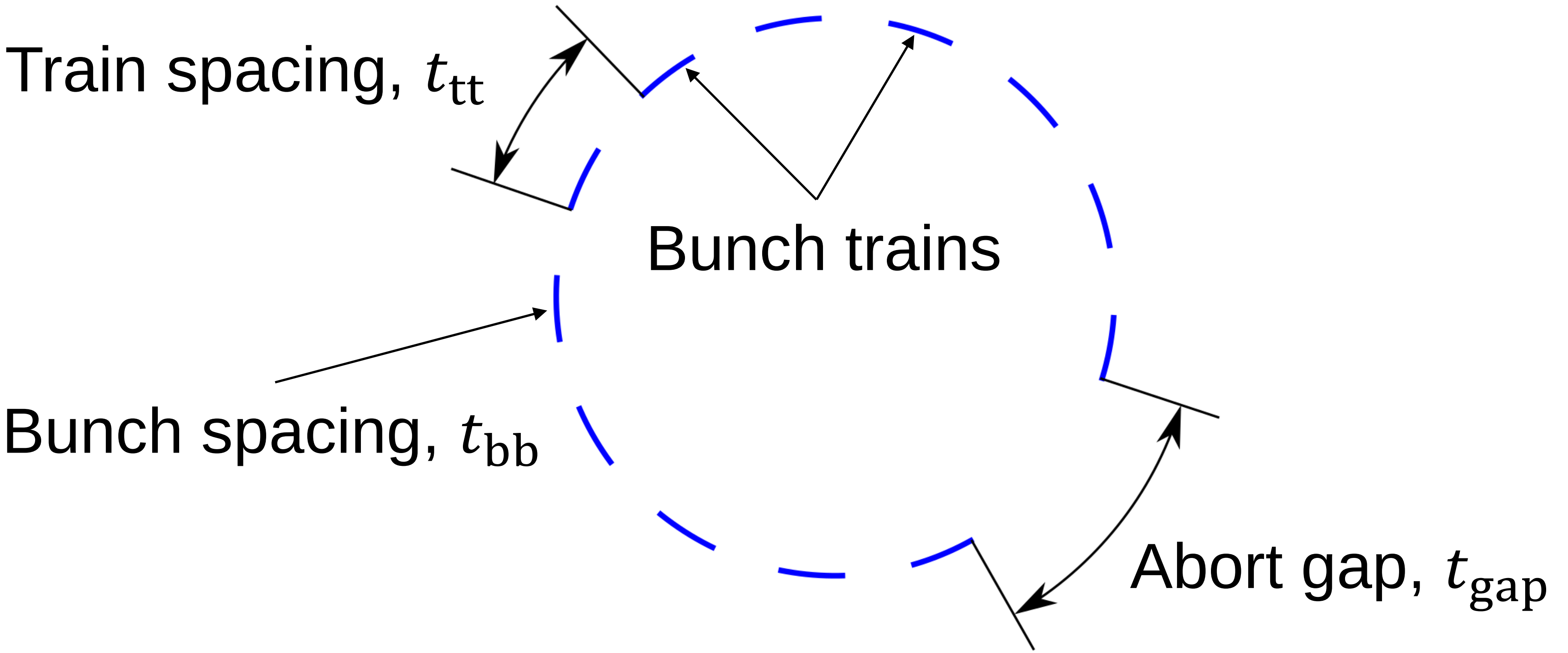
Single-cell cavity impedance



HOM parameters: $f_\mathrm{r} \approx 694$ MHz, $R/Q \approx 10\ \Omega$ (CST EMS simulations)

→ Only one mode below cut-off frequency can affect power losses

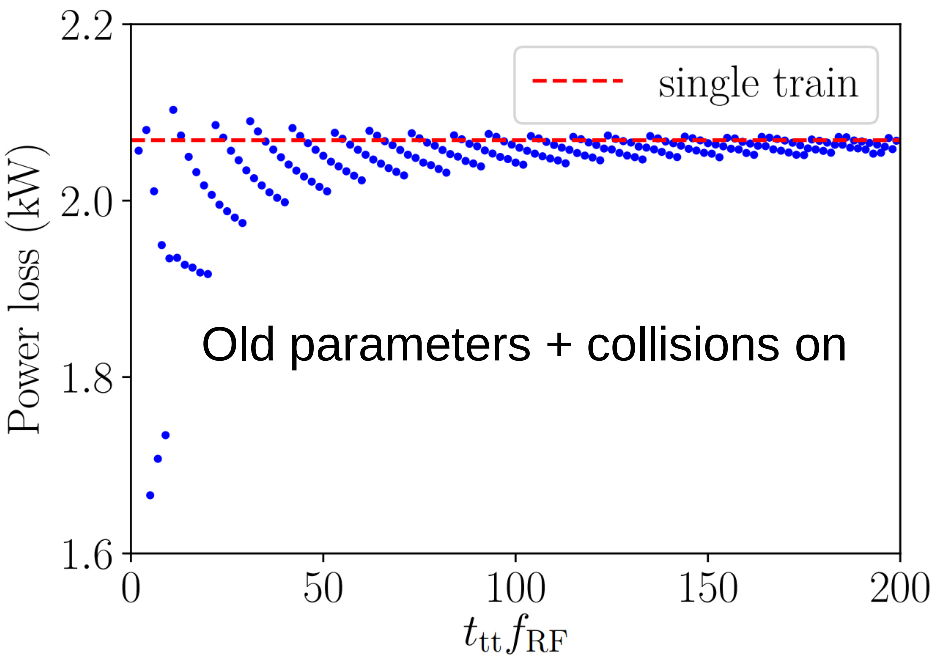
Beam spectrum for different filling schemes

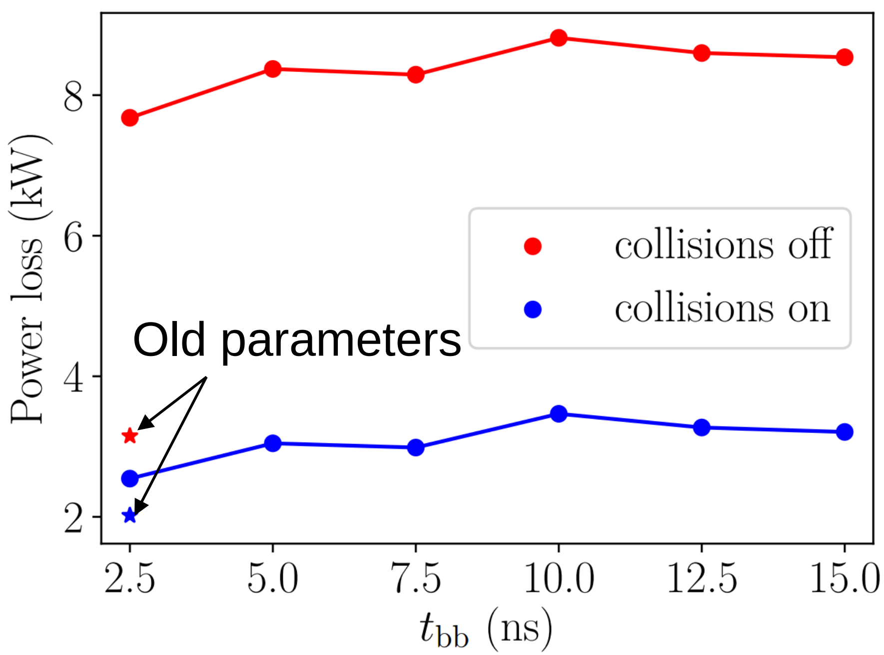


Spectrum is dominated by:
$1/t_{\mathrm{bb}}$ lines (always present)
+ $1/t_{\mathrm{tt}}$ lines (depending on number of trains)

Power loss above cut-off frequency

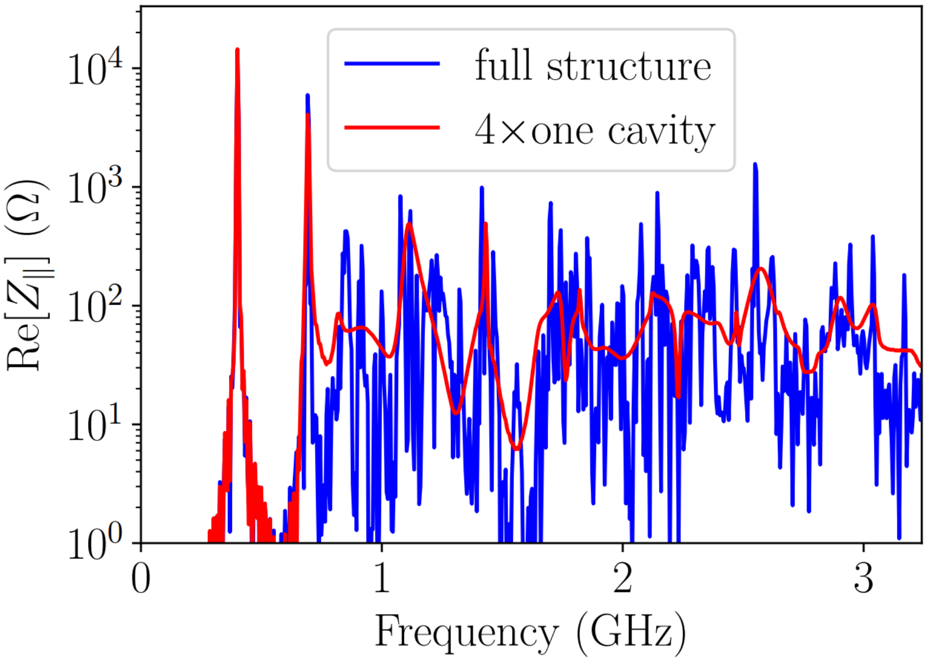
Constant parameters: total current ≤ 1.4 A, abort gap length, bunch population
Variable parameters: number of bunches in the train, number of trains, train spacing

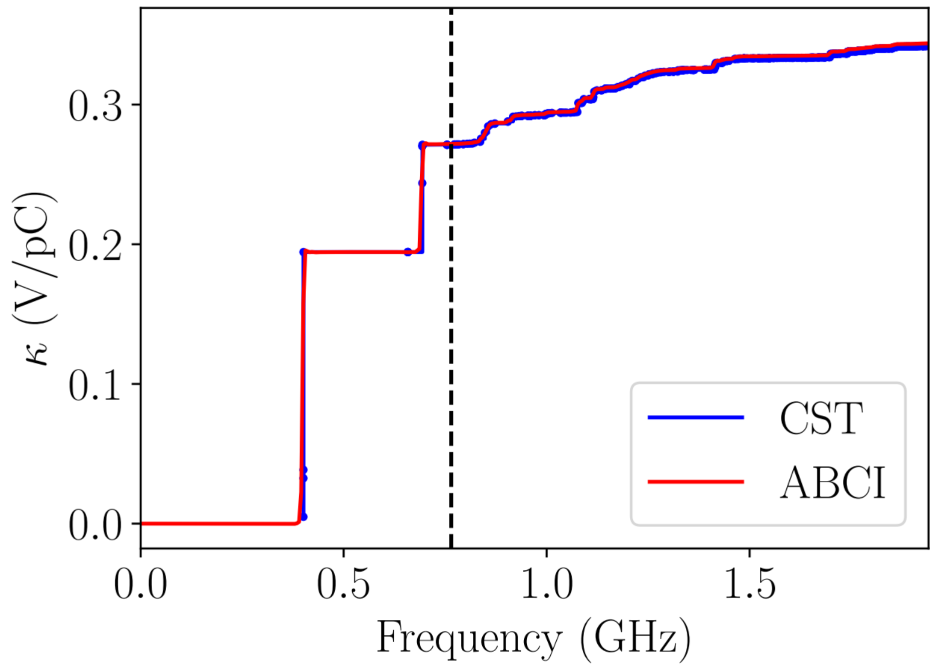




Power loss is moderate for the present cavity design for bunches in collisions
There is a weak dependence on train spacing and bunch spacing

Impedance below 3 GHz





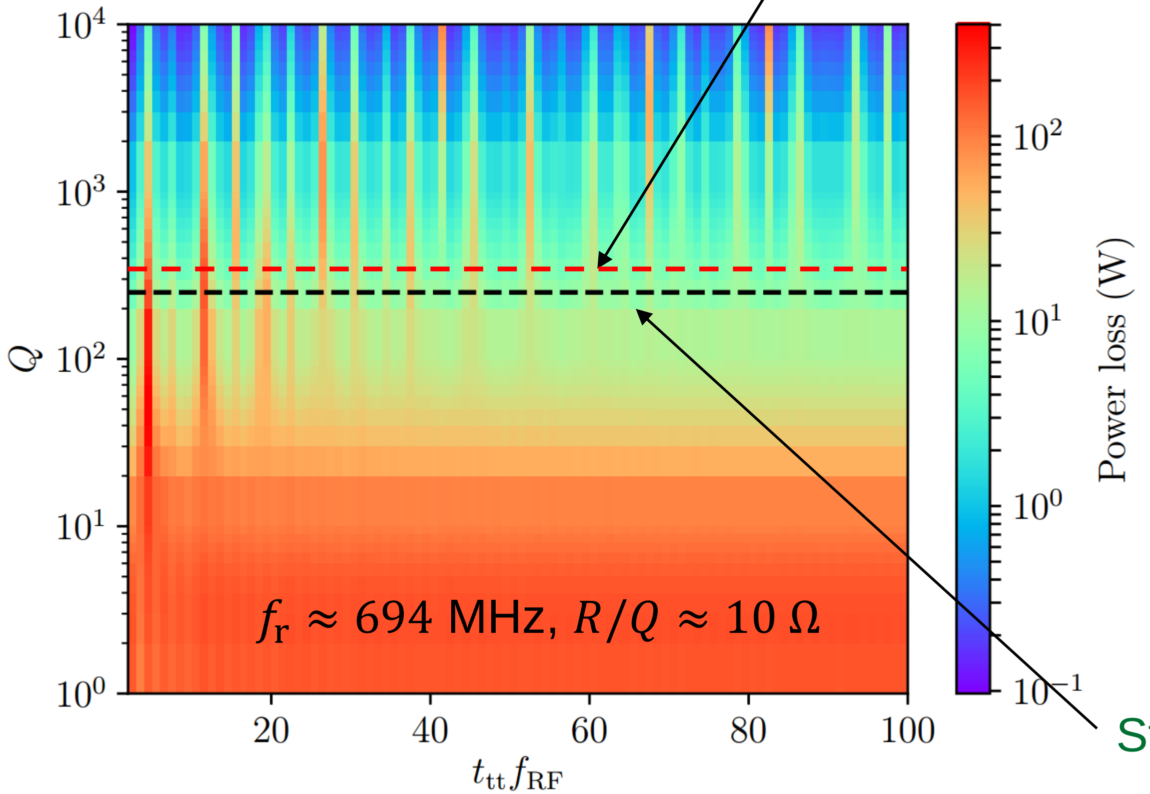
Four single-cell cavity displaced by 3λ/2
+ 3 m long tapers from 15 cm to 5 cm

For CST $$\kappa = \sum_n \pi f_n \left(\frac{R}{Q}\right)_n \mathrm{e}^{-(2\pi f_n \sigma_t)^2}$$

There are still a few modes below cut-off frequency of the cavity with high *R/Q*.
Higher frequency HOMs have small *R/Q* values

Power loss for HOM below cut-off frequency

For new parameters



Stability threshold for 1 MV/cavity accelerating gradient

Longitudinal coupled-bunch instability growth rate

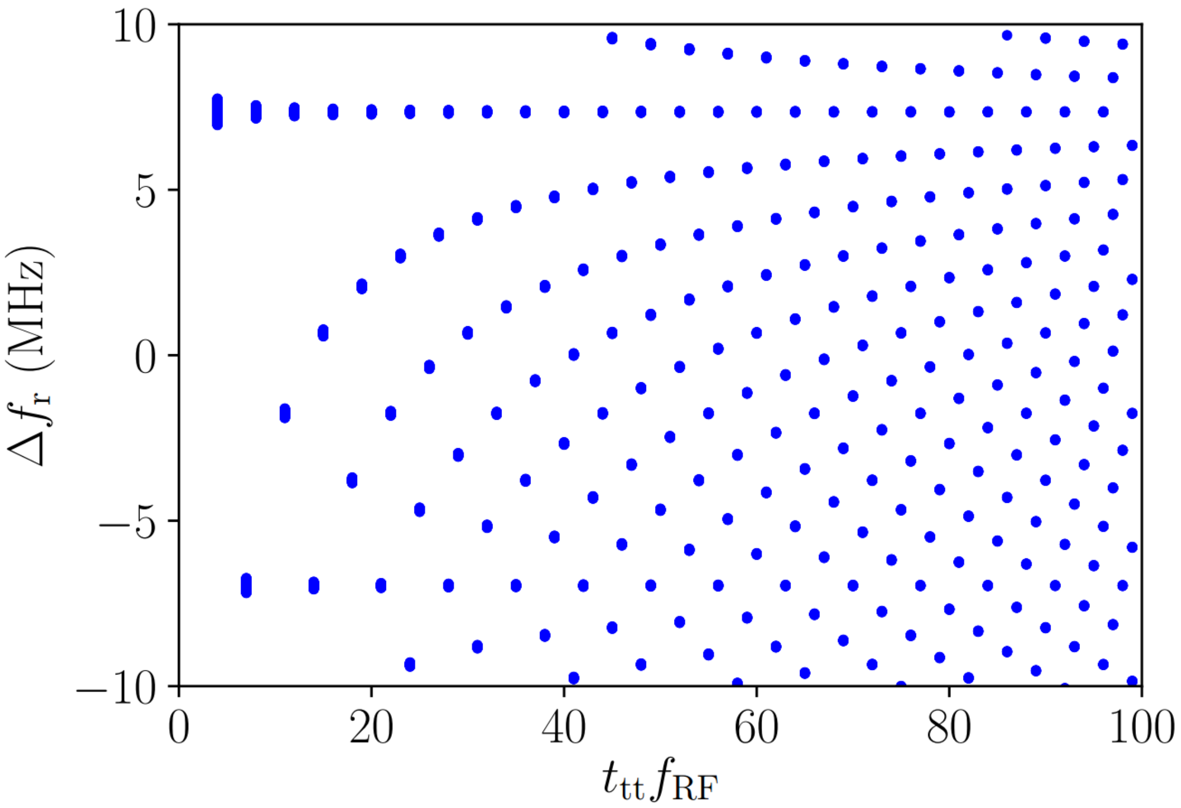
$$\frac{1}{\tau} = \frac{e|\eta|J_A}{2EQ_s} f_\mathrm{r} R$$

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

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

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

Shift of the resonant frequency

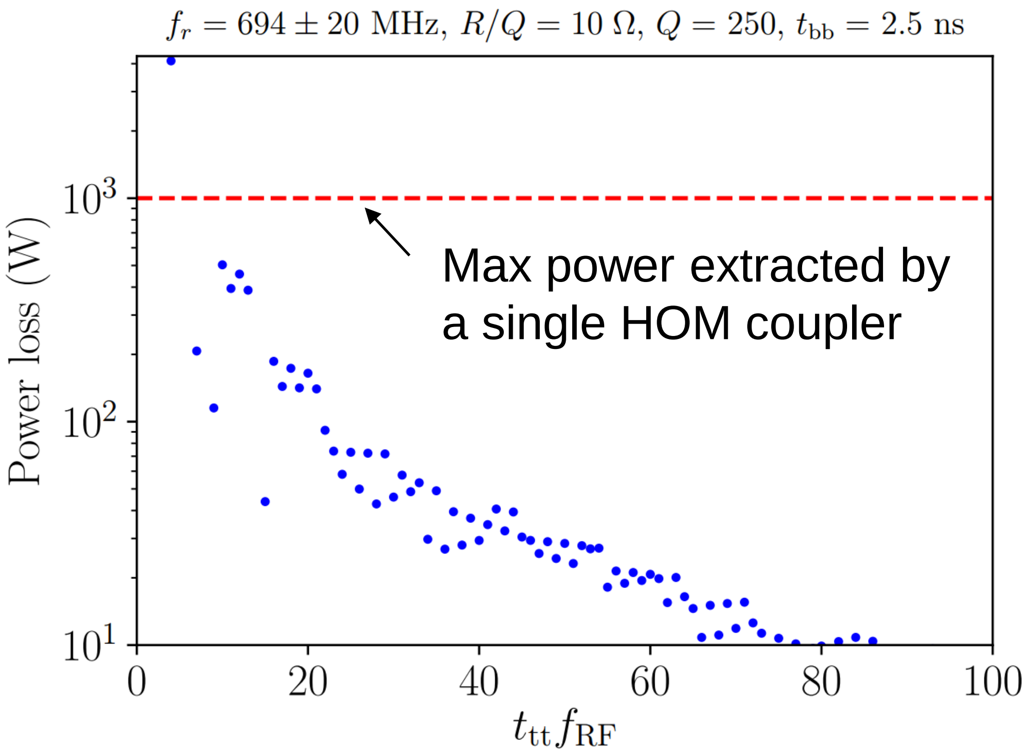


"Resonant" condition $\left|1 - \frac{[f_{\mathrm{r}} t_{\mathrm{tt}}]}{f_{\mathrm{r}} t_{\mathrm{tt}}}\right| < \frac{1}{Q}$

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

→ Not all of them are dangerous

Power losses for old parameters

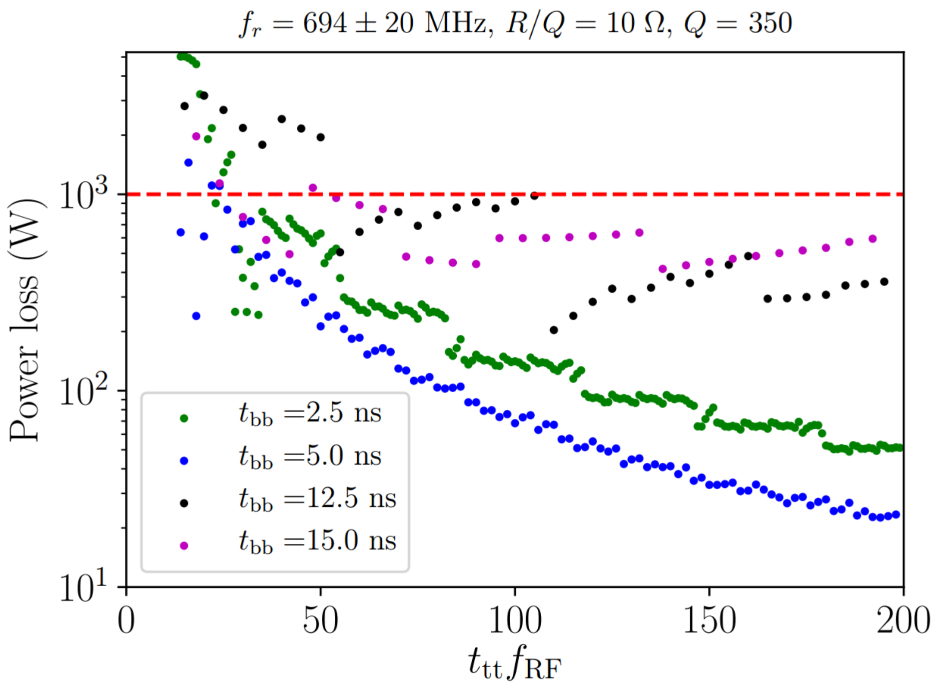


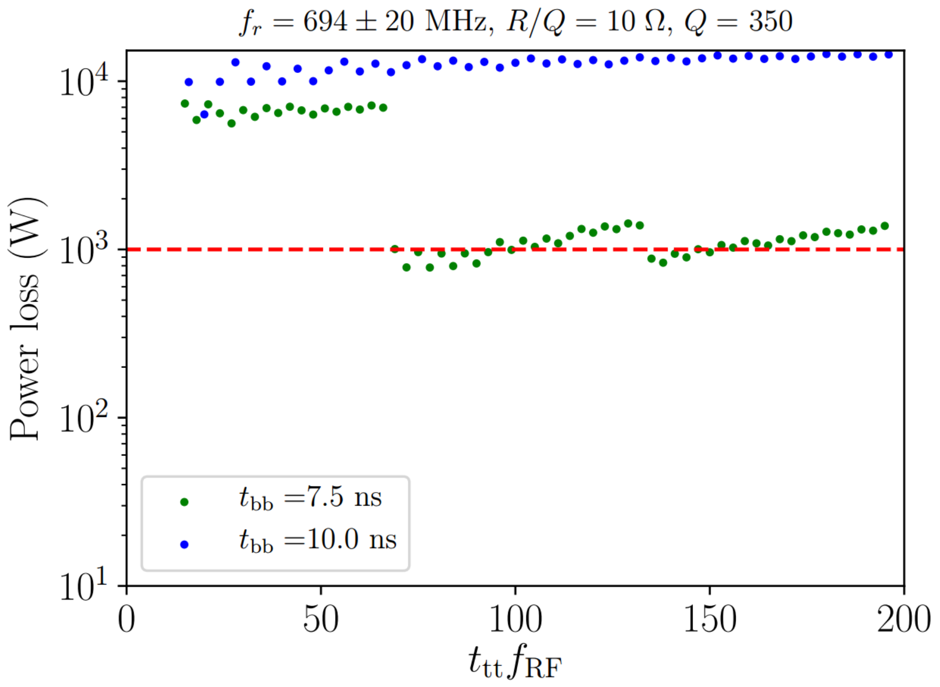
Calculation parameters:

- Constant total current $J_A = 1.4$ A
- Abort gap length $t_{gap} = 2$ μs
- Bunch population $N_p = 4 \times 10^{10}$

→ Damped HOM is not dangerous if $t_{tt} f_{RF} > 4$

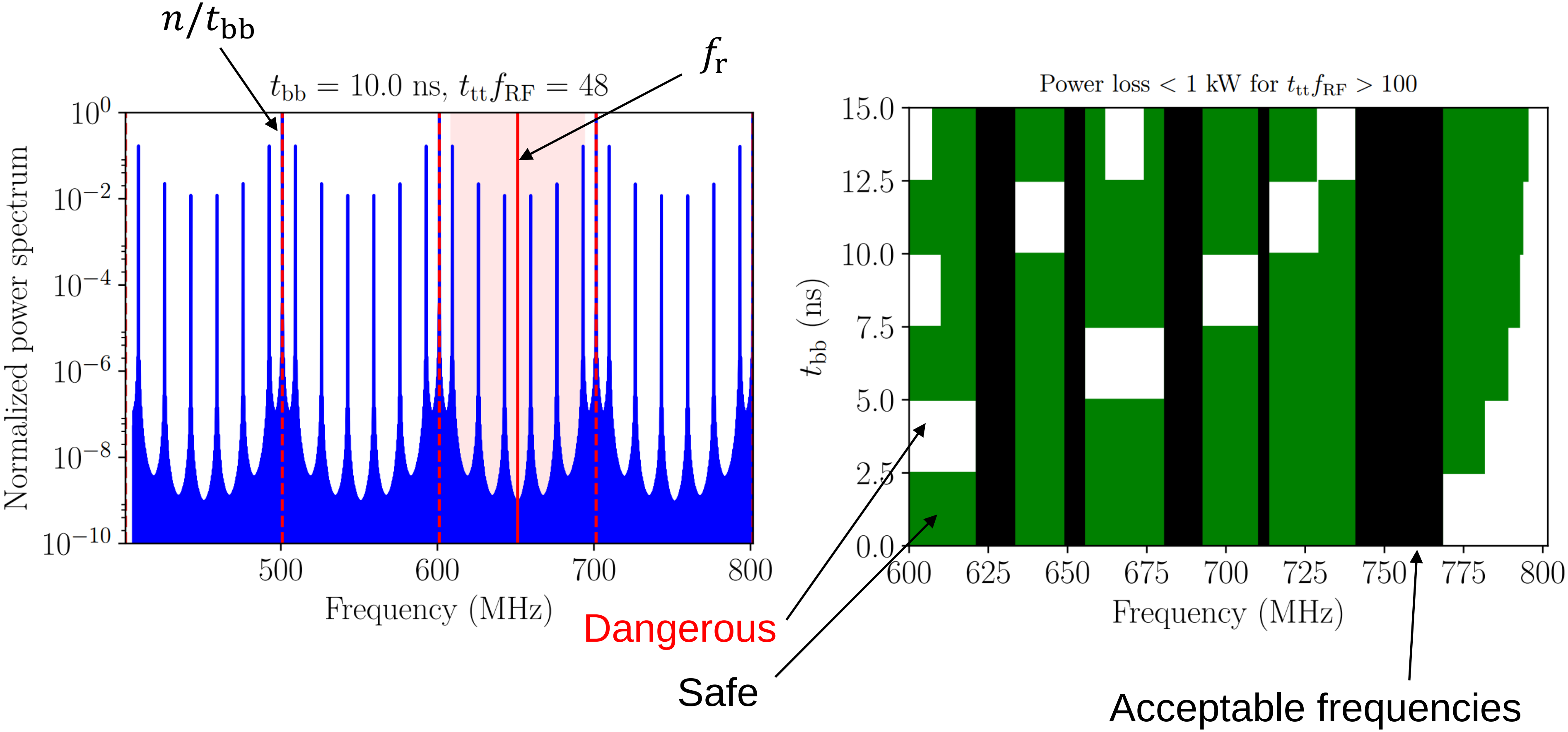
Power losses for new parameters





→ More values of train spacing should be avoided in operation
→ Strong power losses for 7.5 ns and 10 ns bunch spacings

More “general” case



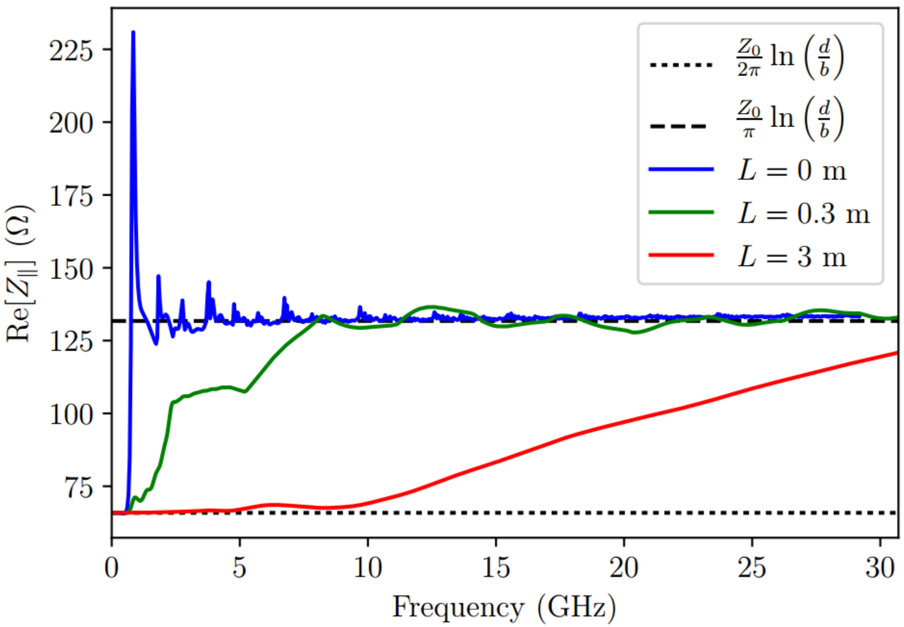
→ Operation settings define recommendations for the cavity design (position of HOMs)

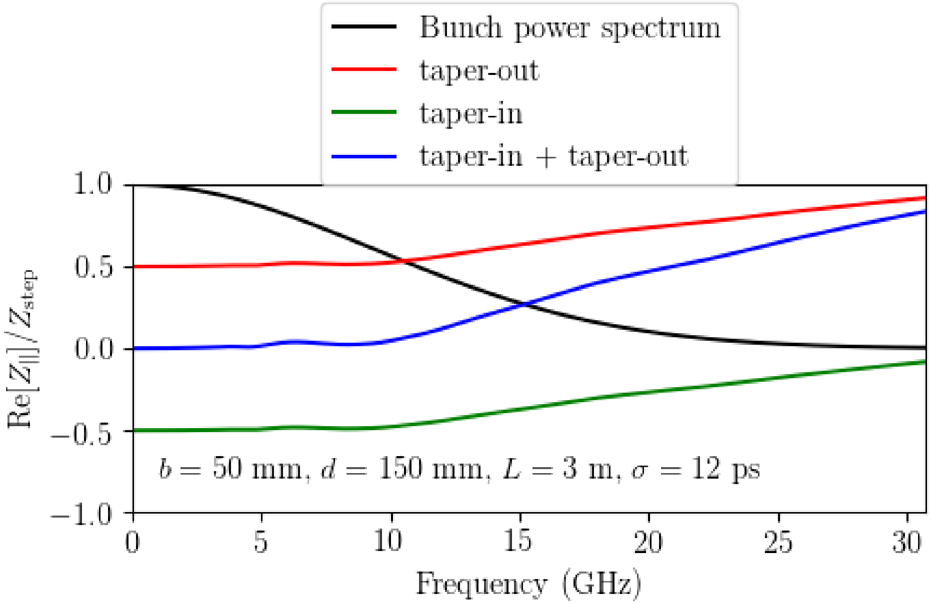
Summary of power loss for a single-cell cavity design for the Z machine

- Contributions from continuous spectrum:
  - Power losses are around 2 kW and 3 kW for old and new parameters, correspondingly (bunches are in collisions).
  - Taper length can be reduced for new parameters
- Below cut-off frequency there is one HOM with high R/Q (can split in 4 modes for the full structure) that can significantly contribute to power losses
- Critical filling schemes were identified and should be avoided in operation for the given cavity design
- For new parameters:
  - For the single-cell cavity design 7.5 ns and 10 ns bunch spacings are not feasible
  - Other bunch spacings can be used, but some particular filling schemes (t_{tt}) should be avoided in operation
  - HOM frequency ranges for new cavity designs which are “safe” for all bunch spacings were identified

Thank you for your attention!

Contribution of tapers





For $c\sigma_t \;<<\; b \;< d$, impedance of step transition at high frequencies

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

Transition region from $Z_{\text{step}}/2$ to Z_{step} depends on taper length.

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

$$L_{\text{opt}} = \frac{(d-b)^2}{c\sigma_t}$$

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