BOOSTER COUPLED BUNCH INSTABILITIES AND RAMP OPTIMISATION

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Acknowledgements: Rama Calaga, Ivan Karpov, Heiko Damerau

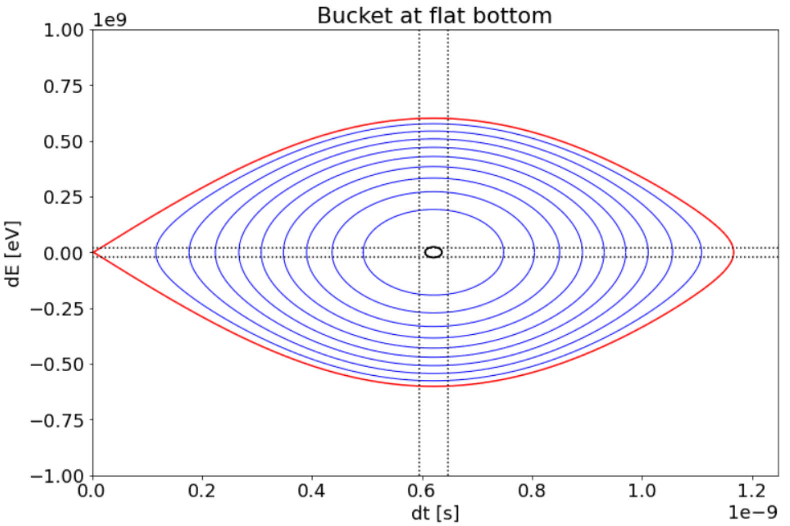
RF parameter table for the HEB (injection from a 20 GeV Linac)

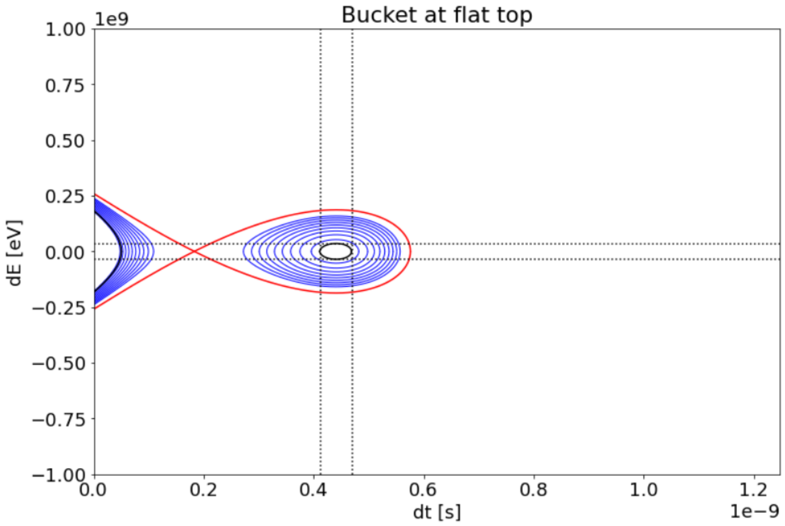
Running mode	Z	W	Higgs	ttbar
Injection energy [GeV]	20			
Extraction energy [GeV]	45.6	80	120	182.5
Arc optics FODO	$60°/60°$		$90°/90°$	
Momentum compaction	$14.9 \cdot 10^{-6}$		$7.34 \cdot 10^{-6}$	
Inj. RF voltage [MV]	104.9		52.85	
Ext. RF voltage [MV]	49.48	458.6	2015	11533
Ramp time [s]	0.32	0.75	1.25	2.03
Ramp number of turns	1058	2480	4133	6713
Current [mA]	128	13.5	2.67	0.49
Inj. en. loss/turn [MeV]	1.45			
Ext. en. loss/turn [MeV]	39.4	374	1890	10420

Courtesy of Barbara Delena

Booster:
Ramp optimisation for the Z mode

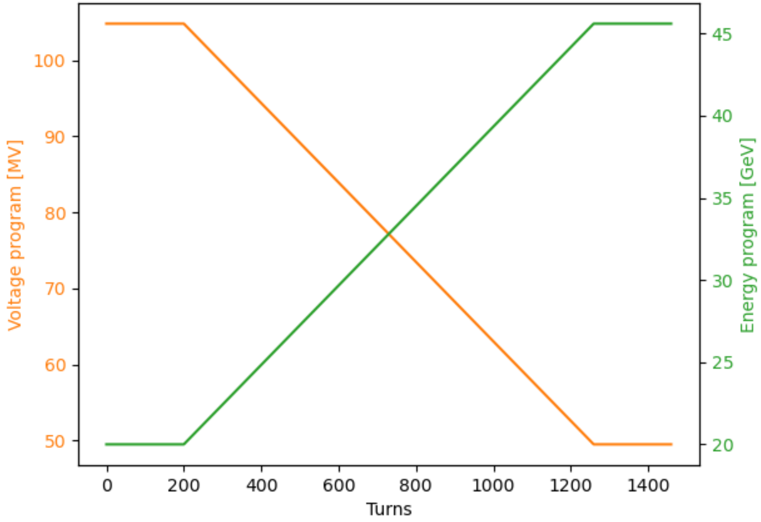
Boundary conditions for the Z operation

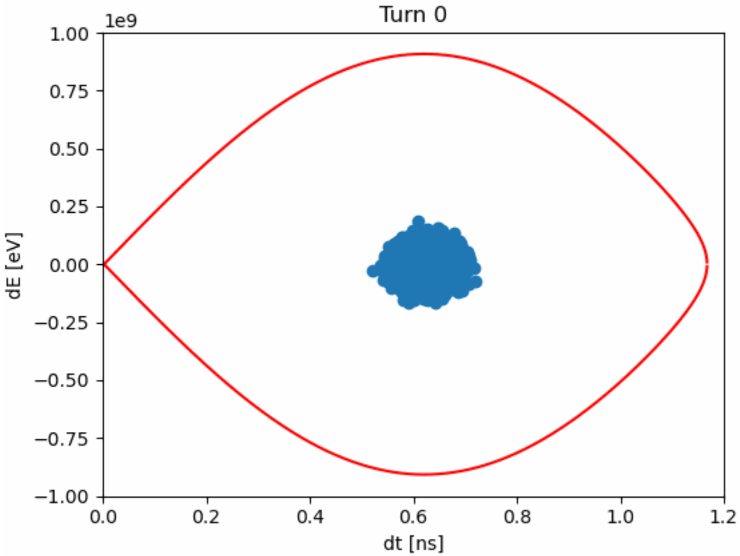




	Flat bottom	Flat top
Energy [GeV]	20	45.6
Voltage [MV]	104.8	49.48
Bunch length [mm]	4	4.38
Power [MW]	0.2	5
Emittance [meVs]	3.42	3.49

What happens with linear voltage and energy ramps?



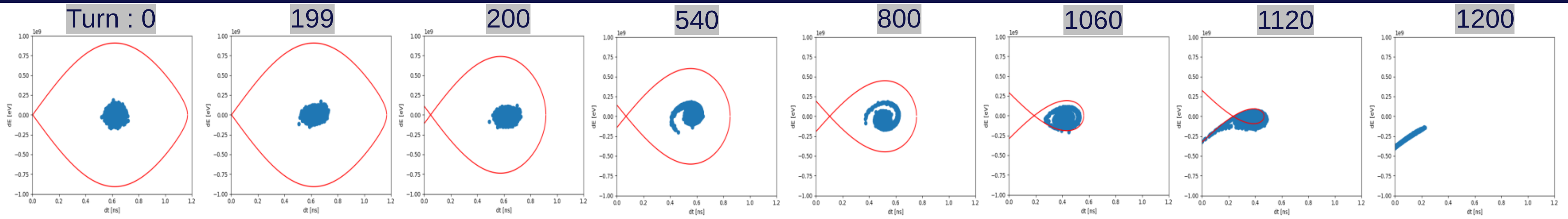


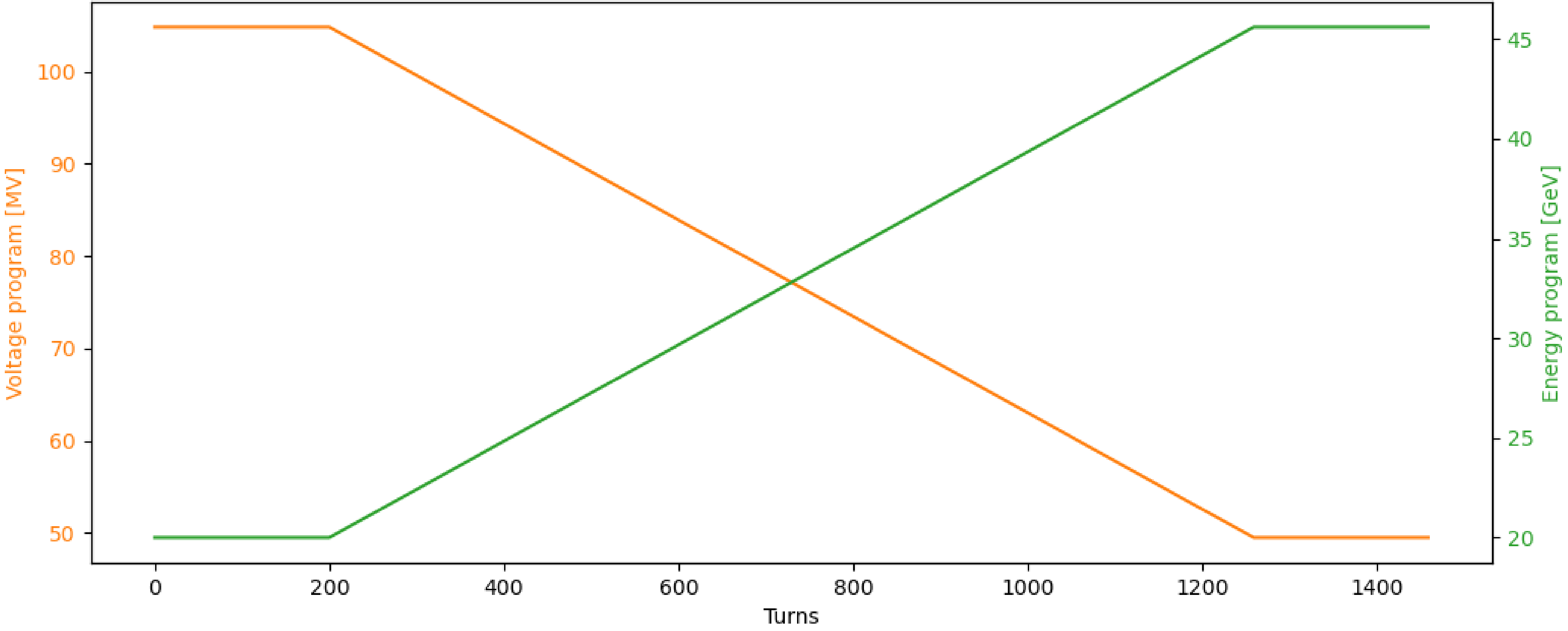
We lose the beam before reaching the flat top.

Toy model implemented in BLonD [link] with:

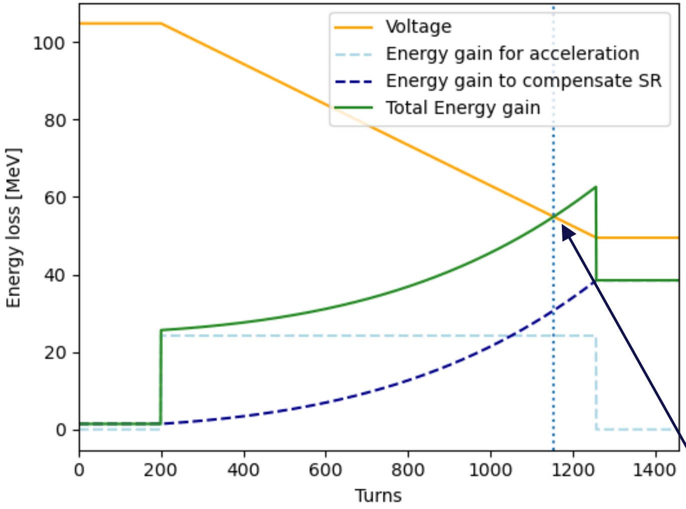
- 200 turns flat bottom
- 1058 turns ramp (0.32 seconds)
- 200 turns flat top

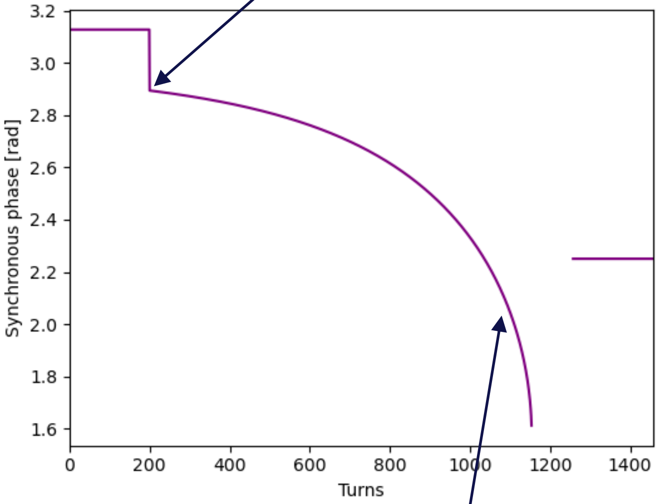
(considers QE and SR, but no IBS)


Turn : 0
199
200
540
800
1060
1120
1200
dE [eV]
dt [ns]


Voltage program [MV]
Energy program [GeV]
Turns

Why are we loosing the beam?





Bunch shocked at ramp beginning

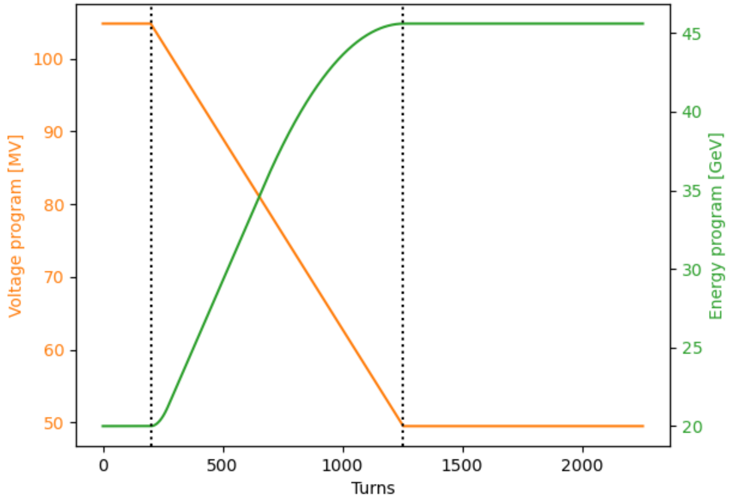
Voltage too low to compensate SR and accelerate the beam

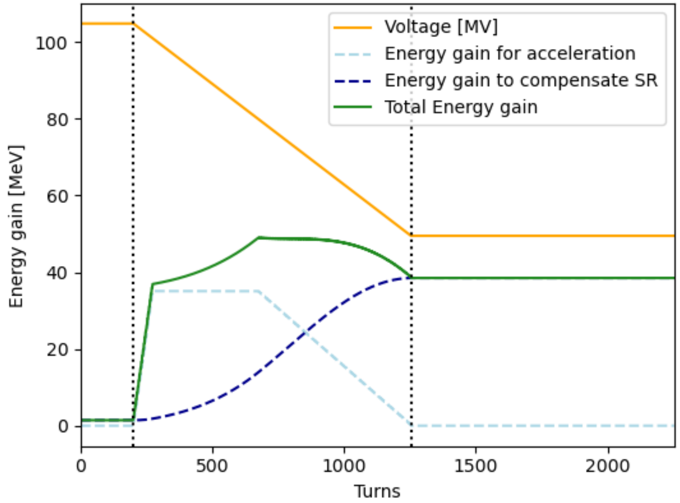
Synchronous phase dropping too quickly

The linear ramp does not work

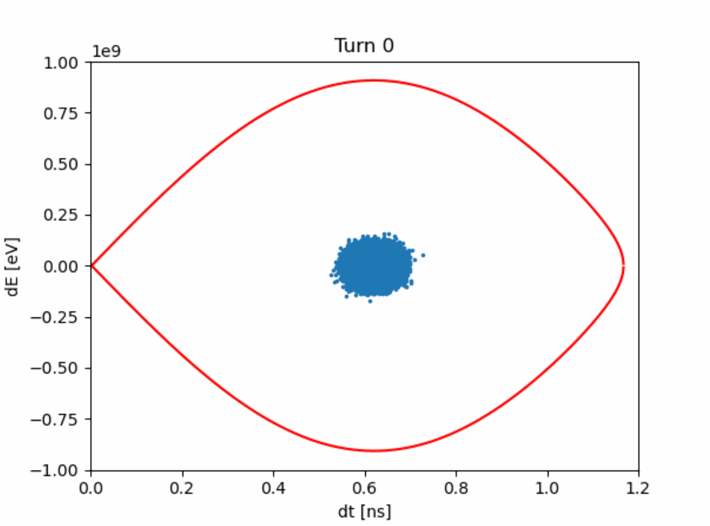
Preliminary solution with a double parabolic energy ramp and linear voltage

- Adiabatic start of the ramp (5% of initial energy gain)
- Steep linear energy ramp in the middle
- Adiabatic approach of the flat top energy (40% of total gain)

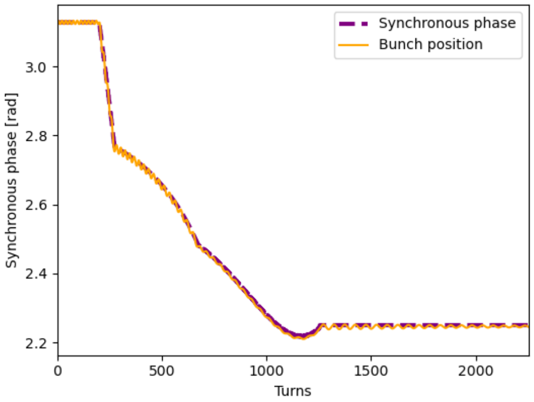


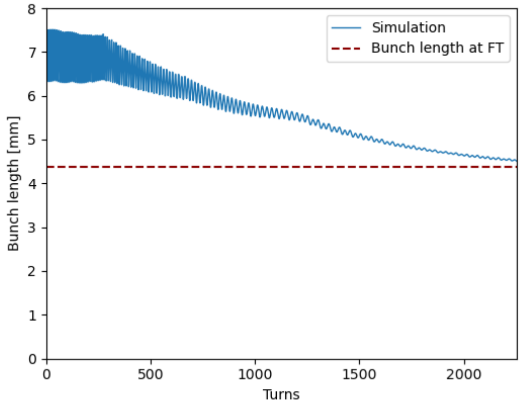


Preliminary solution with a double parabolic energy ramp and linear voltage



Slight mismatch during bunch generation, causing oscillations throughout the cycle.





Summary and outlook

- For the Z energy, a doubly parabolic ramp near the flat bottom and flat tops seems promising.
- We use a linear voltage program.
- We need to ensure that the steep linear energy ramp is possible (gain 14 GeV within 0.12 seconds).
- We must consider the power consumption during the ramp.
- We need to look into beam stability during the ramp.

Booster:
Coupled Bunch Instabilities (CBI) excited by High-Order Modes (HOM)

Coupled Bunched Instabilities due to HOMs:

Standard formulae for the shunt impedance threshold (only one sideband contributes) are:

$$Z_{\parallel}(f) = \frac{2E_b Q_s}{eI_b \eta \tau_{\parallel}} \frac{1}{f} \qquad Z_{\perp} = \frac{2E_b T_0}{eI_b \beta_{\perp} \tau_{\perp}}$$

- proportional to the energy
- inversely proportional to the current

Operating at low energy in the booster ring (20GeV) drives coupled bunched instabilities. What is the maximum current allowed in the booster ring at each working point? **The damping time τ can be acted upon to mitigate the threshold :** Will synchrotron radiation suffice to suppress transverse CBI due to HOMs or is a bunch-by-bunch feedback system required?

Synchrotron radiation determines the damping coefficient. The damping in the longitudinal plane is assumed to be twice as fast as the damping in the transverse plane:

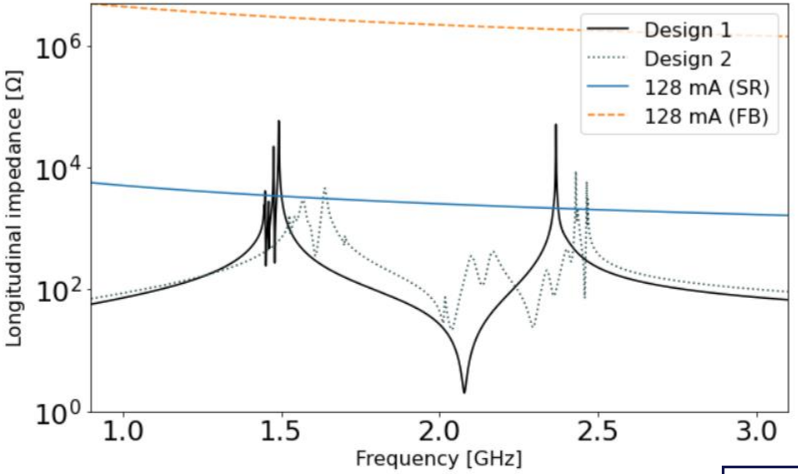
$$\tau_{\perp}^{SR} = 2\tau_{\parallel}^{SR}$$

In addition to the natural damping, a **multi-bunch feedback system** is often implemented. The damping term is taken to be:

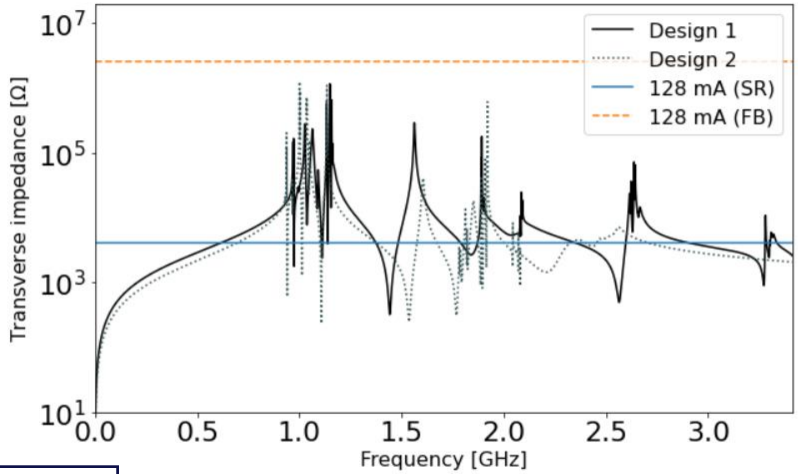
$$\tau_{\parallel}^{FB} = \frac{2T_0}{Q_s} \qquad \tau_{\perp}^{FB} = 100T_0$$

Z operation, $E = 20$ GeV, $I_{nominal} = 128$ mA, $f_{RF} = 800$ MHz – 5 cells

Longitudinal plane



Transverse plane



I_{max}	$\tau_{SR}^{\parallel}$ (=4.54s)	$\tau_{FB}^{\parallel}$ (=11ms)
Design 1	5.12 mA	4.48 A
Design 2	32 mA	27 A

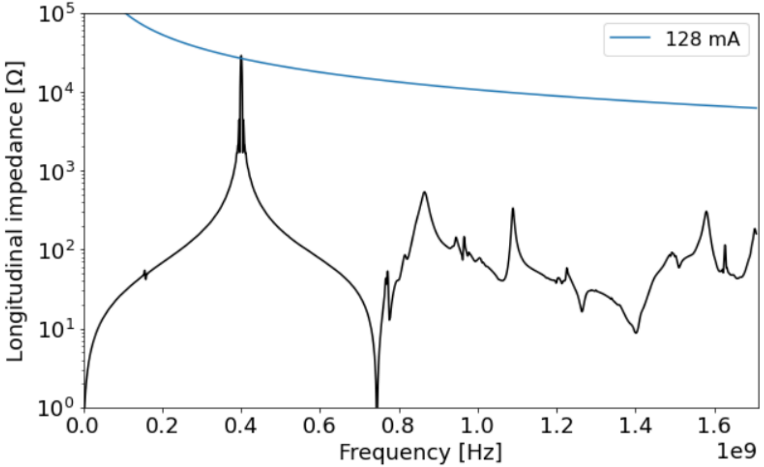
Design 1: Shahnam Z. Gorgi, current CDR scenario, UROS5
Design 2: Sosoho-Abasi Udongwo, C3795

I_{max}	$\tau_{SR}^{\perp}$ (=9s)	$\tau_{FB}^{\perp}$ (=30ms)
Design 1	0.453 mA	284 mA
Design 2	0.417 mA	261 mA

- Feedback system necessary for both designs in both longitudinal and transverse planes
- Design 2 better than design 1 by factor of 4 (similar in transverse plane)
- Can the longitudinal mode around 2.4 GHz be further damped ?

Z operation, $E = 20$ GeV, $I_{nominal} = 128$ mA, $f_{RF} = 400$ MHz – 2 cells

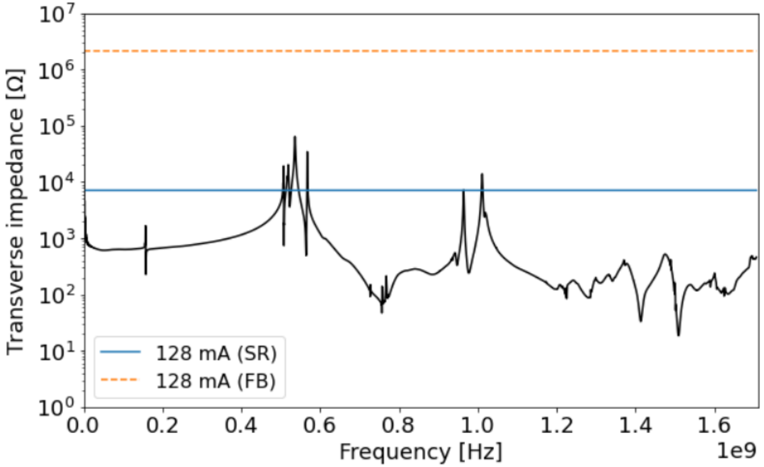
Longitudinal plane



I_{max}	$\tau_{SR}^{\|\|}$ (=4.54s)	$\tau_{FB}^{\|\|}$ (=11ms)
Design 3	896 mA	269 A

Design 3: Sosoho-Abasi Udongwo, C3794 (preliminary results with wakefield simulations)

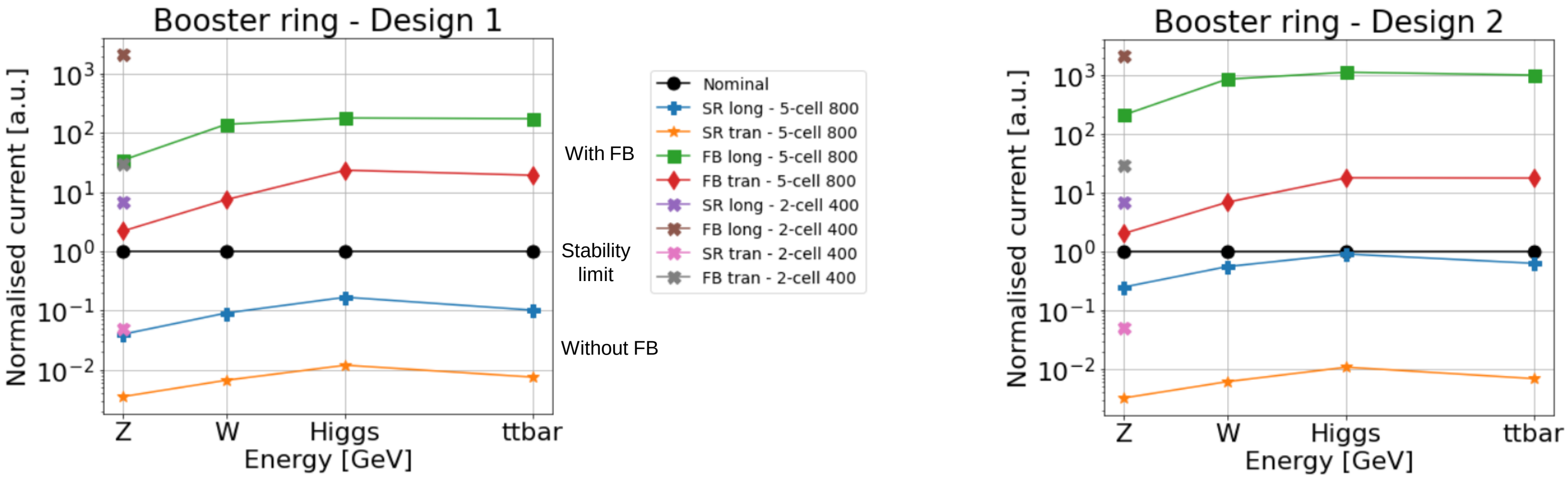
Transverse plane



I_{max}	$\tau_{SR}^{\perp}$ (=9s)	$\tau_{FB}^{\perp}$ (=30ms)
Design 3	6.40 mA	3.84 A

- A lot better than the 800 MHz – 5 cells design (FB system only required in the transverse plane)
- Is it worth adding a different RF system just for Z to avoid installing a longitudinal feedback system?

Comparison between designs 1 and 2:



- With the <u>800 MHz 5-cell cavities</u>, the multi-bunch feedback system is needed for all modes.
- The current feedback system is sufficient, but the margin is low at Z.
- With the <u>400 MHz 2-cell cavities</u>, for the Z operation, the multi-bunch feedback system is only necessary in the transverse plane.
- New design optimised for the HOM seems promising for the longitudinal plane.

Summary and outlook

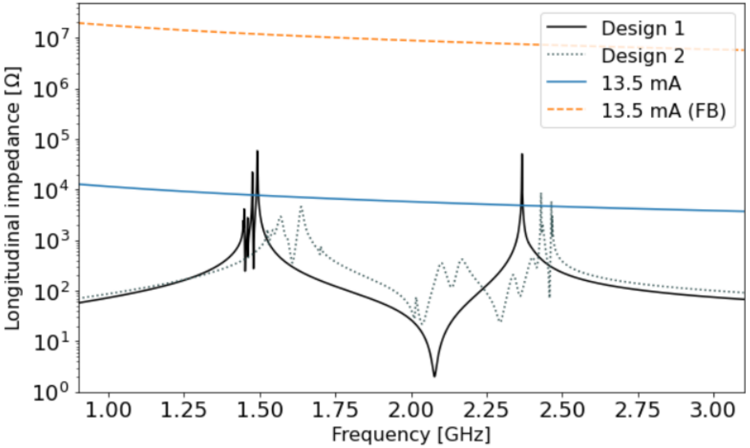
- Coupled bunched instabilities due to higher order modes are most critical at the Z energy, however the 2-cell 400MHz cavities allow higher currents. Is installing another RF system just for Z worth it? Is it easier than putting a feedback system for the longitudinal plane?
- Recent 5-cell designs from Rostock University look promising. Could the longitudinal mode around 2.4GHz be further damped?
- Feasibility of more aggressive transverse feedback should be explored (<100 turns).
- This analysis ensures stability at flat bottom. Considering the optimised voltage program that will be implemented for the ramp, we will need to run additional stability tests for CBI due to HOMs during the ramp.
- Further studies are critical to ensure feasibility of the present scheme:
    - Stability margins could be reduced due to fundamental mode impedance
    - RF power limits due to beam loading
    - Higher-order modes power losses

Thank you for your attention.

Additional Slides

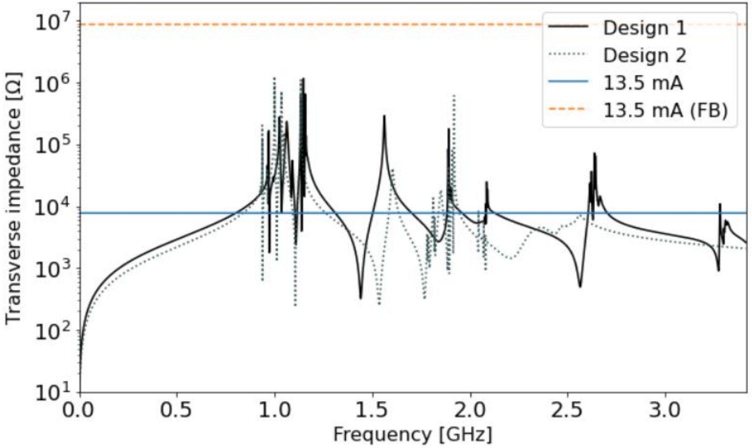
3.3. W operation, $E = 20$ GeV, $I_{nominal} = 13.5$ mA, $f_{RF} = 800$ MHz – 5 cells

Longitudinal plane



I_{max}	$\tau_{SR}^{\|\|}$ (=17s)	$\tau_{FB}^{\|\|}$ (=11ms)
Design 1	1.23 mA	1.89 A
Design 2	7.50 mA	11.5 A

Transverse plane



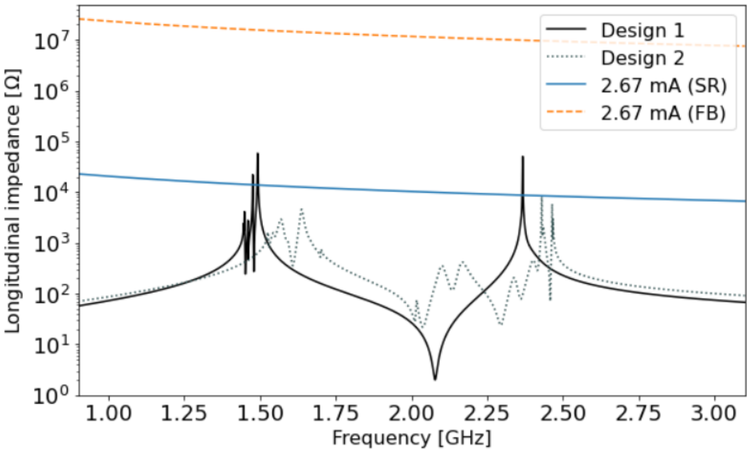
Design 1: Shahnam Z. Gorgi, current CDR scenario, UROS5
Design 2: Sosoho-Abasi Udongwo, C3795

I_{max}	$\tau_{SR}^{\perp}$ (=34s)	$\tau_{FB}^{\perp}$(=30ms)
Design 1	0.090 mA	101 mA
Design 2	0.083 mA	93 mA

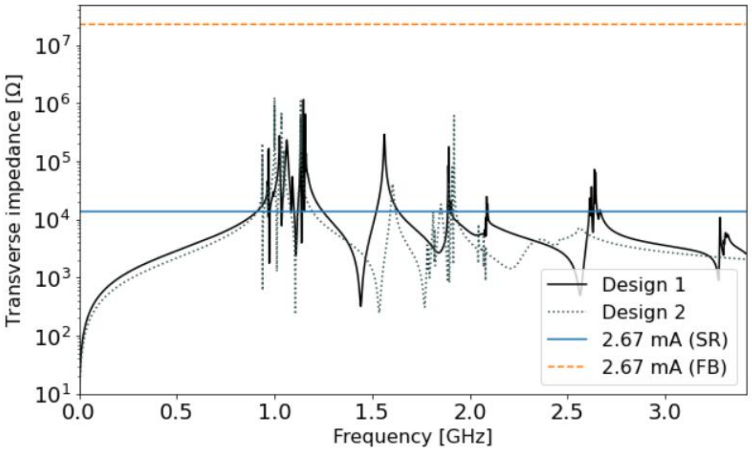
- Feedback system necessary for both designs in both longitudinal and transverse planes
- Design 2 better than design 1 by factor of 5 in the longitudinal plane (similar performances in the transverse plane)

3.3. **H** operation, $E = 20$ GeV, $I_{nominal} = 2.67$ mA, $f_{RF} = 800$ MHz – 5 cells

Longitudinal plane



Transverse plane



I_{max}	$\tau_{SR}^{\|\|}$ (=25s)	$\tau_{FB}^{\|\|}$ (=22ms)
Design 1	0.45 mA	0.48 A
Design 2	2.43 mA	2.99 A

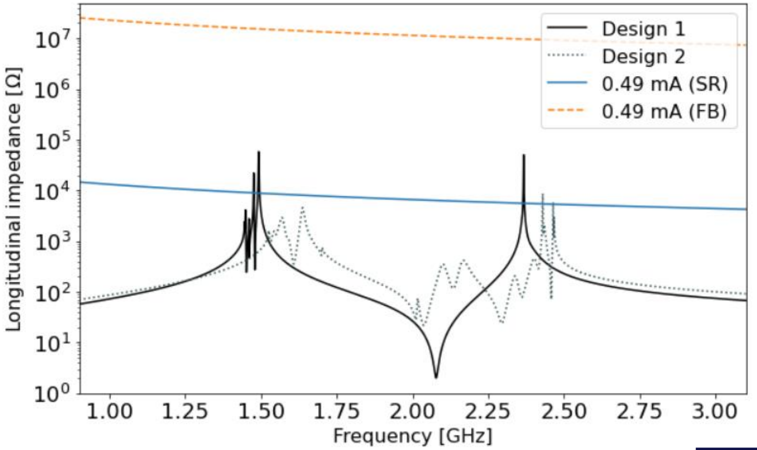
Design 1: Shahnam Z. Gorgi, current CDR scenario, UROS5
Design 2: Sosoho-Abasi Udongwo, C3795

I_{max}	$\tau_{SR}^{\perp}$ (=50s)	$\tau_{FB}^{\perp}$(=30ms)
Design 1	0.032 mA	63 mA
Design 2	0.029 mA	48 mA

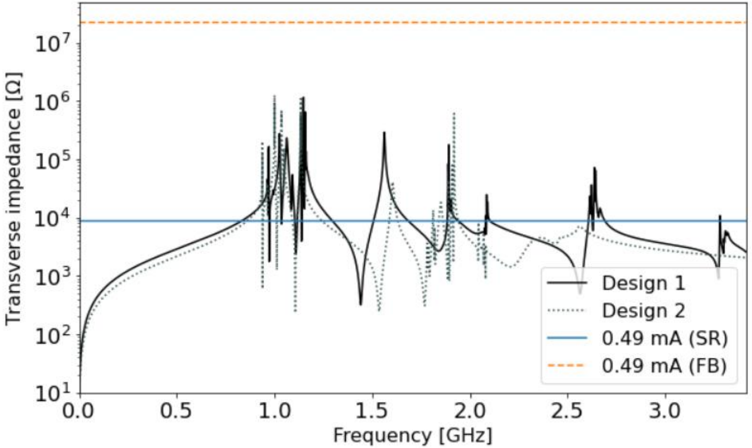
- Feedback system necessary for both designs in both longitudinal and transverse planes
- Design 2 better than design 1 by factor of 5 in the longitudinal plane (similar performances in the transverse plane)

3.3. tt operation, $E = 20$ GeV, $I_{nominal} = 0.49$ mA, $f_{RF} = 800$ MHz – 5 cells

Longitudinal plane



Transverse plane



I_{max}	$\tau_{SR}^{\parallel}$ (=38s)	$\tau_{FB}^{\parallel}$ (=22ms)
Design 1	0.05 mA	85.7 mA
Design 2	0.31 mA	0.49 A

Design 1: Shahnam Z. Gorgi, current CDR scenario, UROS5
Design 2: Sosoho-Abasi Udongwo, C3795

I_{max}	$\tau_{SR}^{\perp}$ (=77s)	$\tau_{FB}^{\perp}$(=30ms)
Design 1	0.0037 mA	9.5 mA
Design 2	0.0034 mA	8.7 mA

- Feedback system necessary for both designs in both longitudinal and transverse planes
- Design 2 better than design 1 by factor of 5 in the longitudinal plane (similar performances in the transverse plane)