BEAM DYNAMICS AND RF REQUIREMENTS FOR THE HIGH-ENERGY BOOSTER

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Acknowledgments: Elleanor Lamb, Luke von Freeden, Yann Dutheil, …

Outline

- **Introduction**
- **Energy ramps for ZH, WW and $t\bar{t}$**
- **Requirements for Z mode**
- **Conclusion**

Changes from FCC week 2024

Energy ramps for the high-energy booster

Motivation: Optimization of the energy and voltage ramps for all four modes, including Reverse Phase Operation (RPO)*, homogenize dynamic losses and reduce RF requirements.

- **Analytical tools** to compute the energy and voltage ramps of the high-energy booster
- **Faster optimization** including dynamic effects.
- Single bunch, no intensity effect, no beam loading

Booster operation mode selected parameters

	Z	WW	ZH	ttbar
Characteristics of the ramp				
Injection energy [GeV]	20			
Extraction energy [GeV]	45.2	80	120	182.5
Accumulation time [s]	2.8	2.32	3.0	0.64
Total ramping time [s]	1.0 (**1.14s**)	1.6	2.6	4.3
Cycle length [s]	3.8	3.92	5.6	4.94
Bunches per cycle	1120	928	300	64
Number of cavities	112	112	112	112 + 336
Extraction requirements**				
$(\varepsilon_x, \varepsilon_y)$ [nm.rad, pm.rad]	(0.12, 10)	(0.27, 5)	(0.6, 12)	(1.4, 28)
Energy spread σ_E	$0.38 * 10^{-4}$	$0.67 * 10^{-4}$	$1 * 10^{-4}$	$1.5 * 10^{-4}$
RMS bunch length [mm]	2.43	2.56	2.26	2

* I. Karpov, FCC week 2025, 21/05/2025

** Specified by Y. Dutheil, FCCee injectors parameters - Google Sheets and presented in 3rd Meeting of the FCC-ee Layout and Optics Design (30 avril 2025) · Indico

ENERGY RAMPS FOR ALL MODES

Energy ramp proposal for ZH, WW and $t\bar{t}$

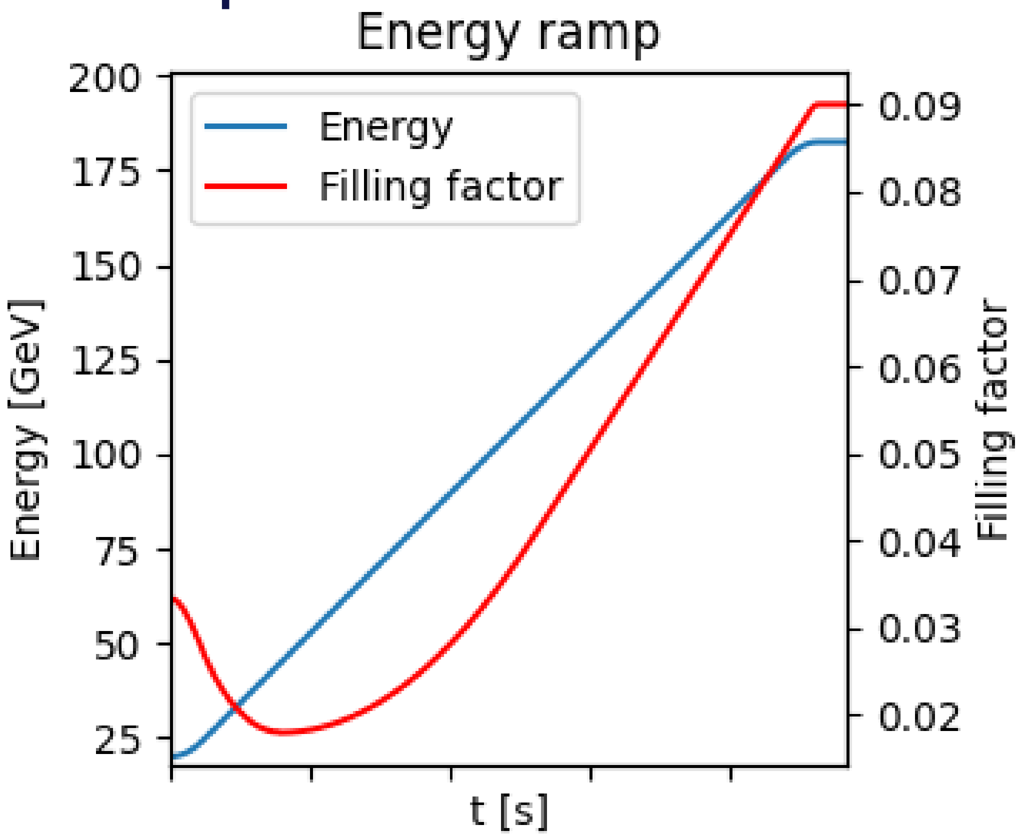
“Double parabolic” energy ramps

- Double parabolic for adiabatic acceleration at the start and end of the ramp
- Energy gain dominated by the compensation of synchrotron radiation losses
- Larger filling factor at the beginning of the ramp for ‘adiabatic capture’

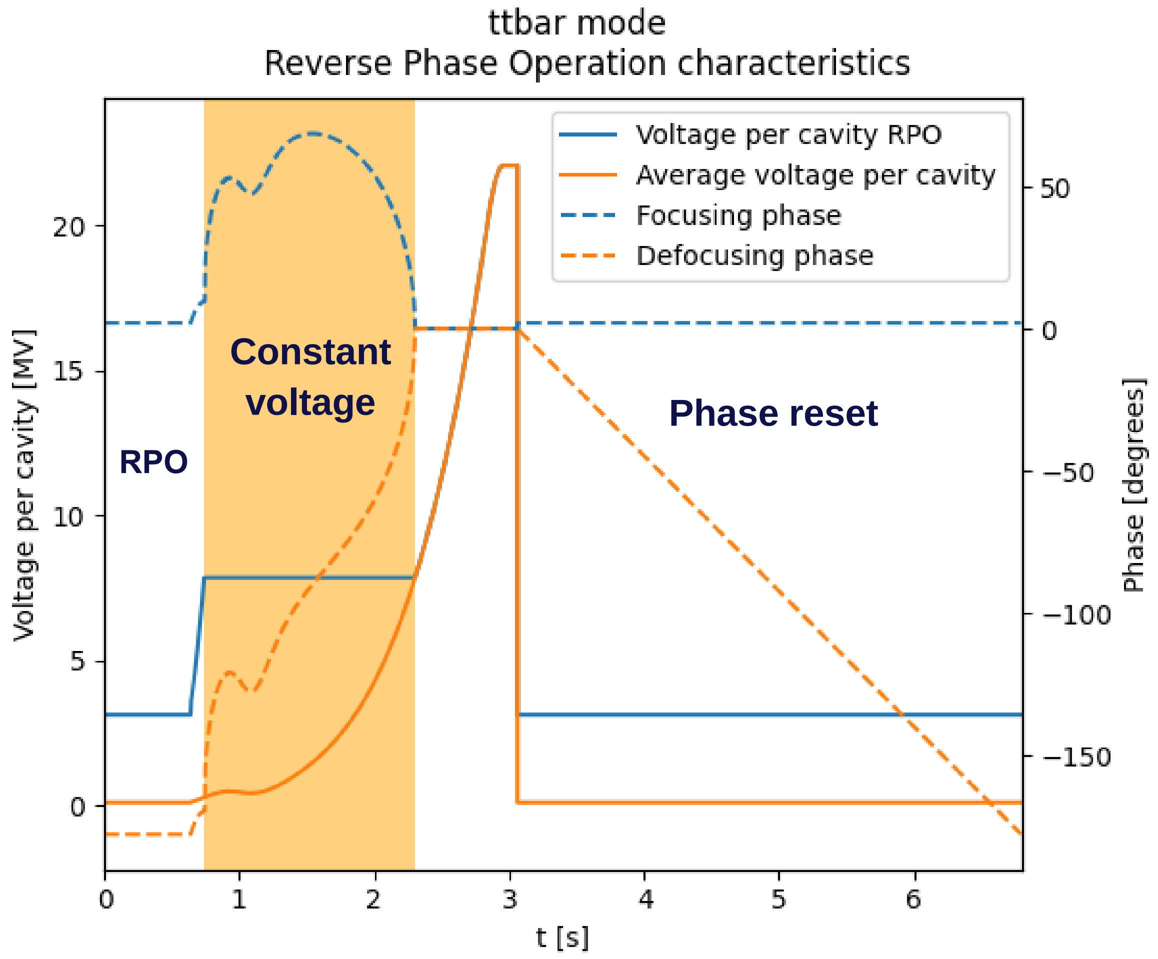
Natural transverse emittances and natural energy spread reached by the end of the ramp

Voltage at flat top **adjusted to match bunch length requirements**

Example of $t\bar{t}$



Voltage per cavity with Reverse Phase Operation



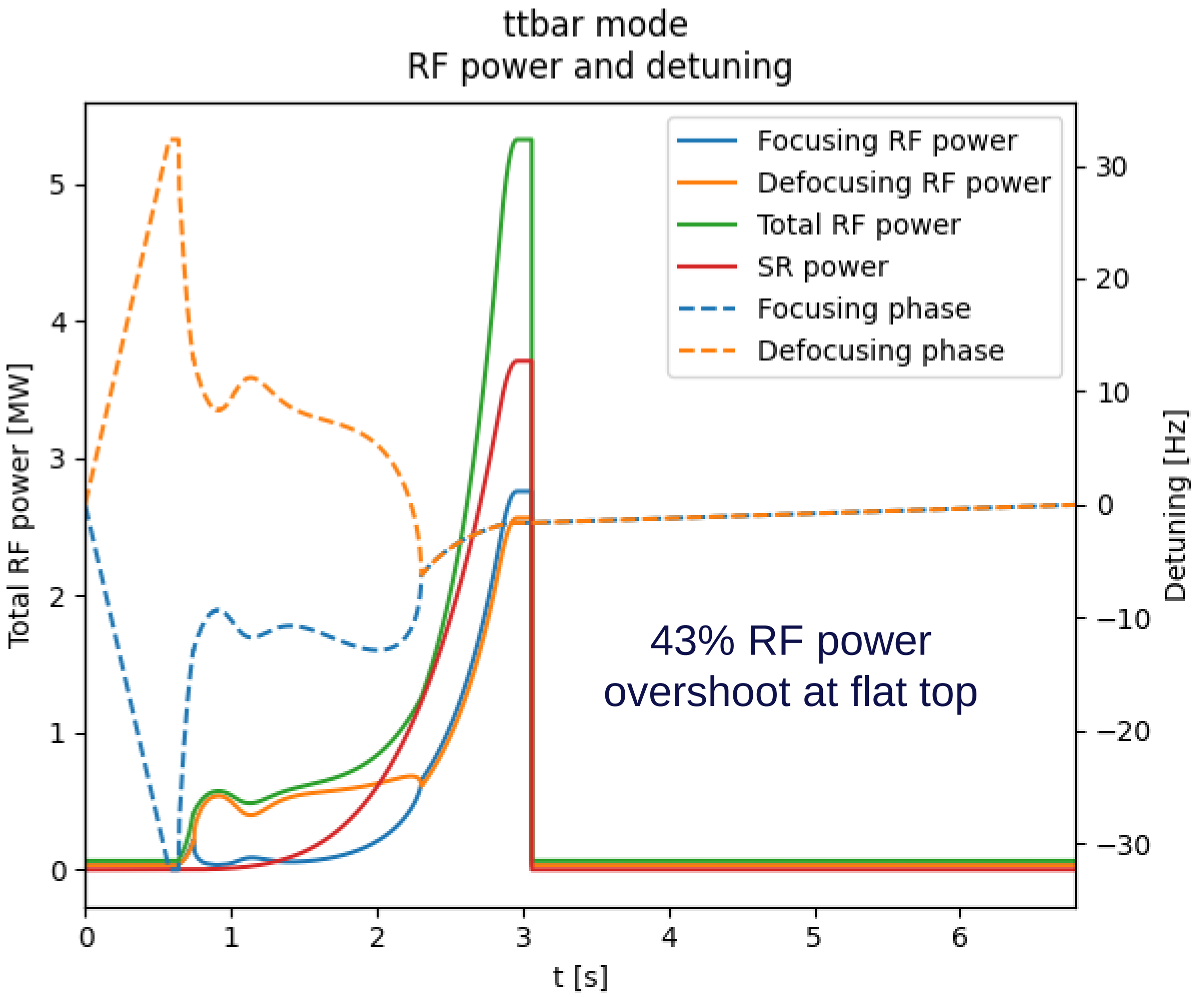
Voltage per cavity during the ramp ($t\bar{t}$)

- Reverse Phase Operation* to maintain a minimum voltage per cavity $\left(V_{cav}^{min} \approx 2\ \mathrm{MV}\right)$**
- $\Delta N = N_f - N_d = 16$ between focusing and defocusing cavities

Calculation quantities		
R/Q		$315.2\ \Omega$
Q***	Z, WW, ZH	10^7
	$t\bar{t}$	$2.7 * 10^7$
Q_0	$3 * 10^{10}$	

* I. Karpov, FCC_optics_meeting_08082024_IK.pdf
** S. Gorgi Zadeh, FM passband
*** I. Karpov, FCC_optics_meeting_27022025_IK.pdf

RF power requirements for $t\bar{t}$ mode



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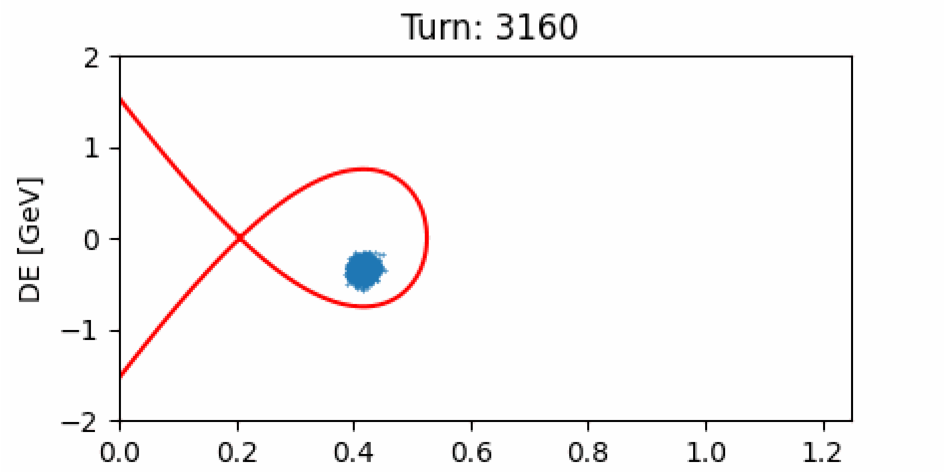
Injection error in the booster: WW ramp

Acceleration of an early-injected bunch

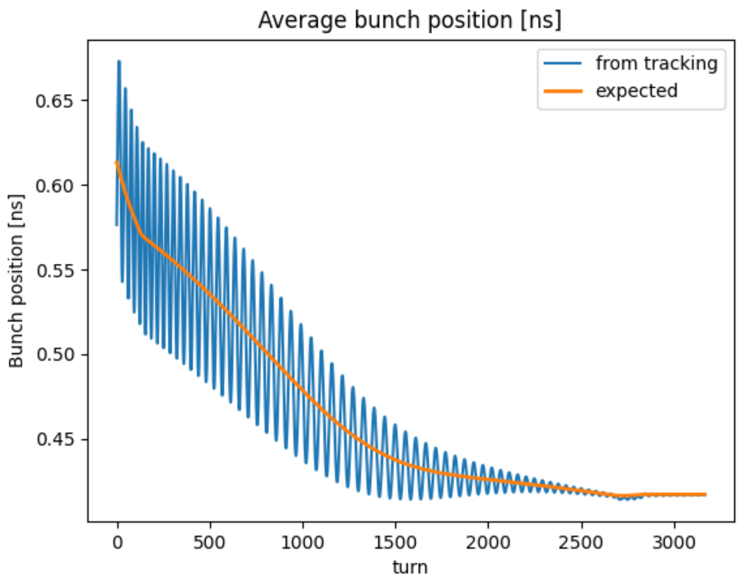
Maximum jitter implemented in the BLonD simulation of the acceleration:

- 50ps time jitter
- $3 * 10^{-3}$ relative energy error

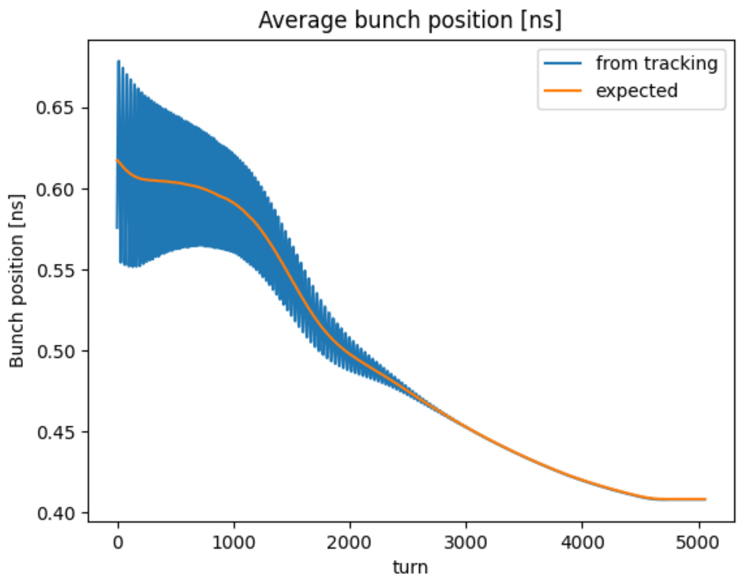
No remaining oscillations by extraction



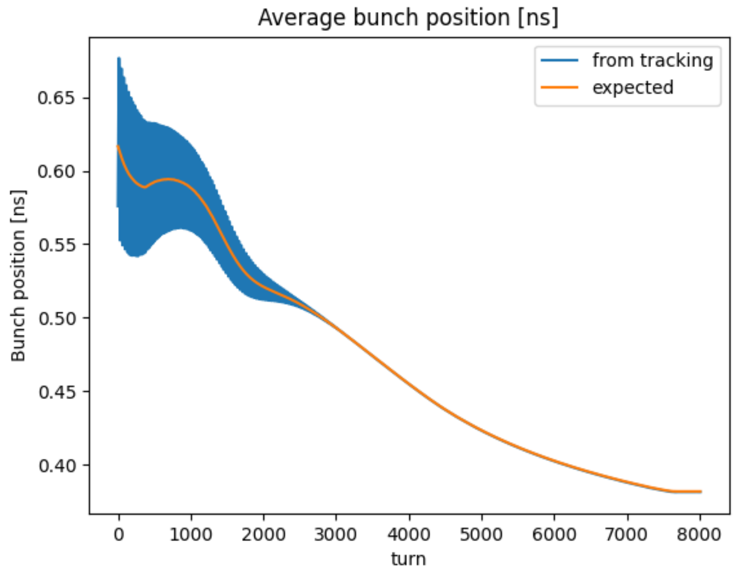
WW



ZH



$t\bar{t}$



BOOSTER RAMPING STRATEGIES FOR Z MODE

Booster ramping strategies for Z mode

Maximum energy gain: 100 GeV/s

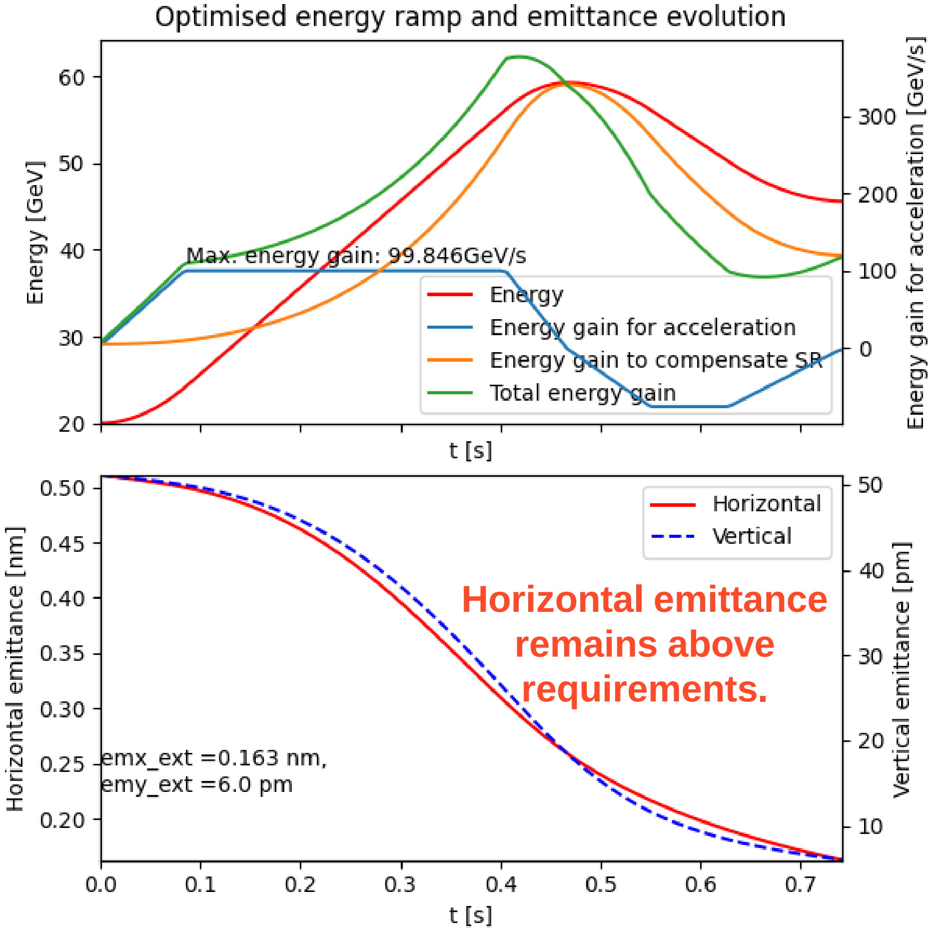
Transverse emittances requirements at extraction energy (45.6 GeV)*:

$$\varepsilon_{x,RMS} = 0.12 \text{ nm.rad} \times \varepsilon_{y,RMS} < 10 \text{ pm.rad}$$
and $\sigma_E = 0.38 * 10^{-3}$

Acceleration during 0,7s (total cycle 1/1.14s) for large damping times.

Damping times	20 GeV	45.6 GeV
$\tau_x, \tau_y(s)$	9.05	0.74
$\tau_z(s)$	4.52	0.37

A boost of synchrotron radiation is required to reach the target beam sizes at extraction.



Optimized overshoot energy ramp with Particle Swarm Optimization (PSO) for lower transverse emittances at extraction**

* Specified by Y. Dutheil, FCCee injectors parameters - Google Sheets and presented in 3rd Meeting of the FCC-ee Layout and Optics Design (30 avril 2025) · Indico
** L.Valle, FCC_WP1_25_03_2025.pdf

Booster ramping strategies for Z mode

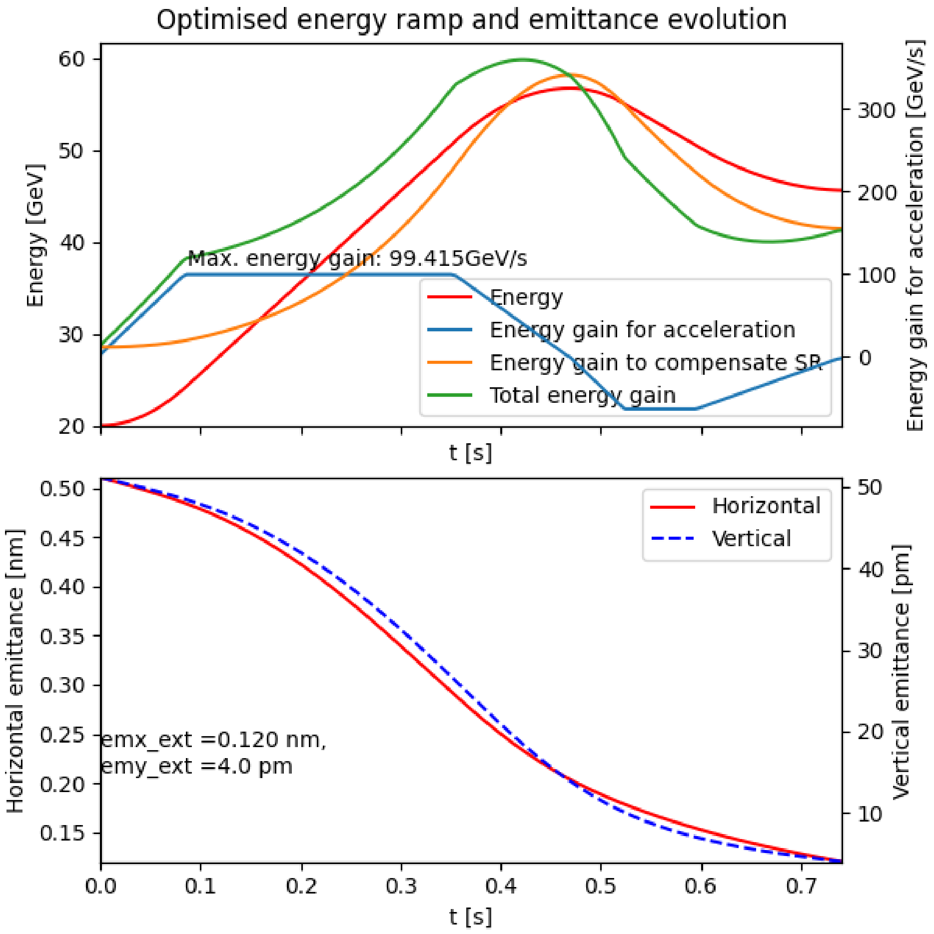
Maximum energy gain: 100 GeV/s

Adding damping wigglers…

Already considered for stability considerations at injection. *

First approach: $n_w = 2$ wigglers of constant magnetic field (1T), 4.925m long, 43 95mm-long poles, gap of 20mm (collider specifications)

Natural energy spread at 45.6 GeV blows up from $\mathbf{0.38 * 10^{-3}}$ to $\mathbf{1.11 * 10^{-3}}$ ($n_w = 1$) or $\mathbf{1.44 * 10^{-3}}$ ($n_w = 2$)



Optimized overshoot energy ramp with Particle Swarm Optimization (PSO) including two damping wigglers**

* S. Gorgi Zadeh, FM passband
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Booster ramping strategies for Z mode

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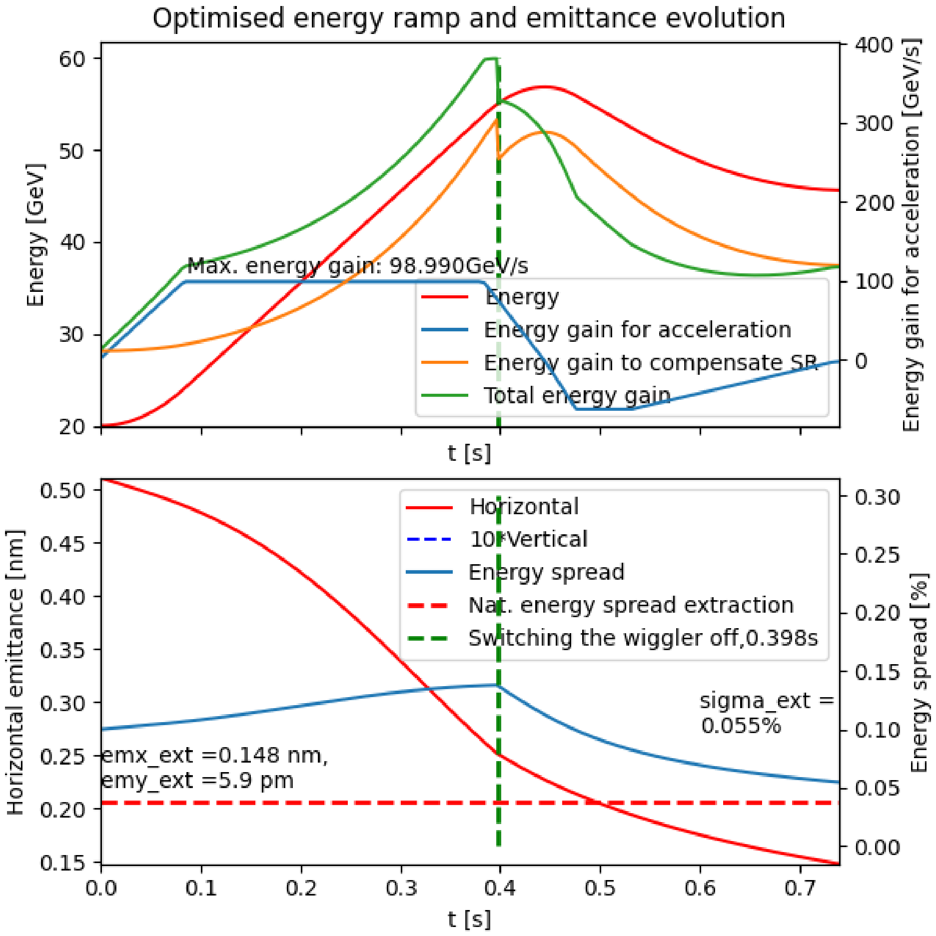
Idea: Switch the wigglers off during the ramp to restore the expected natural energy spread or move the beam away from the wiggler.
Acceleration and deceleration in 1.14s

Getting closer to the target parameters.
Wiggler parameters to be optimized.



Optimized overshoot energy ramp with Particle Swarm Optimization (PSO) including two damping wigglers disabled during the ramp**

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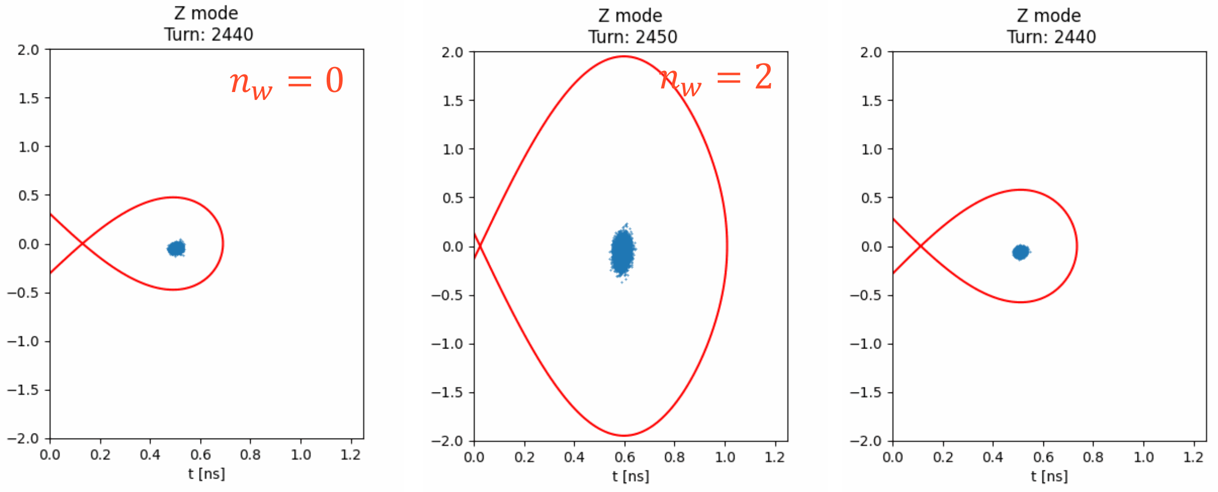
Injection error in the booster: Z ramp

Acceleration of an early-injected bunch

Maximum jitter implemented in the BLonD simulation of the acceleration:

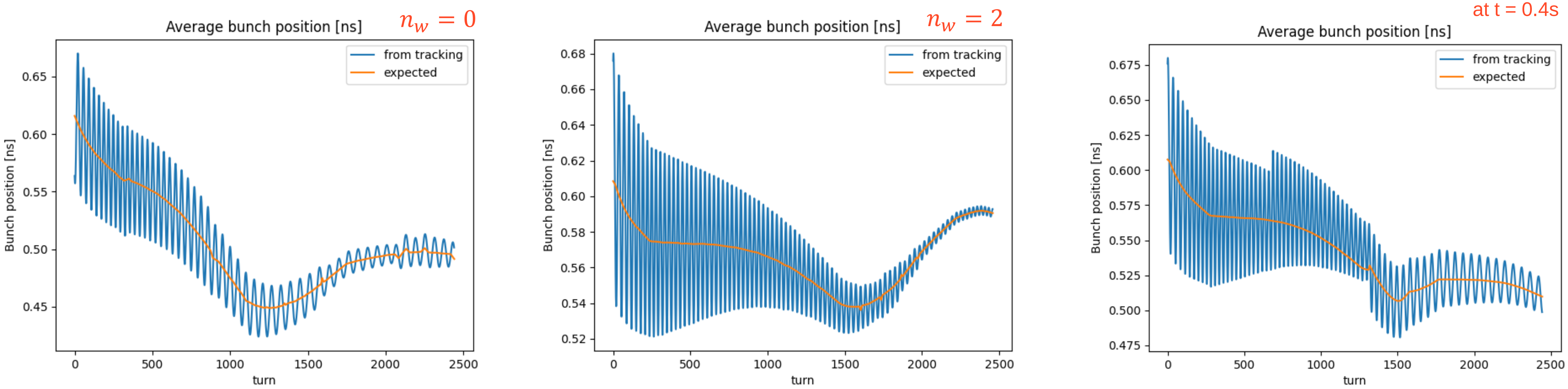
- 50ps time jitter
- $3 * 10^{-3}$ relative energy error

Slight oscillations remaining at extraction, almost fully damped with the wigglers.

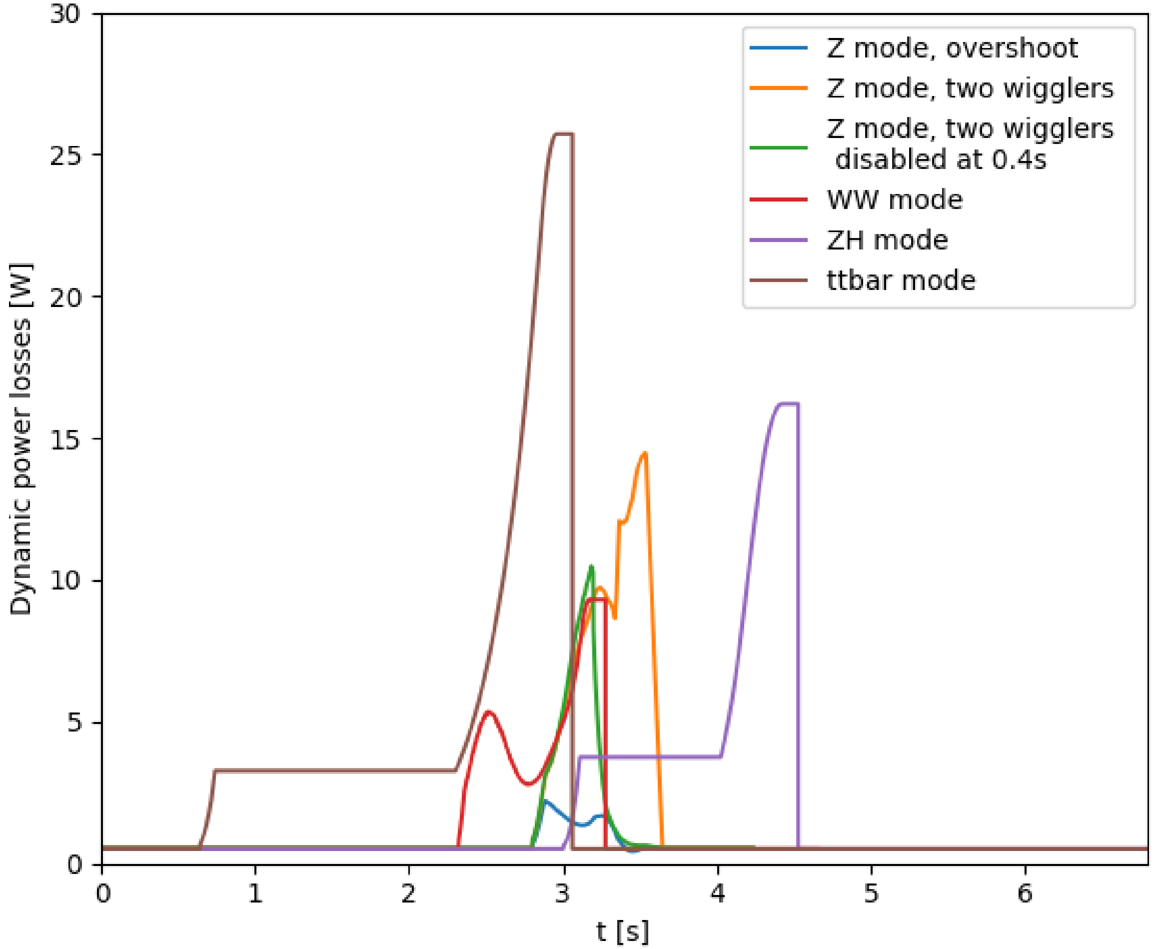


led

at t = 0.4s



Dynamic losses for cryogenics of all presented ramps



Dynamic power losses during a total cycle

	Z	WW	ZH	ttbar
Peak [W]	…	9.29	16.2	25.7
Average [W]	…	4.54	5.9	6.4
Duty factor (average/peak)	…	0.49	0.37	0.25

Dynamic power losses for shown Z mode energy ramps

	SE	$n_w = 0$	$n_w = 2$	$n_w = 2$, disabled at 0.4s	…
Peak [W]	1.3	2.2	14.5	10.5	
Average [W]	0.57	1.2	7.4	3.6	
Duty factor (average/peak)	0.44	0.54	0.51	0.34	

Conclusions

Summary

- Analytical tools to compute the energy and voltage ramps of the high-energy booster
- Faster optimization including dynamic effects. Ongoing process
- Single bunch, no intensity effect, no beam loading
- Double parabolic energy ramps ZH, WW and $t\bar{t}$ modes
- Longitudinal simulations including jitters for all modes
- Different methods were explored to reach the beam sizes requirements at extraction for Z mode

Next steps…

Further optimisation of all energy ramps to homogenise RF requirements through all modes

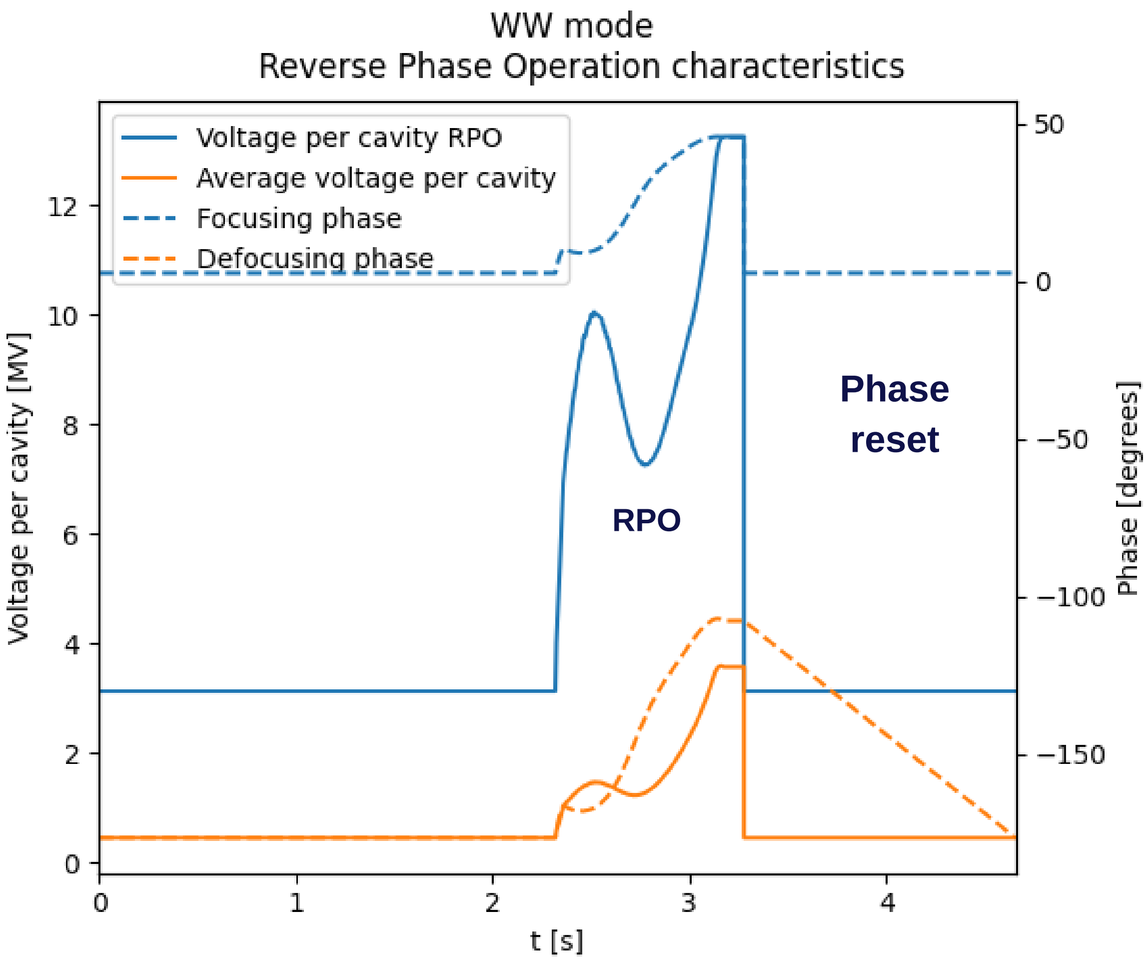
Study **RF power transient** during injection in the booster

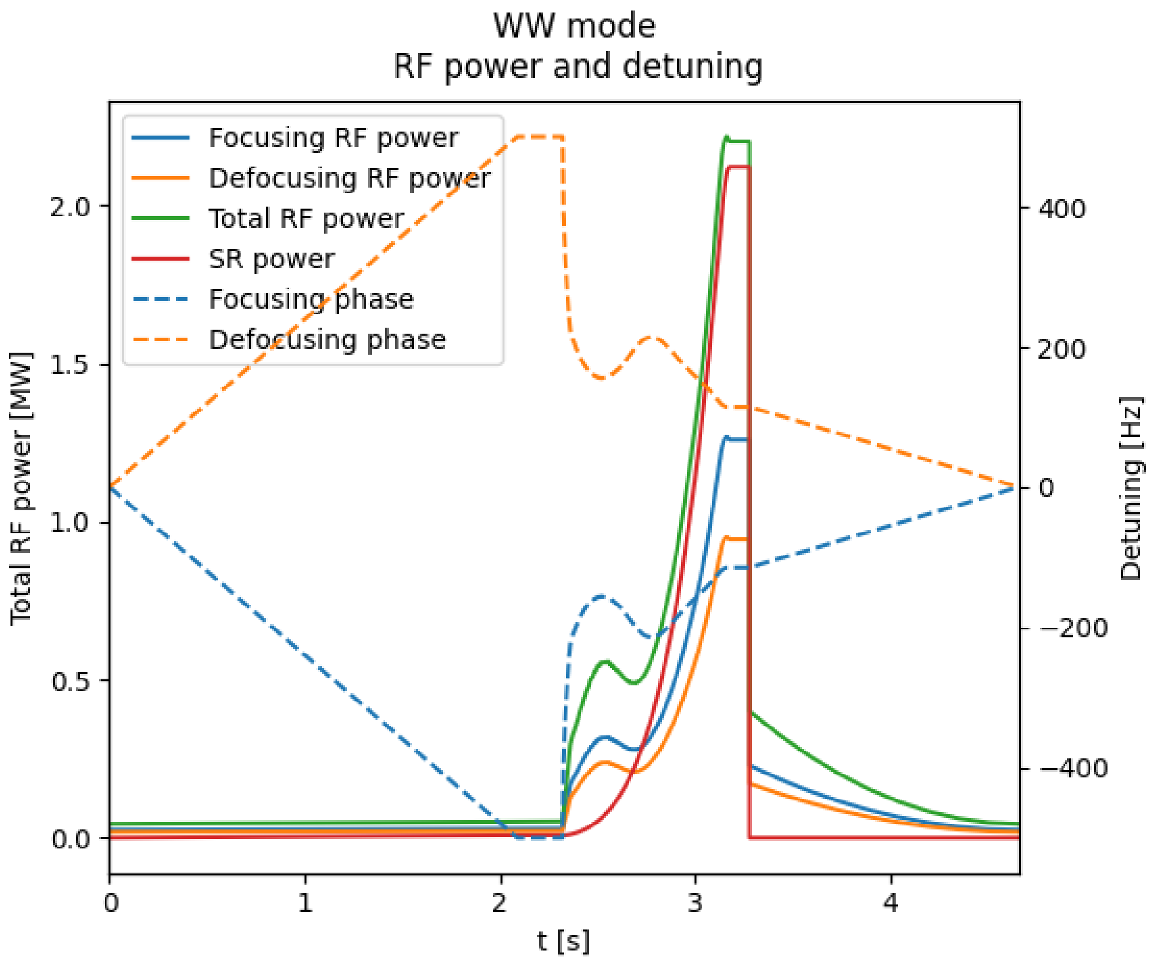
Energy ramp for Z mode in progress.

- Overshoot energy to be mitigated with maximum energy gain,
- Damping wigglers requirements to meet the extraction targets to be determined,
- Bunch rotation at flat top to transfer energy spread into bunch length,

THANK YOU

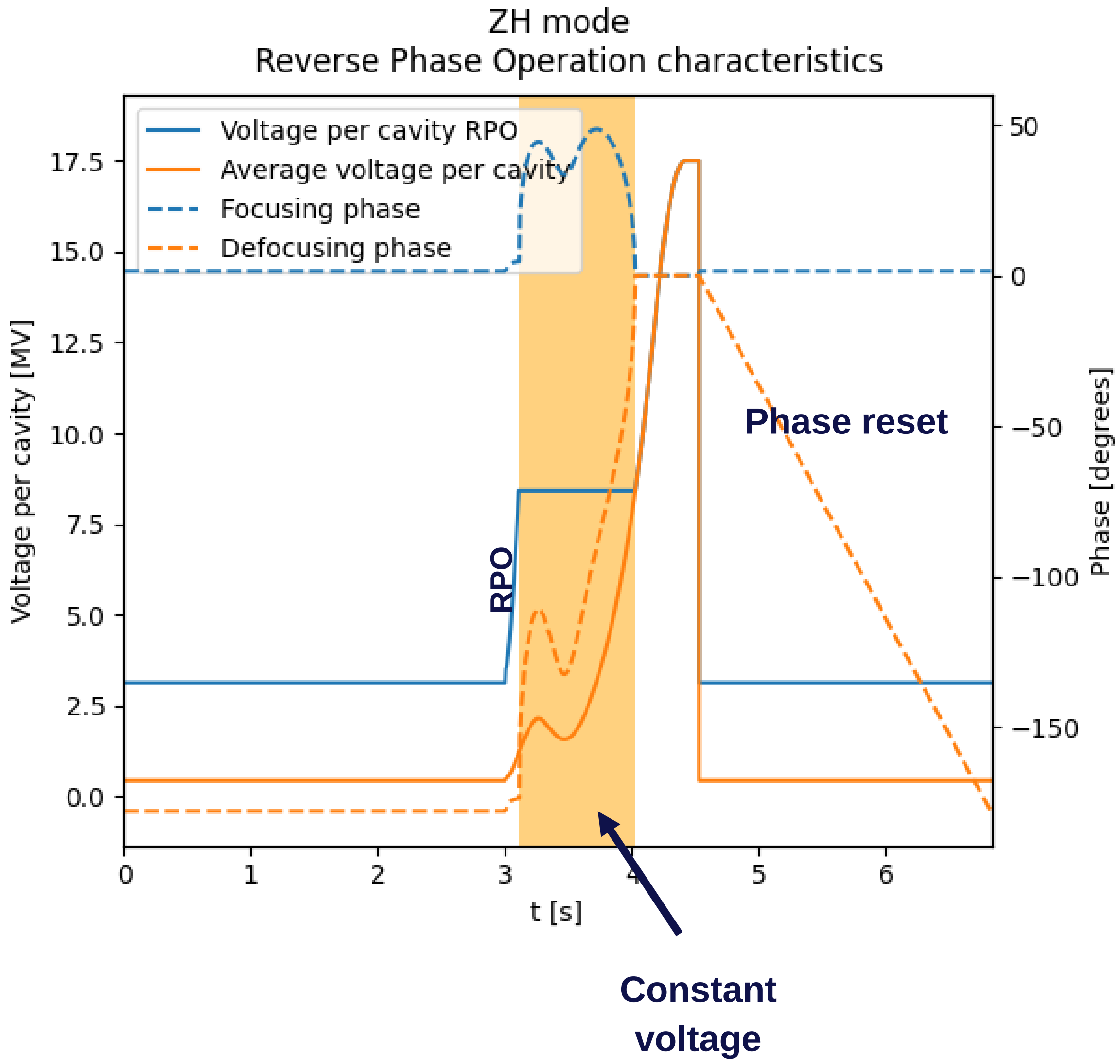
WW voltage per cavity for RPO and RF power

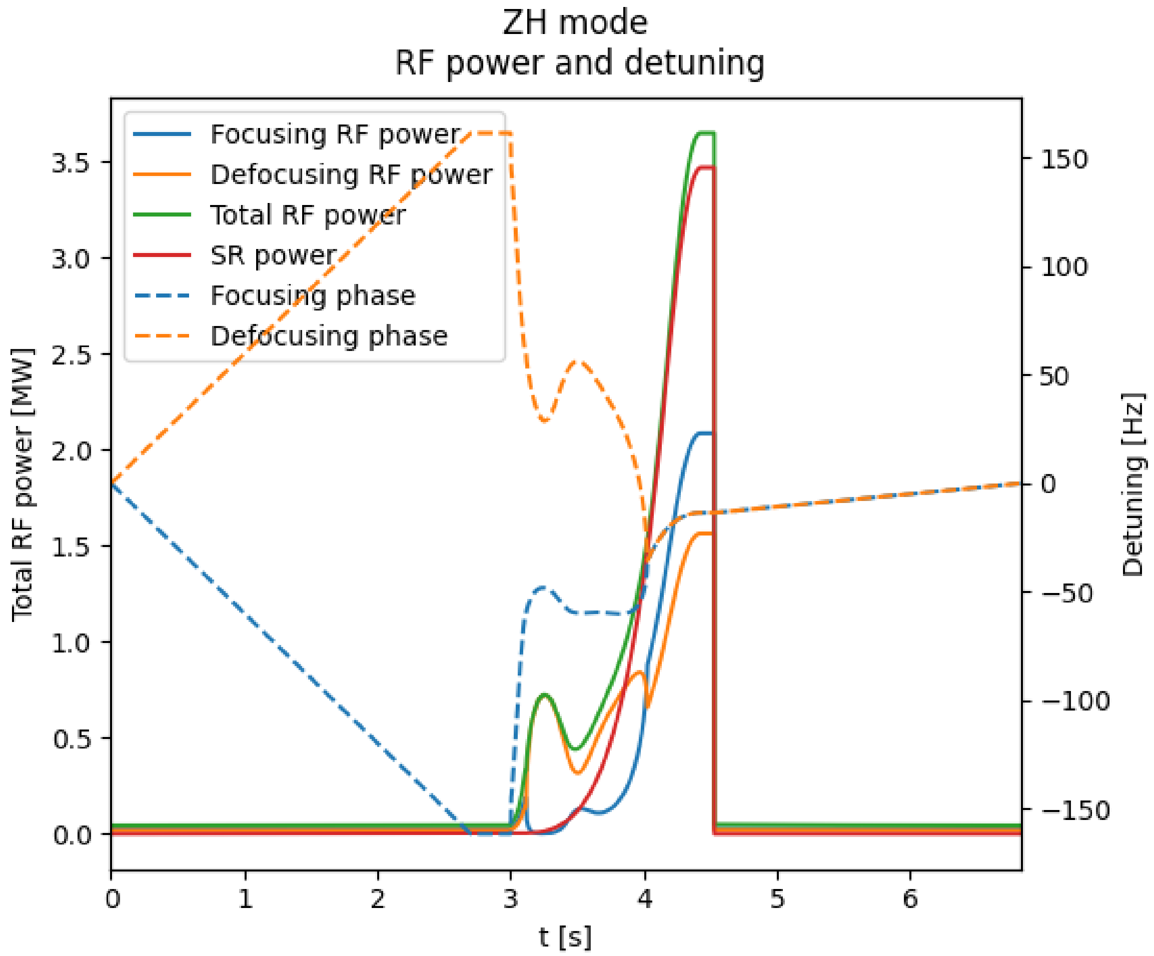




4.5% RF power overshoot at flat top

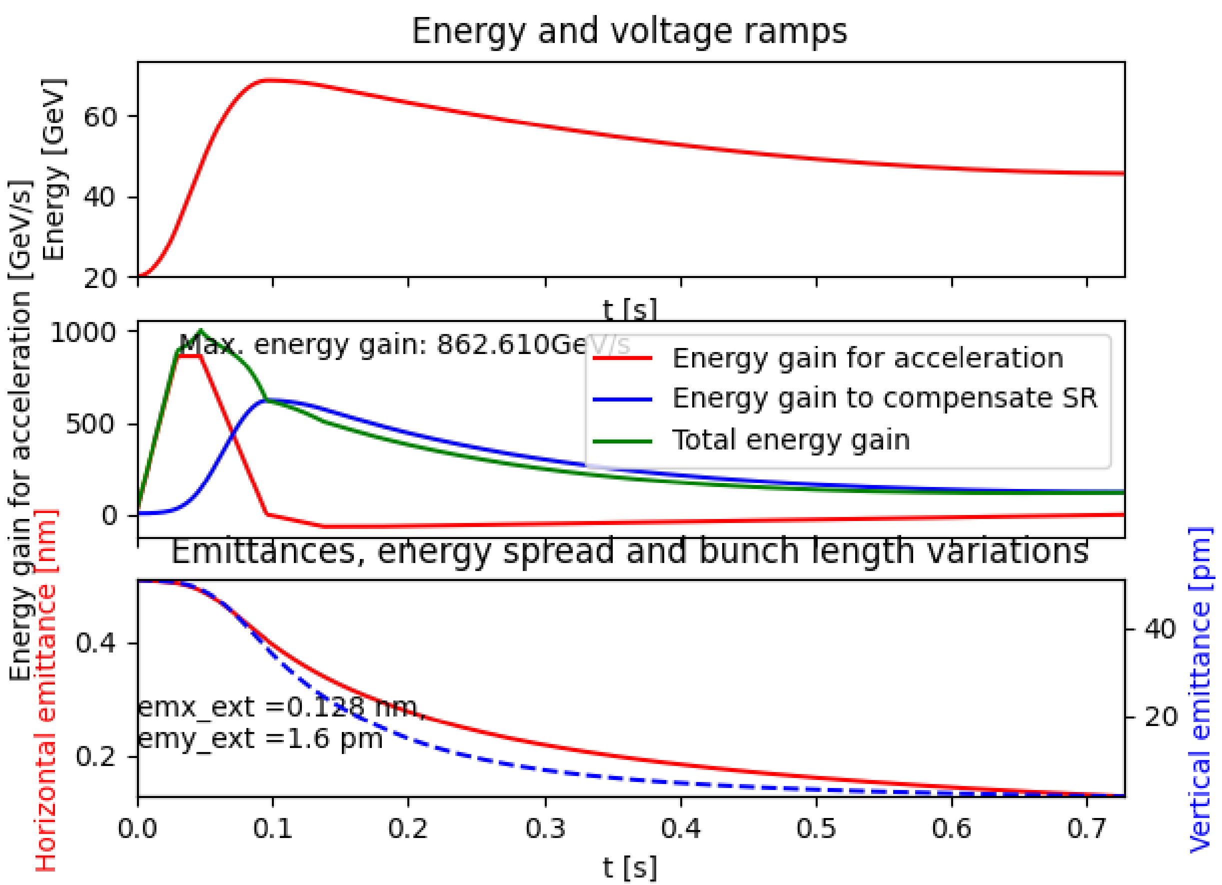
ZH voltage per cavity for RPO and RF power





5% RF power overshoot at flat top

Z mode overshoot



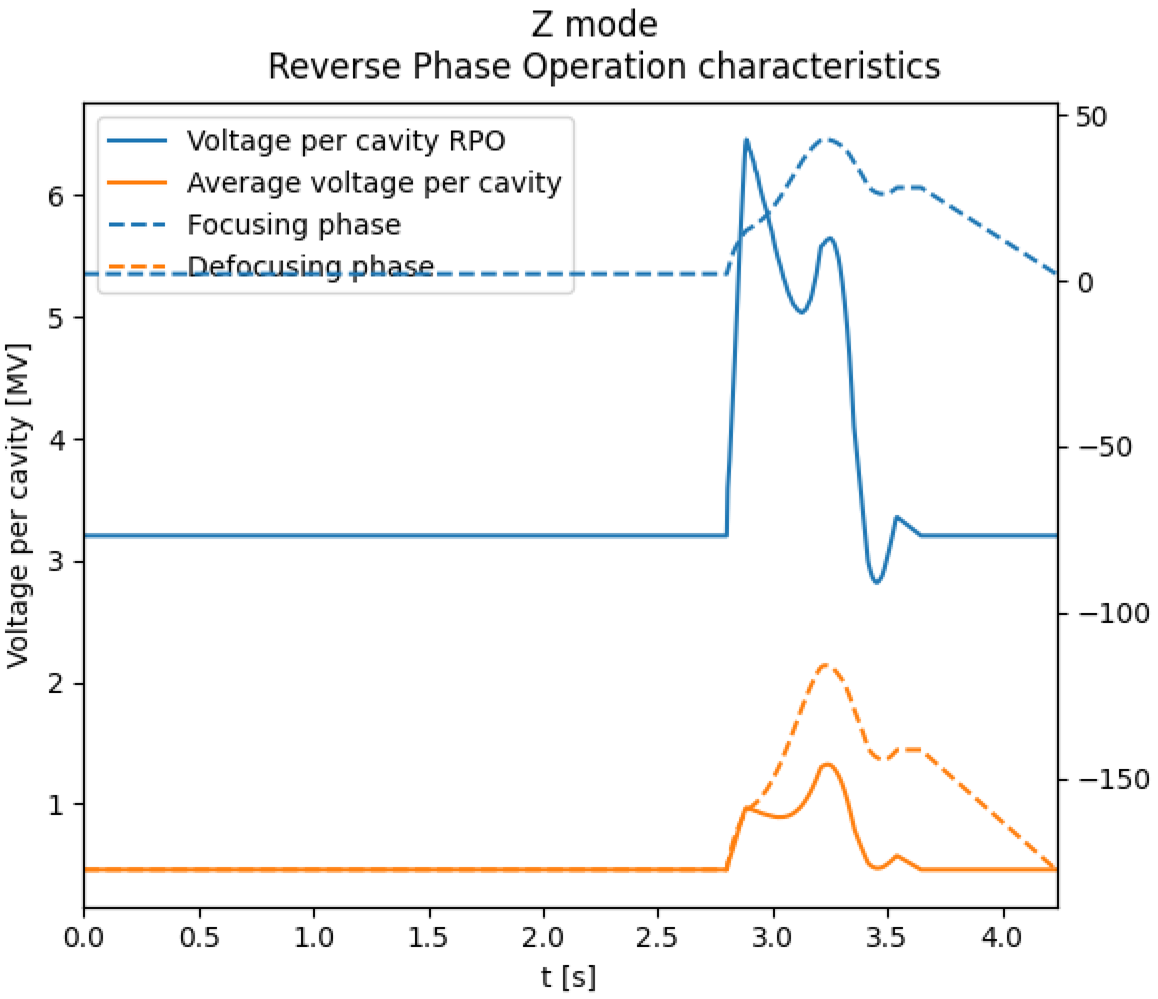
Overshoot energy ramp could meet the requirements on the extraction transverse emittance…

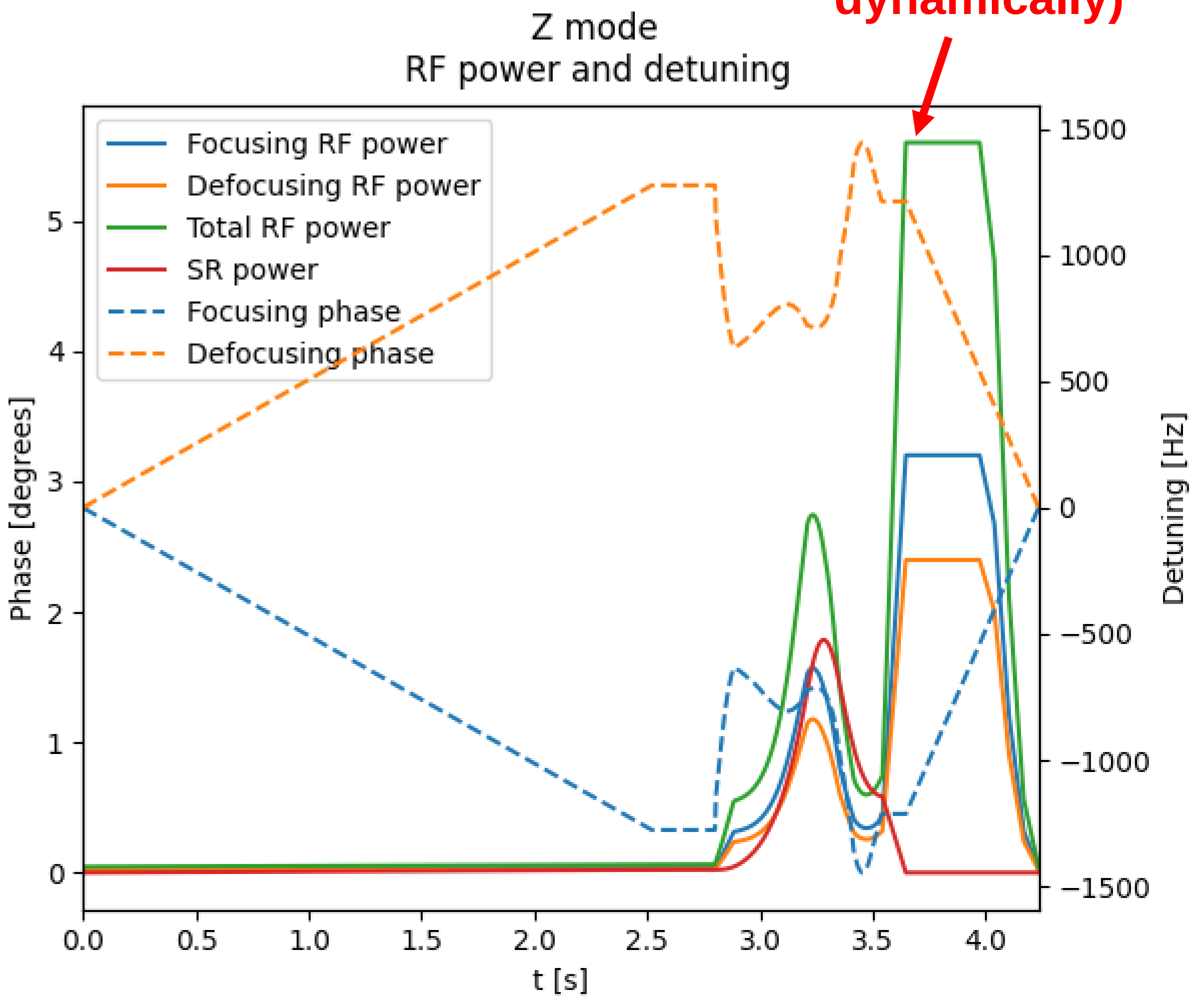
with at least 850 GeV/s energy gain in less than 0.05s!

Z voltage per cavity for RPO and RF power

Optimized overshoot, no wigglers

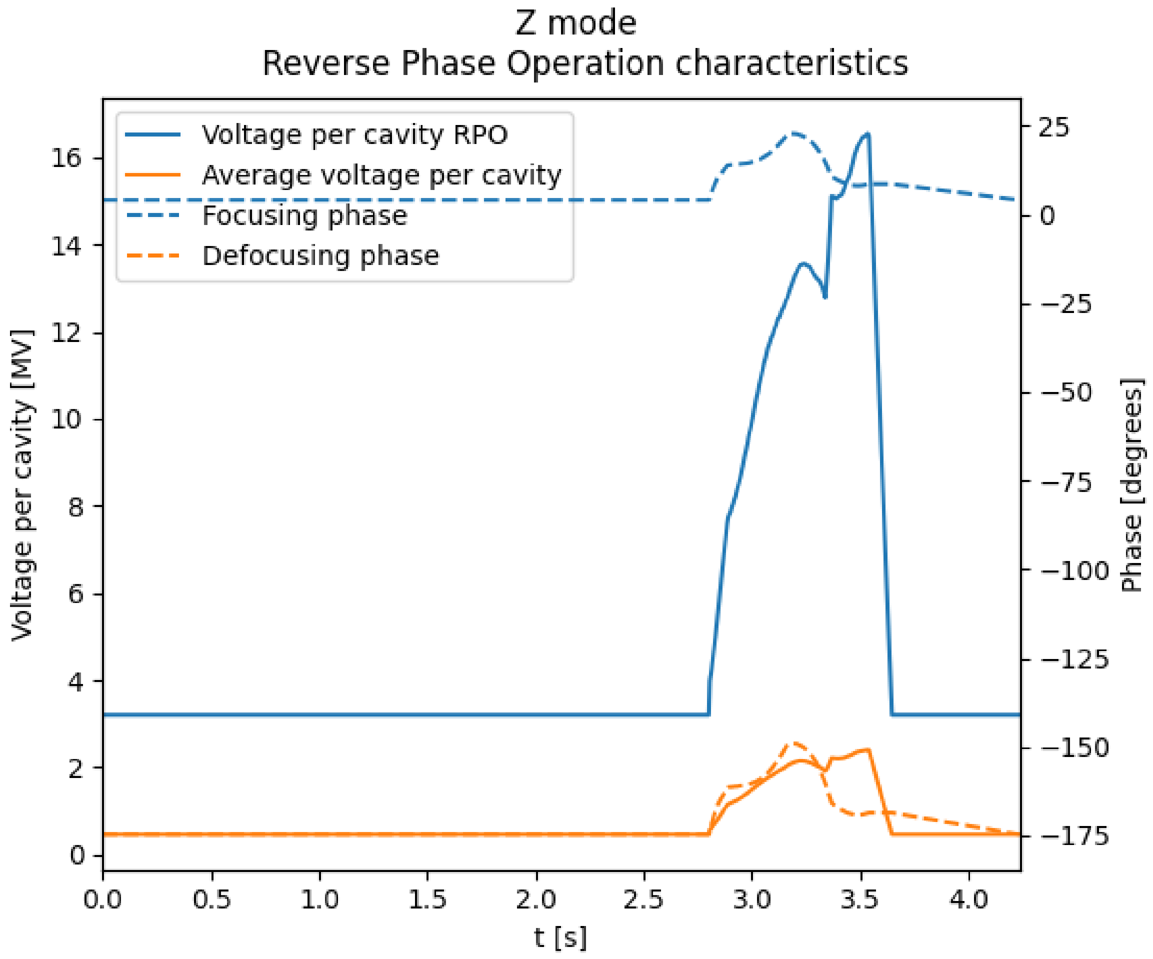
Clamp at 50kW per cavity (overshot to be verified dynamically)

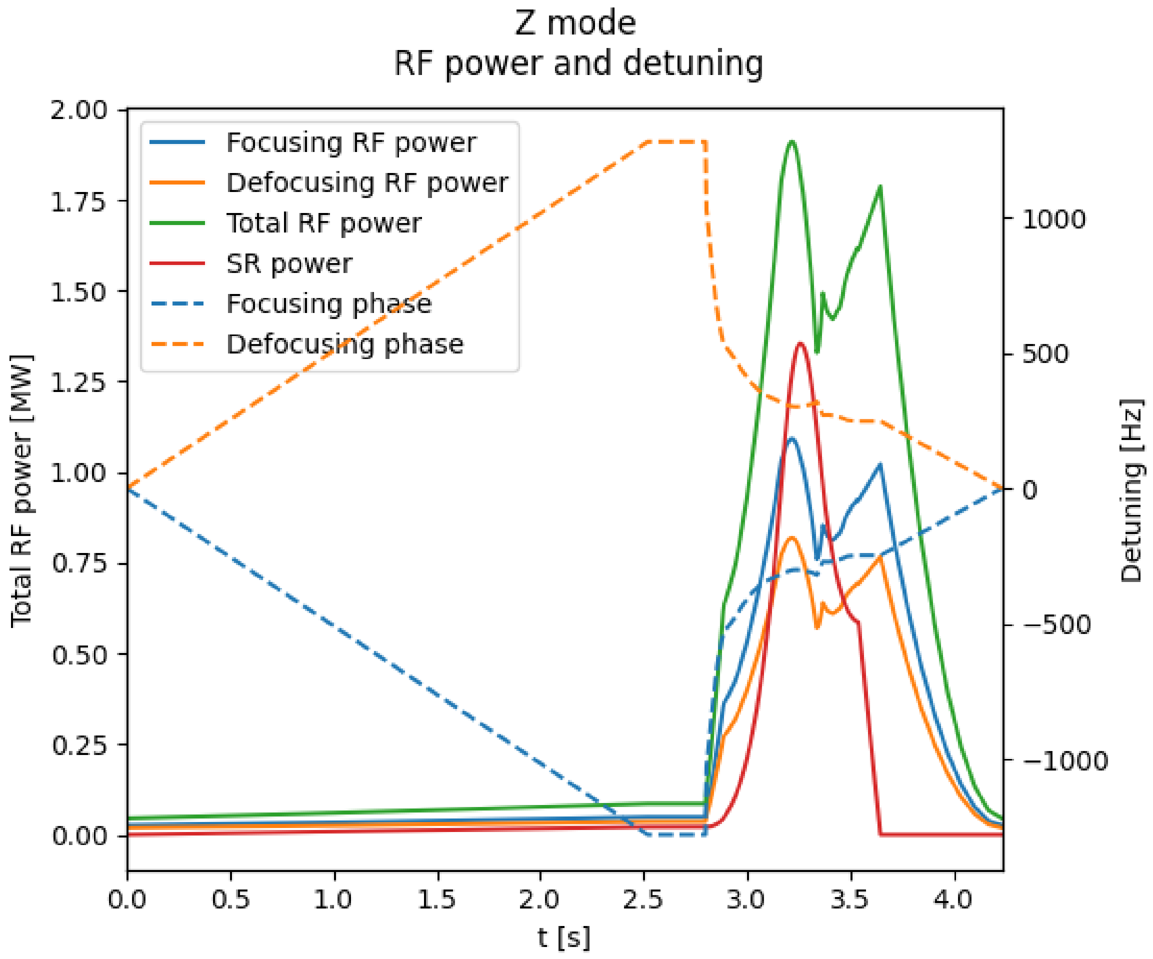




Z voltage per cavity for RPO and RF power

Optimized overshoot, two wigglers





Z voltage per cavity for RPO and RF power

Optimized overshoot, two wigglers, disabled at 0.20s

Clamp at 50kW per cavity (overshot to be verified dynamically)