LONGITUDINAL BEAM DYNAMICS CONSIDERATIONS OF THE FCC-EE HIGH ENERGY BOOSTER

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Acknowledgements: Birk Karlsen-Bæck, Antoine Chance, Karin Canderan, Elleanor Lamb,, Mariangela Marchi and all FCC-ee colleagues

Journées Accélérateurs, 7-10 octobre 2025, Roscoff, France

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Outline

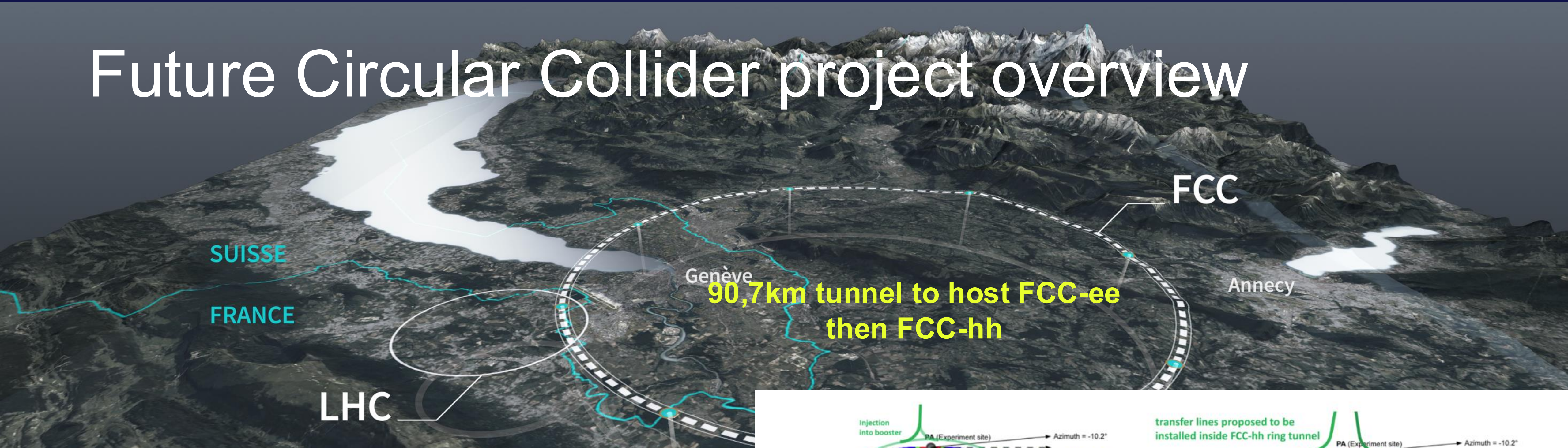
Introduction

Booster cycles: energy ramps for all physics modes

Power transients at injection: Z mode

Summary and next steps

Future Circular Collider project overview

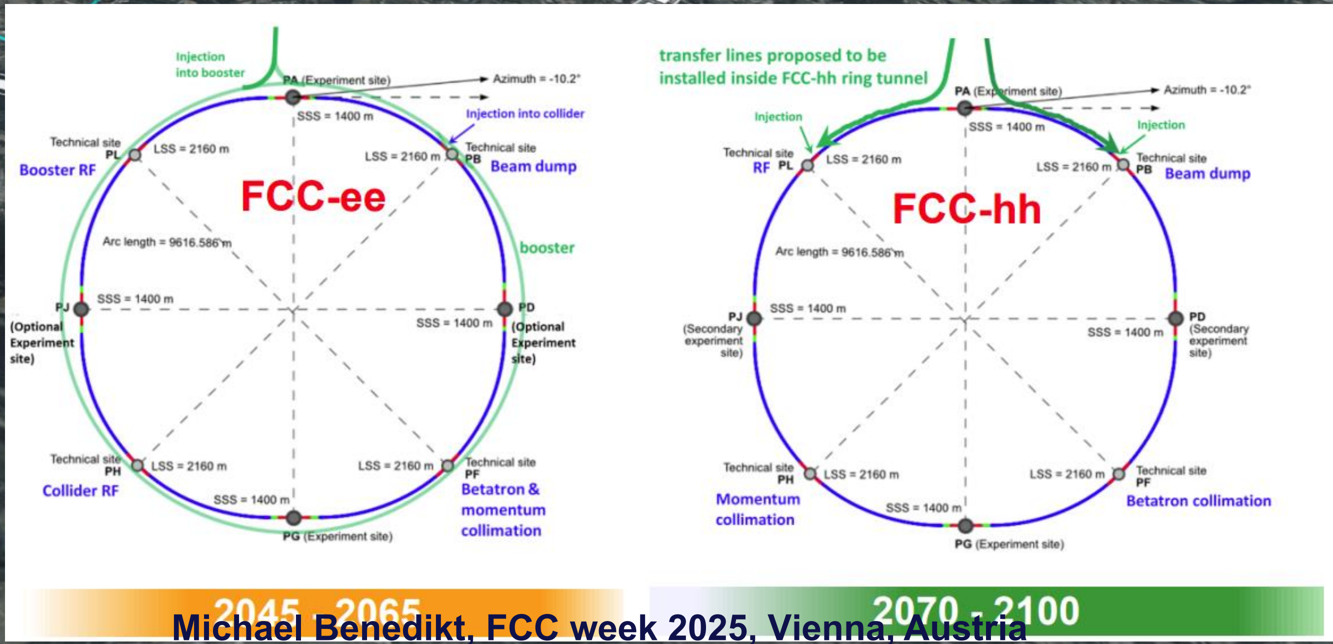


90,7km tunnel to host FCC-ee
then FCC-hh

Stage 1: FCC-ee as a Higgs factory

Four operation energies (per beam):

- Z at 45.6 GeV,
- WW at 80 GeV,
- ZH at 115 GeV,
- $t\bar{t}$ at 180 GeV



Stage 2: FCC-hh (~100 TeV)

Physics of FCC:
https://cds.cern.ch/record/2928193/files/2505.00272.pdf

Michael Benedikt, FCC week 2025, Vienna, Austria

L. Valle, FCCee high-energy booster, Journées Accélérateurs 2025

RF requirements for the FCC-ee booster

The RF section of the booster, located in Point L, will be installed in two stages, with additional cavities installed for $t\bar{t}$ operation.

Therefore, the first 112 cavities need to provide a wide range of voltage (from 50 MV to 2 GV), while minimizing RF power requirements and a minimal voltage per cavity of 2 MV.*

Booster 800 MHz cavities

ZZ, WW, ZH: 112 at 2K in 28 cryomodules (CM)* (4 cavities per CM)

$$Q_0 = 3 \times 10^{10},$$
$$Q_L = 1 \times 10^{7}$$

$t\bar{t}$: 448 at 2K in 112 cryo-modules (4 cavities per CM)

$$Q_L = 2.7 \times 10^{7}$$

*S. Gorgi Zadeh, *800MHz cavity design update*, FCC WP1, January 2025

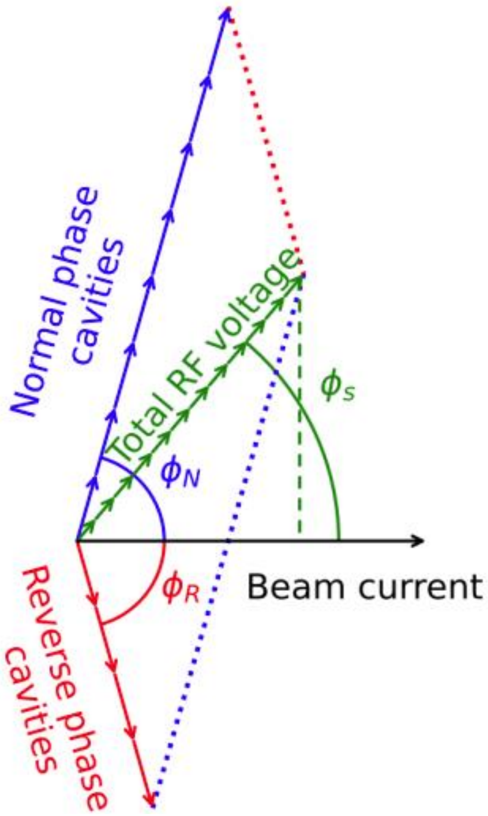
Reverse Phase Operation**
(or counter-phase*)**

- Increased voltage per cavity,
- Optimal static beam loading compensation,
- Homogenized voltage range through all ramps

** Y. Morita et al., SRF, 2009
Experimentally verified in Y. Morita, IPAC, 2010
*** Similar concept used at CERN SPS since the 70s.

I. Karpov, FCC_Week_2025_IK.pdf

$$\Delta N = 16 = N_f - N_d$$



BOOSTER CYCLES

Energy ramps for all physics modes

Booster cycles selected parameters

Continuous operation of the booster in parallel to the collider, following three different modes:

- **Filling mode:** to fill the collider from scratch, with maximum bunch intensity.
- **Top-up mode**: top-up the collider bunches with a personalized charge.
- **Polarized bunches** (Z): for precise energy measurement and pilot bunches.

Extraction energy will be varied in the coming weeks, depending on the collider optics and injection scheme.

Booster physics mode selected parameters

	Z	WW	ZH	ttbar
Characteristics of the ramp				
Injection energy [GeV]	20			
Collider energy [GeV]	45.2	80	120	182.5
Energy deviation at injection	$\pm 1\%$ (TBD)			
Accumulation time [s]	2.8	2.32	3.0	0.64
Total ramping time [s]	1.0 (**1.14**)	1.6	2.6	4.3
Cycle length [s]	3.8	5.5	10	10
Bunches per cycle	1120	928	300	64
Particles per bunch	2.725e10	1.268e10	1.268e10	1.268e10

Changes from FCC week 2025
→ **Increased cycle duration** for WW, ZH and $t\bar{t}$ in **filling mode**
→ The voltage program will be adjusted to match a variable extraction energy ($\pm 1\%$) and the extraction bunch length

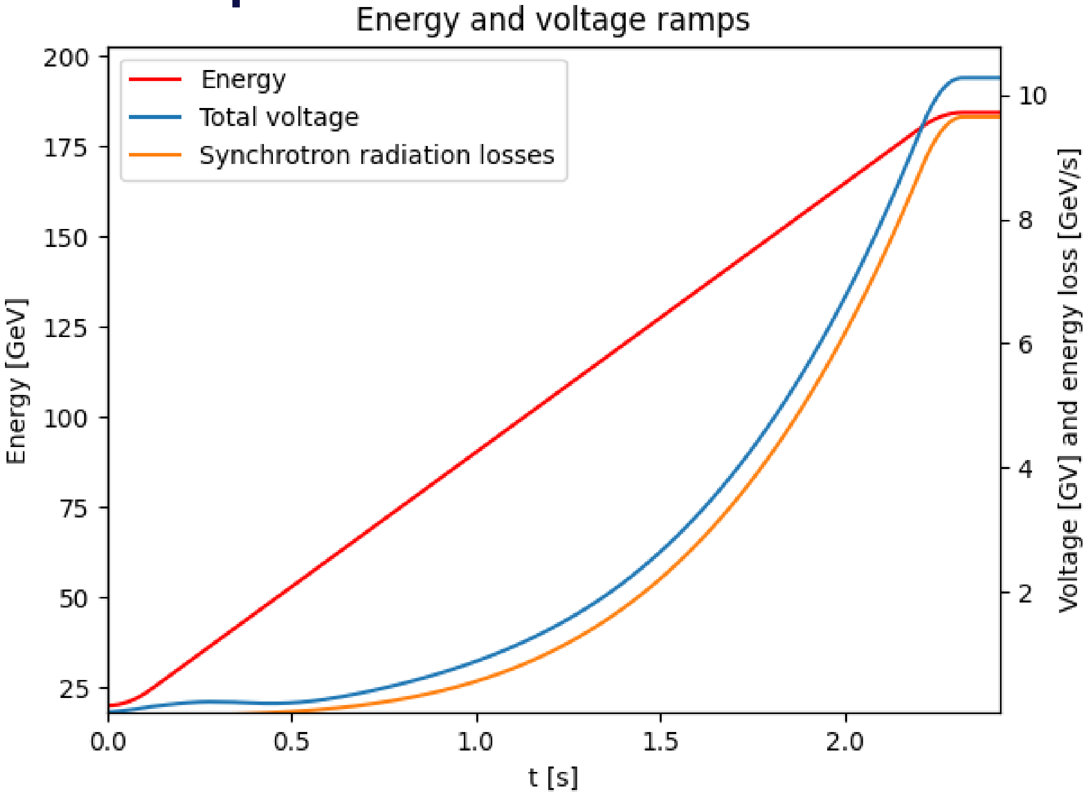
Booster energy ramp analytical computation

Motivation: Optimization the energy and voltage ramps for all four physics modes, all operation modes, including RPO program, homogenize dynamic losses and reduce RF power requirements.

- **Analytical tools** to compute the energy and voltage ramps of the high-energy booster (code on **GitLab**)
- **Faster optimization** including dynamic effects (power transients, beam loading)

For now, energy ramps for a single bunch, no intensity effects.

Example of $t\bar{t}$



Booster ramping strategies for Z mode

Maximum energy gain: 100 GeV/s

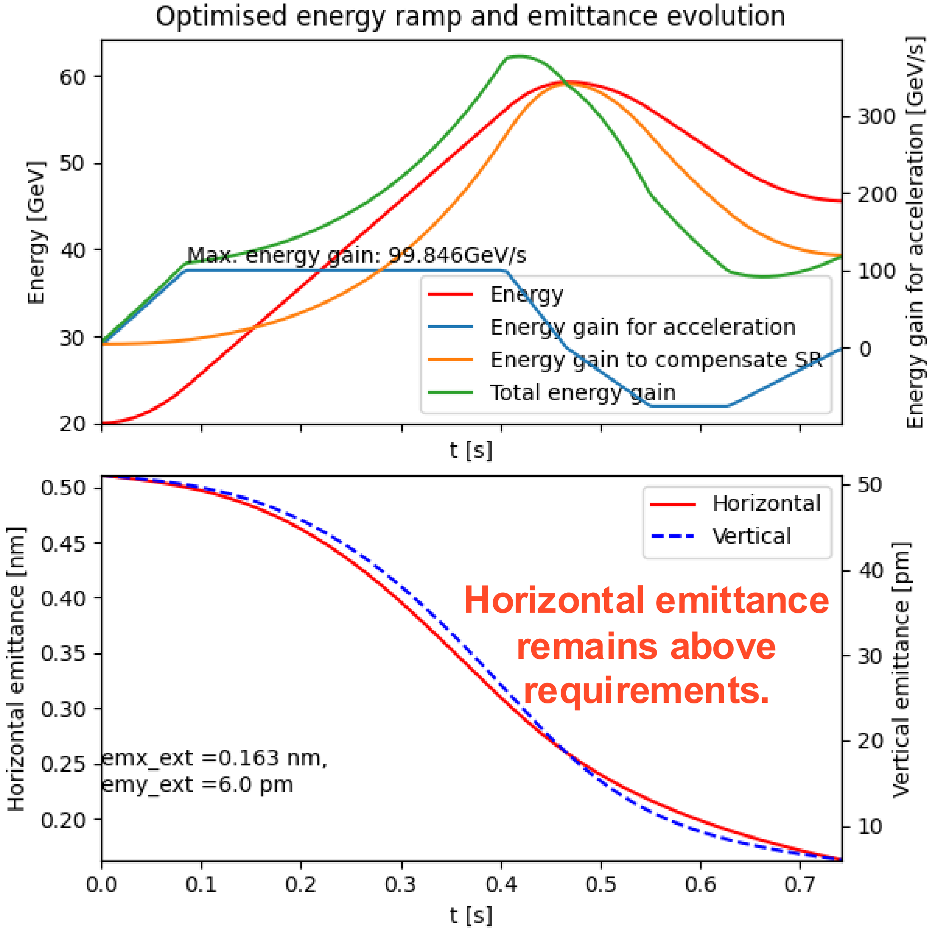
Transverse emittances requirements at extraction energy (45.6 GeV)*:

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

Acceleration during 0.7 s (total cycle 1/1.14 s) 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

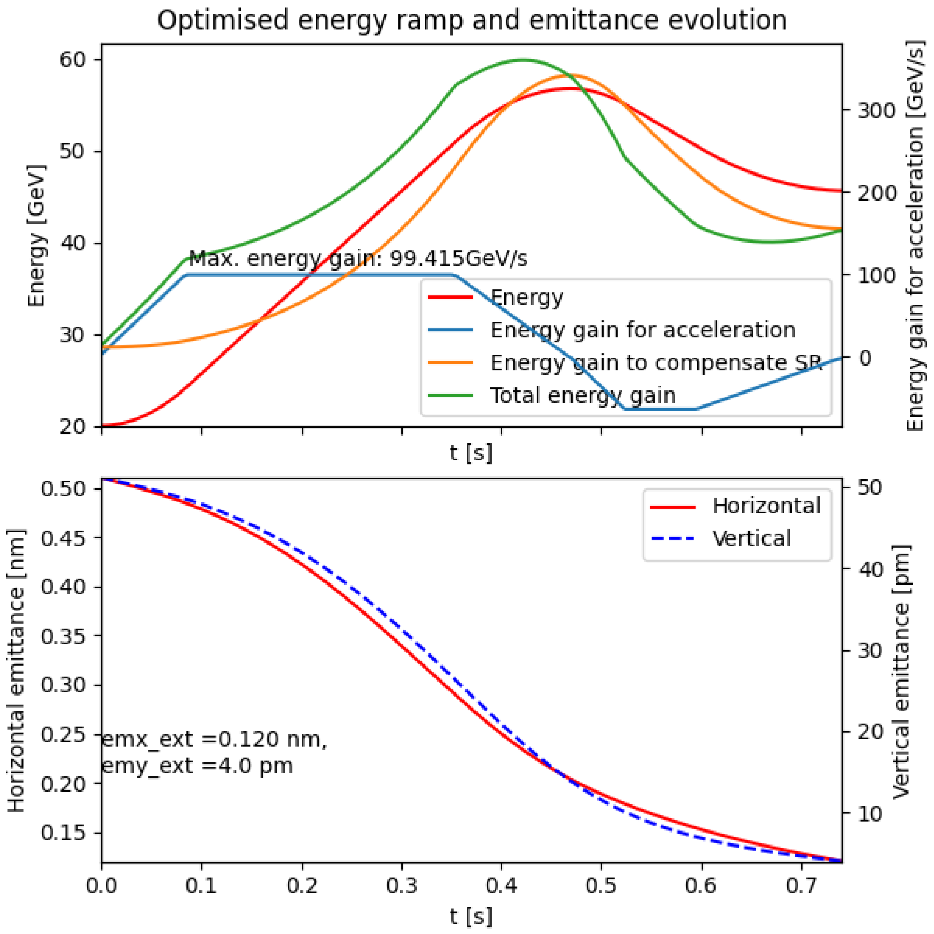
Maximum energy gain: 100 GeV/s

Adding damping wigglers…

Already considered for stability considerations at injection*.

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

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



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

* S. Gorgi Zadeh, FM passband
**L.Valle, FCC_WP1_25_03_2025.pdf

Booster ramping strategies for Z mode

Maximum energy gain: 100 GeV/s

Adding damping wigglers…

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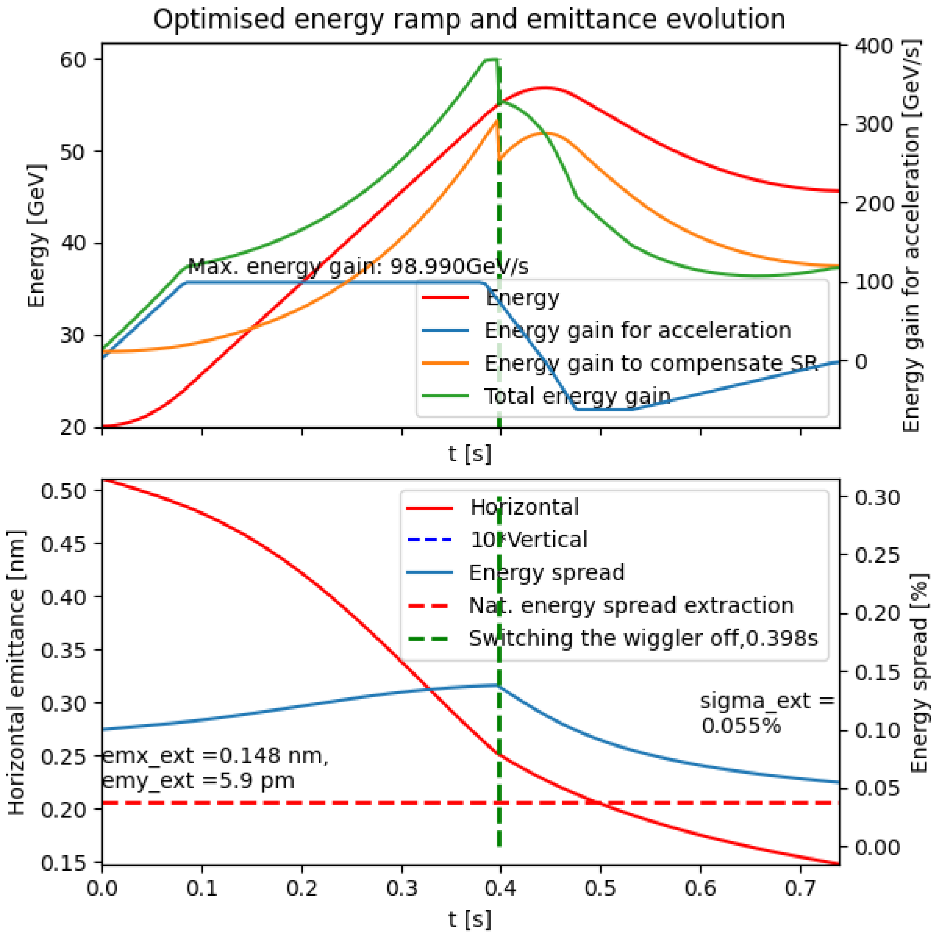
Idea: Switch the wigglers off during the ramp to restore the expected natural energy spread or move the beam away from the wiggler.
Acceleration and deceleration in 1.14 s

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

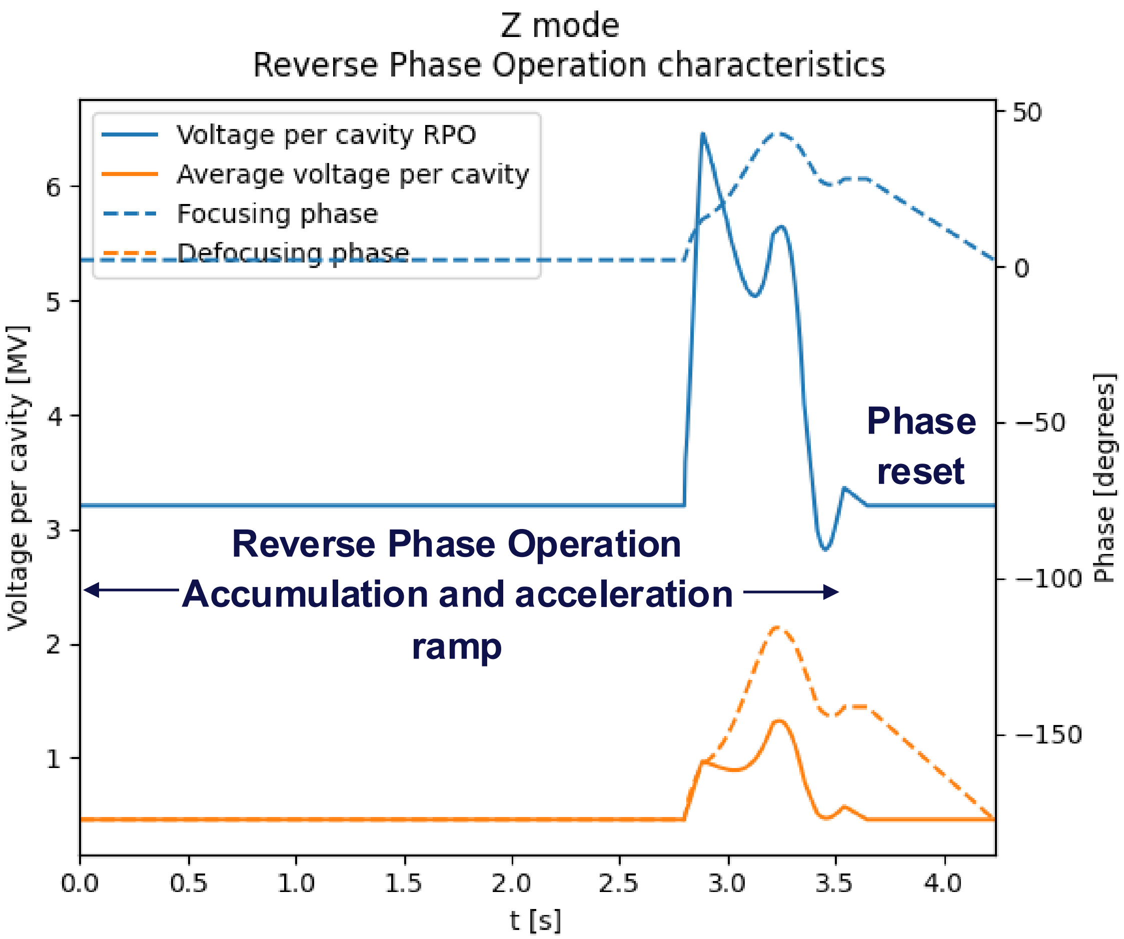


Optimized overshoot energy ramp with Particle Swarm Optimization (PSO) including two damping wigglers disabled during the ramp**

* S. Gorgi Zadeh, FM passband
**L.Valle, FCC_WP1_25_03_2025.pdf

Voltage per cavity program including Reverse Phase Operation

Optimized overshoot, no damping wigglers



Reverse Phase Operation voltage per cavity (identical for all cavities) and phase verify:

- Conservation of the energy gain

Synchronous phase — Total voltage

$$N_f|V_{cav}|\ \cos(\phi_s+\phi_f)+N_d|V_{cav}|\cos(\phi_s+\phi_d)=V_{tot}\cos\phi_s$$

Number of focusing cavities — Voltage per cavity — Defocusing cavity phase

- Conservation of the synchrotron tune

$$N_f|V_{cav}|\ \sin(\phi_s+\phi_f)+N_d|V_{cav}|\sin(\phi_s+\phi_d)=V_{tot}\sin\phi_s$$

A. Blednykh et al, https://www.osti.gov/servlets/purl/1888292

Dynamic power losses in the high-energy booster

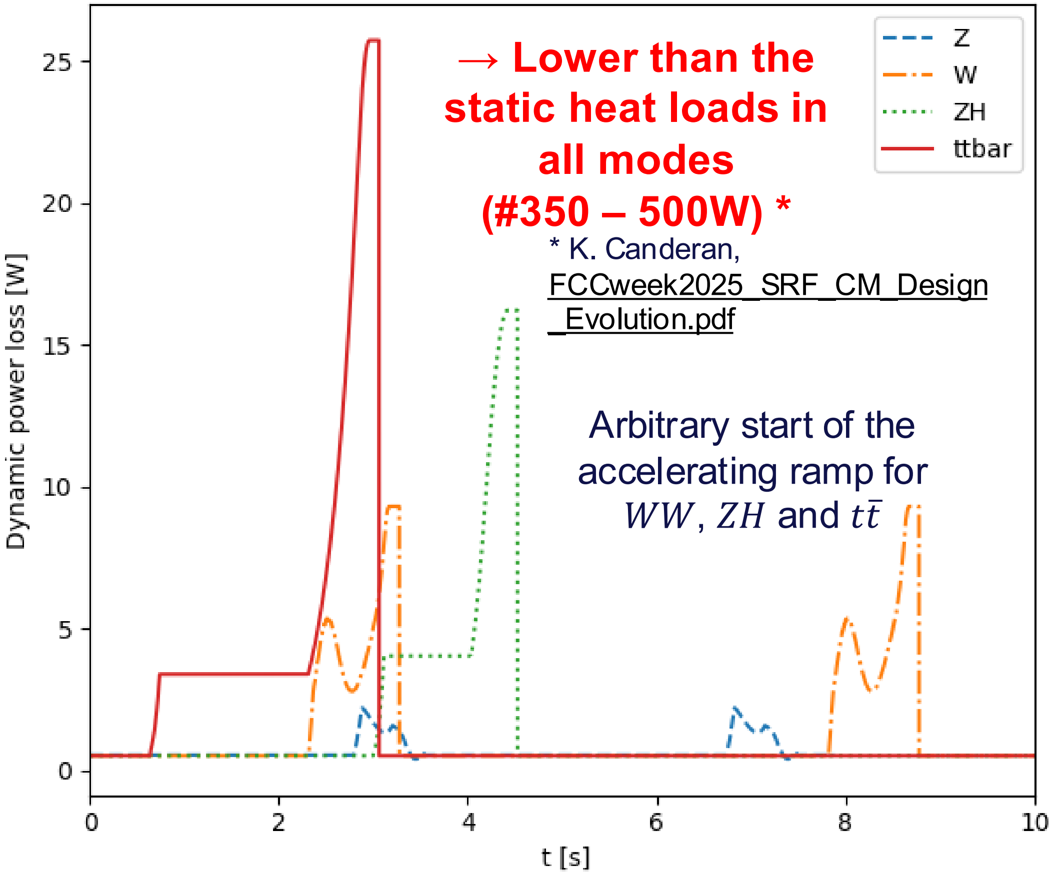
Dynamic power loss is the power dissipated in the RF cavity from its own resistivity. For a superconducting RF cavity, the dynamic power loss is expressed as:

$$P_d = \frac{V_{cav}^2}{2 \times R\_Q \times Q_0}$$

With V_{cav} the voltage per cavity, Q_0 the unloaded Q-factor and R_Q a geometry-dependent factor.

Duty factor for all physics modes	Z	WW	ZH	ttbar
Peak [W]	2.21	9.30	16.2	25.7
Average [W]	**0.676**	**1.29**	**1.42**	**2.02**
Integrated power [W.s]	**2.66**	**10.1**	**14.2**	**20.2**
Duty factor (average/peak)	**0.31**	**0.14**	**0.088**	**0.079**

Dynamic power loss during different booster cycles



POWER TRANSIENTS AT INJECTION Z MODE

Overshoot energy ramp, no damping wigglers.

Results are subjected to large variations depending on the energy ramp strategy and use of damping wigglers throughout the booster cycle.

RF power requirements in the booster with optimal detuning

The power required by the RF cavities can be minimized with the choice of the loaded Q factor and a detuning program $\Delta\omega$.

In the case of FCC-ee, the cavities are fixed, and identical for Z, WW and ZH modes.

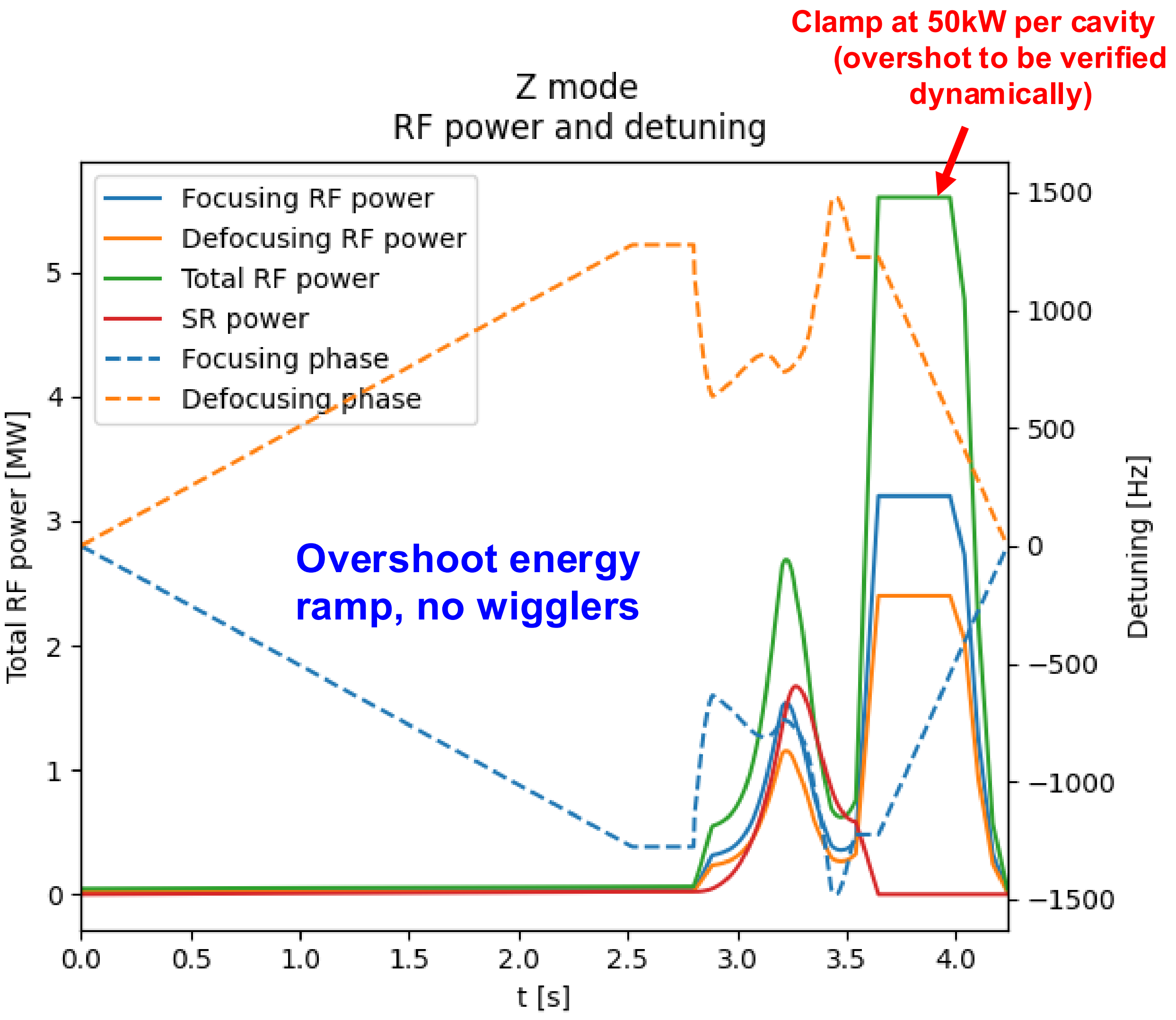
Minimization can therefore only be conducted with detuning of the cavities.

DC beam current

$$P_{RF} = \frac{1}{2} * R\_Q * Q_L * \left(\left[\frac{|V_{cav}|}{2(R\_Q)Q_L} + \frac{|F_b| I_b \cos(\phi_{f,d} + \phi_s)}{2} \right]^2 + \left[\frac{|V_{cav}|}{R\_Q} \times \frac{\Delta\omega}{\omega_{RF}} + \frac{|F_b| I_b \sin(\phi_{f,d} + \phi_s)}{2} \right]^2 \right)$$

Form factor $|F_b| \approx 2$

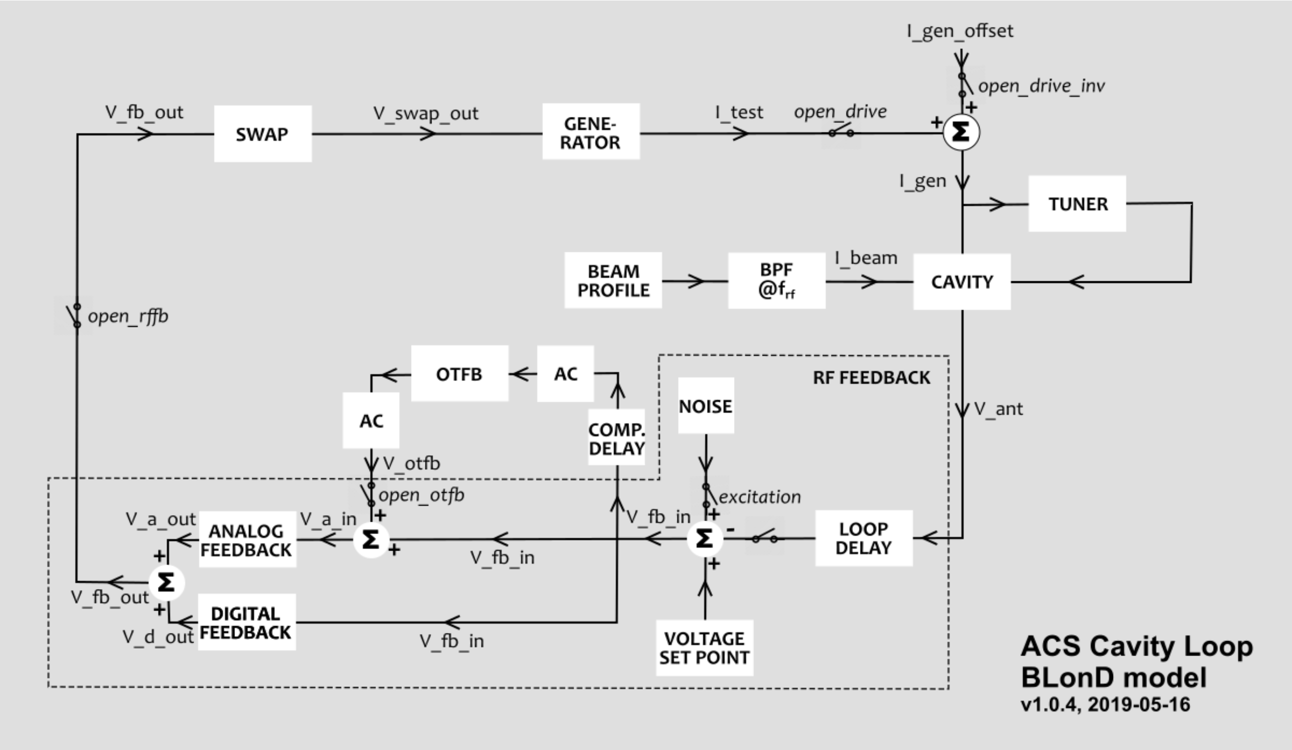
L. Valle, FCCee high-energy boos



RF power transients at injection using BLonD

To complete previous calculations* with tracking tools, RF power requirements are simulated using the code BLonD**.

- **Adapted LHC Cavity Loop class in BLonD****
- **Sampling time: 25 ns (every 20 booster buckets)**
- **Fixed beam in the longitudinal phase space**
- **First four <u>equal</u> bunches injected at $t = 0s$, equally spaced by 25 ns**
- **Two RF cavities: focusing and defocusing, located at the same place, with their own feedback loop.**



LHC Cavity Feedback loop diagram as implemented in BLonD**

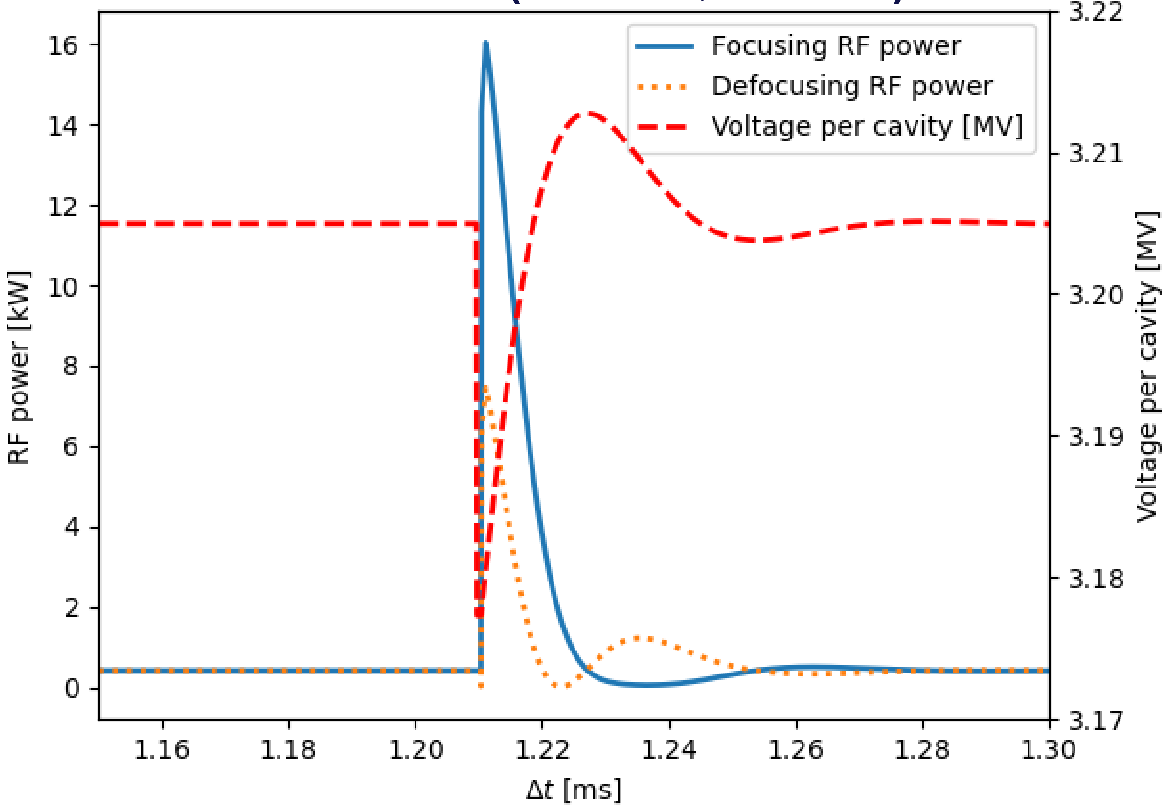
*I. Karpov, FCC_optics_meeting_27022025_IK.pdf
** BLonD, *Beam Longitudinal Dynamics simulator*, https://blond.web.cern.ch/
*** B.E. Karlsen-Bæck, H. Timko, 2024 JINST 19 T04005

Injecting the four first bunches – Z mode

Injection of the first four bunches from the linac:

- 2.725e10 particles per bunch,
- 25 ns bunch spacing,
- No intensity nor injection errors,
- Fixed beam in the longitudinal phase space in a first approach,
- Consistent with expected stabilised value (total 48kW for the first injection)
- Averaged at 70kW including transients

RF power transients per cavity at injection in the booster (Z mode, 20 GeV)



Accelerating ramps and voltage programs from FCC_week_2025_valle.pdf

Summary and next steps

Summary

Codes available on GitLab (develop branch)

- Energy ramp designing and optimizing functions for all target physics modes
- LHC Cavity feedback loop being adapted to the FCC-ee booster for RF power transient calculation
- Power transients studied during the first turns after injection in the booster, for Z mode bunches

Next steps

- **Ongoing optimization of the energy ramps (esp. Z):**
  - Damping wigglers requirements to meet the extraction targets to be determined,
  - Bunch rotation at flat top to transfer energy spread into bunch length,
- **Study of booster availability**
  - Trips of RF cavity, redundancy, recovery procedures, …
- **Full injection scheme (multi-turn injection) in BLonD(3?) in filling and top-up mode:**
  - Booster filling scheme,
  - Injection mismatches, inhomogeneous bunches,
  - Coupled-bunch instabilities to be assessed (P. Hickersberger)

BLonD 3 source code at:
https://gitlab.cern.ch/blond/BLonD/-/tree/blonder?ref_type=heads

Accelerator Early Career Researchers (AccelECRs)

An accelerator science and technology ECR community is in the pipelines. Our goals:

- Build a Europe-wide network of early-career researchers (ECRs) in accelerator science and technology,
- Support ECRs with their professional and personal development, career and research opportunities,
- Organize topical workshops locally and globally to maximize knowledge sharing and interactions of the community

Get involved in building this community!

How to join:

Simply subscribe to the ‘accelerator-ecr’ e-group mailing list here:

https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=accelerator-ecr

For now: CERN-based, we are looking to build antennas in different European labs ☺

Thank you for your attention

Introduction - appendices

RF operation requirements for FCC-ee and its high-energy booster

Main challenge: SYNCHROTRON RADIATION LOSSES up to 10 GeV energy loss per turn.

Compensation of SR losses require many RF cavities

Booster

800MHz cavities

ZZ, WW, ZH: 112 at 2K in 28 cryomodules* (4 cavities per CM)

$Q_0 = 3 \times 10^{10}$,
$Q_L = 1 \times 10^7$

$t\bar{t}$: 448 at 2K in 112 cryo-modules (4 cavities per CM)
$Q_L = 2.7 \times 10^7$

Collider

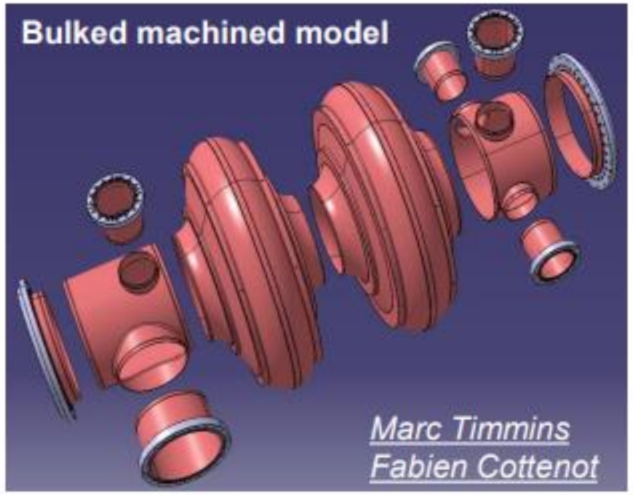
400MHz cavities

ZZ, WW, ZH: 132 at 2K in 66 cryomodules

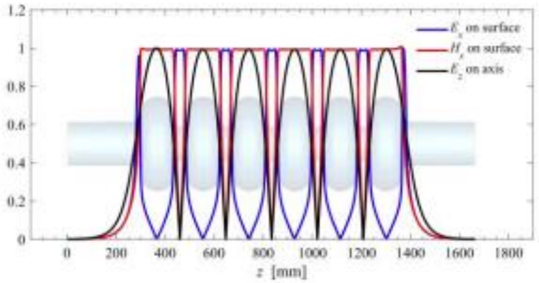
800MHz cavities

$t\bar{t}$: + 408 at 2K in 102 cryo-modules

400 MHz 2-cell cavity

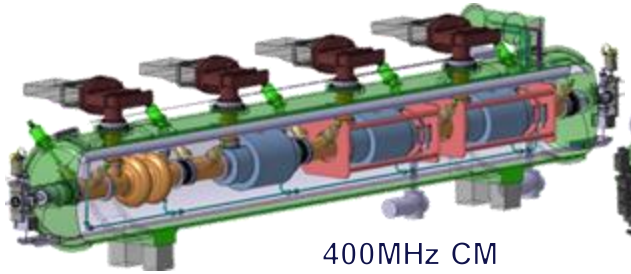


800 MHz 6-cell cavity

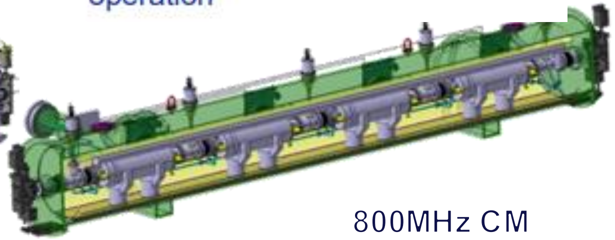


Courtesy Marco Chiodini

112 cavities for Z, W and H booster
408+336 additional cavities for ttbar operation



400MHz CM



800MHz CM

S. Gorgi Zadeh, Accelerating cavities with HOM damping for FCC-ee.pdf

* K. Canderan, FCCweek2025_SRF_CM_Design_Evolution.pdf
** See Ivan's talks (e.g. FCC_Week_2025_IK.pdf)

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Collider

400MHz cavities

ZZ, WW, ZH: 112 at 2K in 66 cryomodules

800MHz cavities

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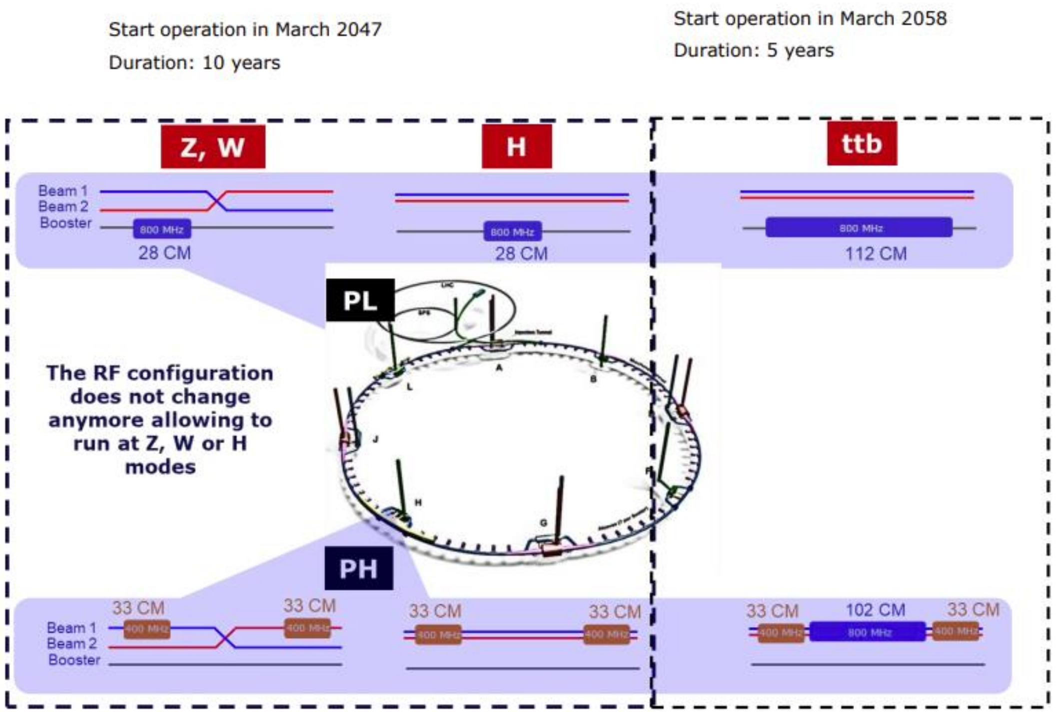
Layout of the FCC$_{ee}$ SRF system

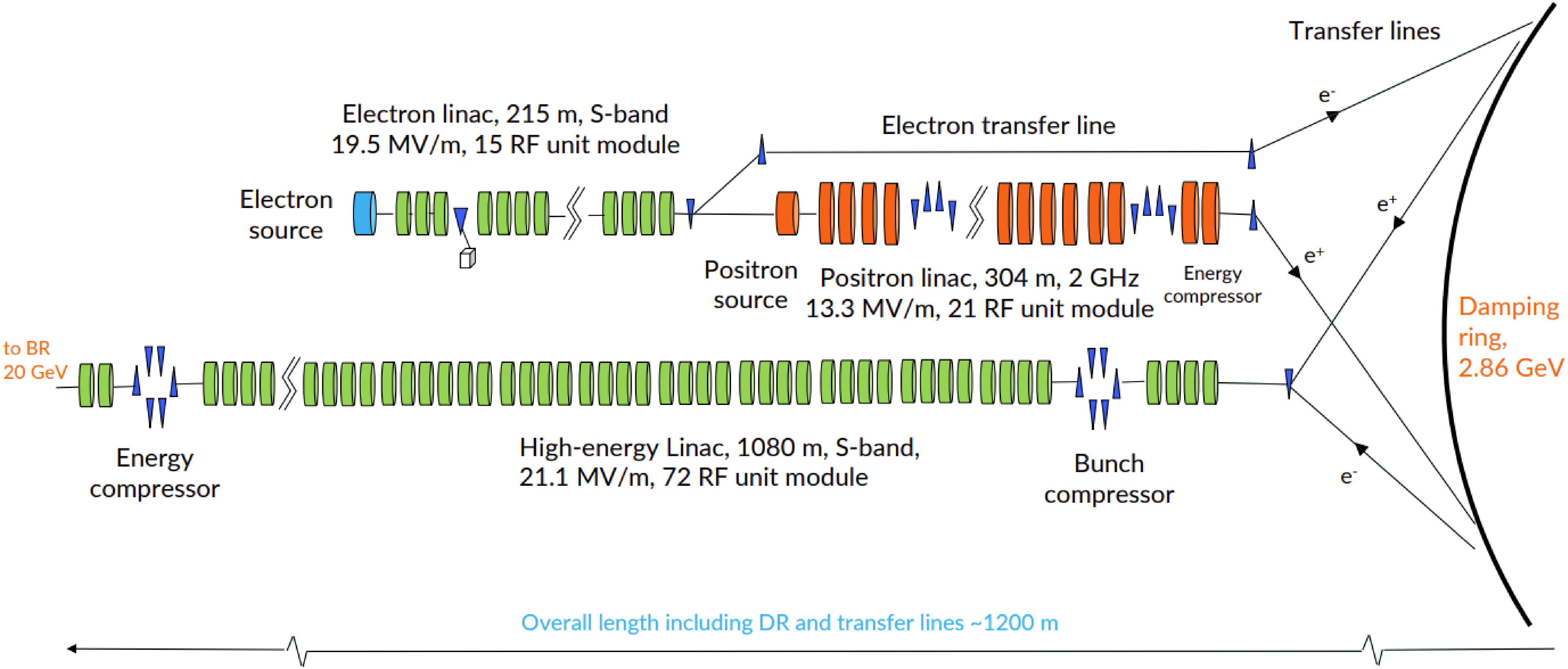


* K. Canderan, FCCweek2025_SRF_CM_Design_Evolution.pdf

** See Ivan's talks (e.g. FCC_Week_2025_IK.pdf)

I. Syratchev, FCC_Week_2025_Syratchev.pdf

Injection chain into the FCC-ee



Synchrotron radiation in Beam LONgitudinal Dynamics (BLonD)

BLonD* is a CERN simulation suite for longitudinal particle tracking in synchrotrons.

Its latest version includes:

- Synchrotron radiation damping and quantum excitation (using synchrotron radiation integrals),
- FCCee booster feedback loops adapted from the LHC cavity loops

BLonD3 is a restructuration of BLonD and is under development, and will be adapted to future accelerators (FCCee, muon colliders especially.)

- Developer and beginner friendly,
- High test coverage and numerous examples (training in preparation),
- XSuite wrappers for lattice import,
- No backward compatibility with BLonD.

BLonD 3 source code at:
https://gitlab.cern.ch/blond/BLonD/-/tree/blonder?ref_type=heads

*BLonD website: https://blond.web.cern.ch/

Energy ramps - appendices

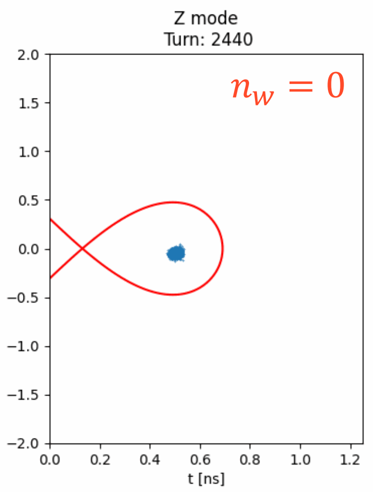
Injection error in the booster: Z ramp

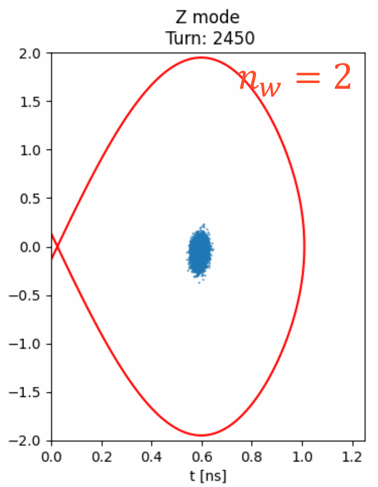
Acceleration of an early-injected bunch

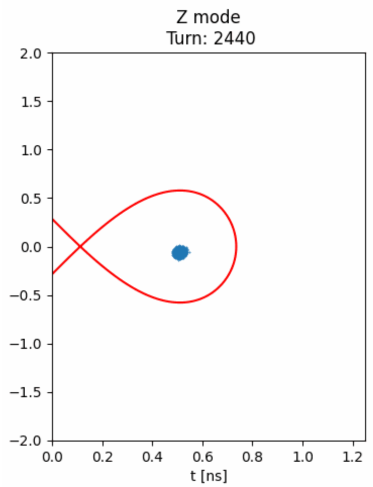
Maximum jitter implemented in the BLonD simulation of the acceleration:

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

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







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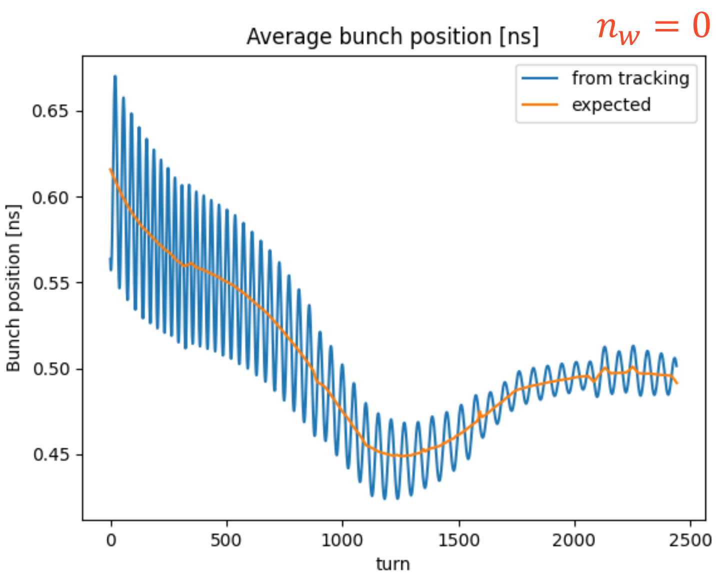
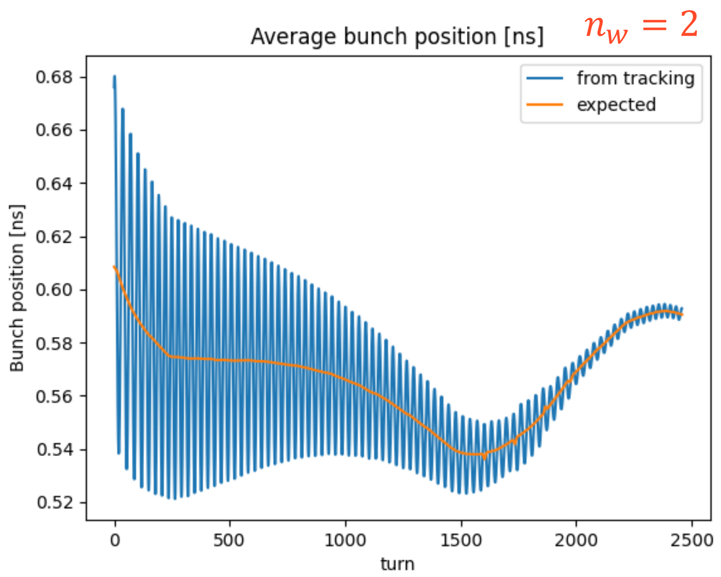
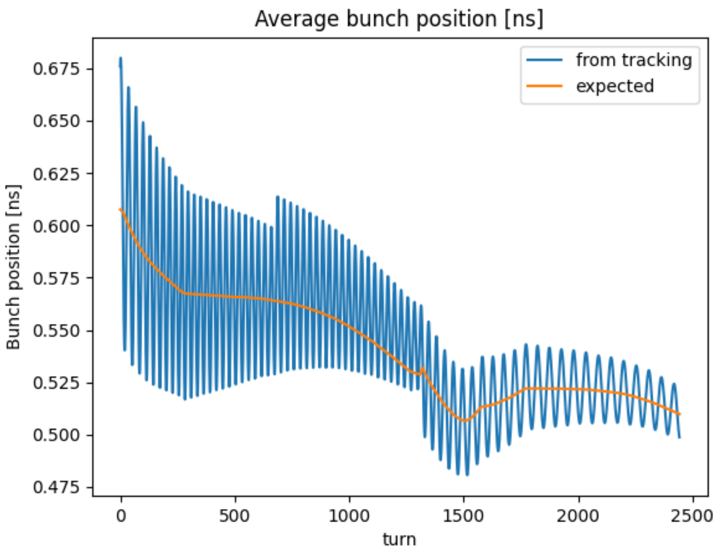
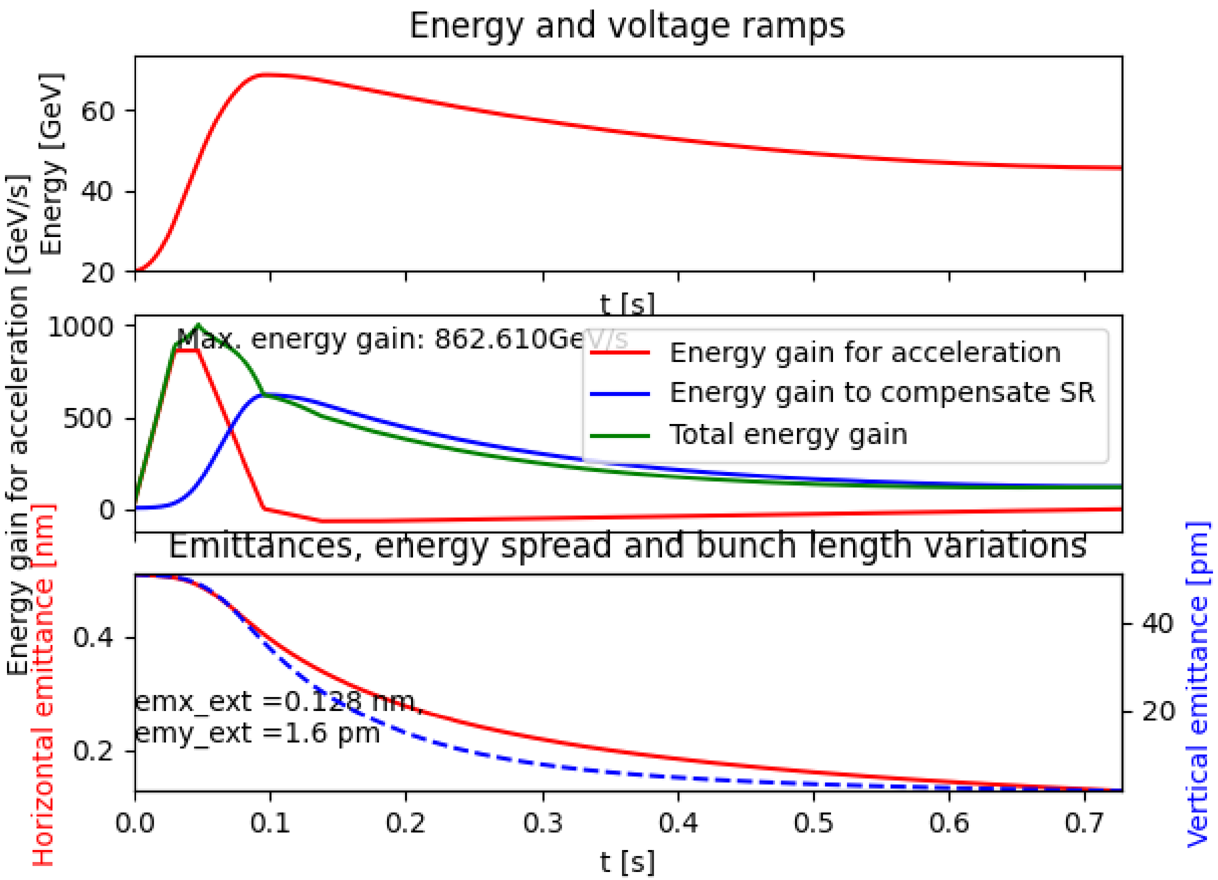
at t = 0.4s







Z mode overshoot



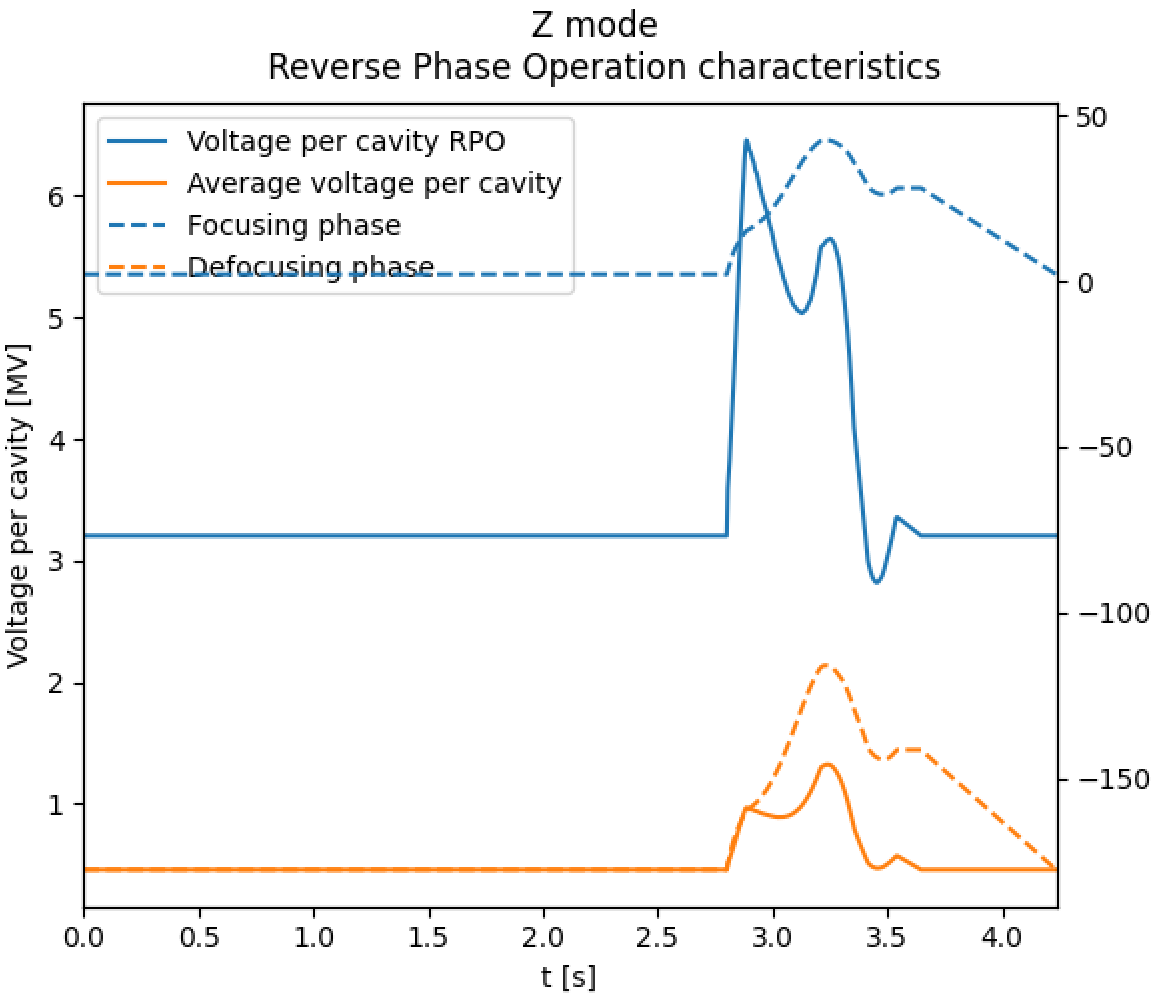
Overshoot energy ramp could meet the requirements on the extraction transverse emittance…

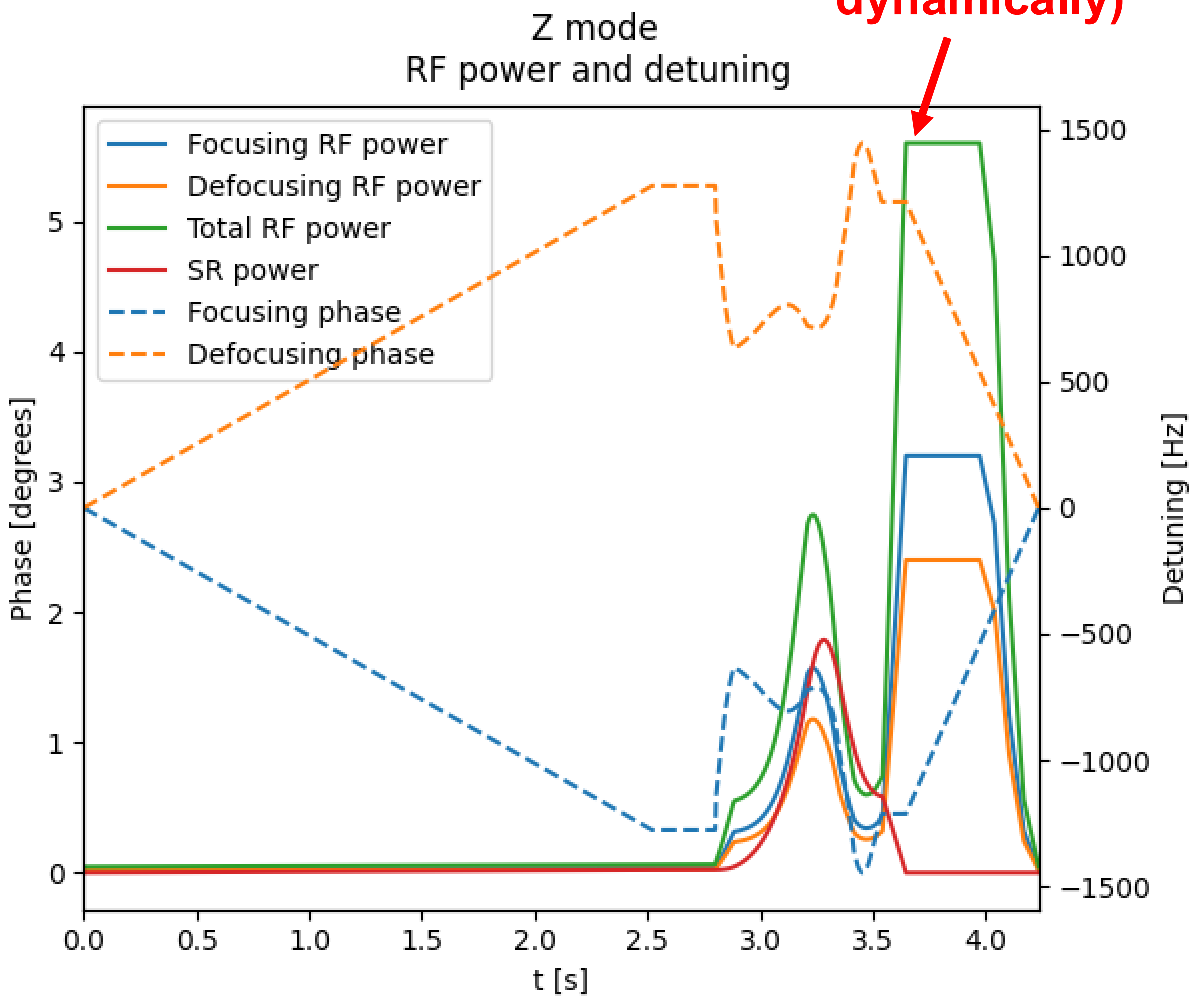
with at least 850 GeV/s energy gain in less than 0.05s!

Z voltage per cavity for RPO and RF power

Optimized overshoot, no wigglers

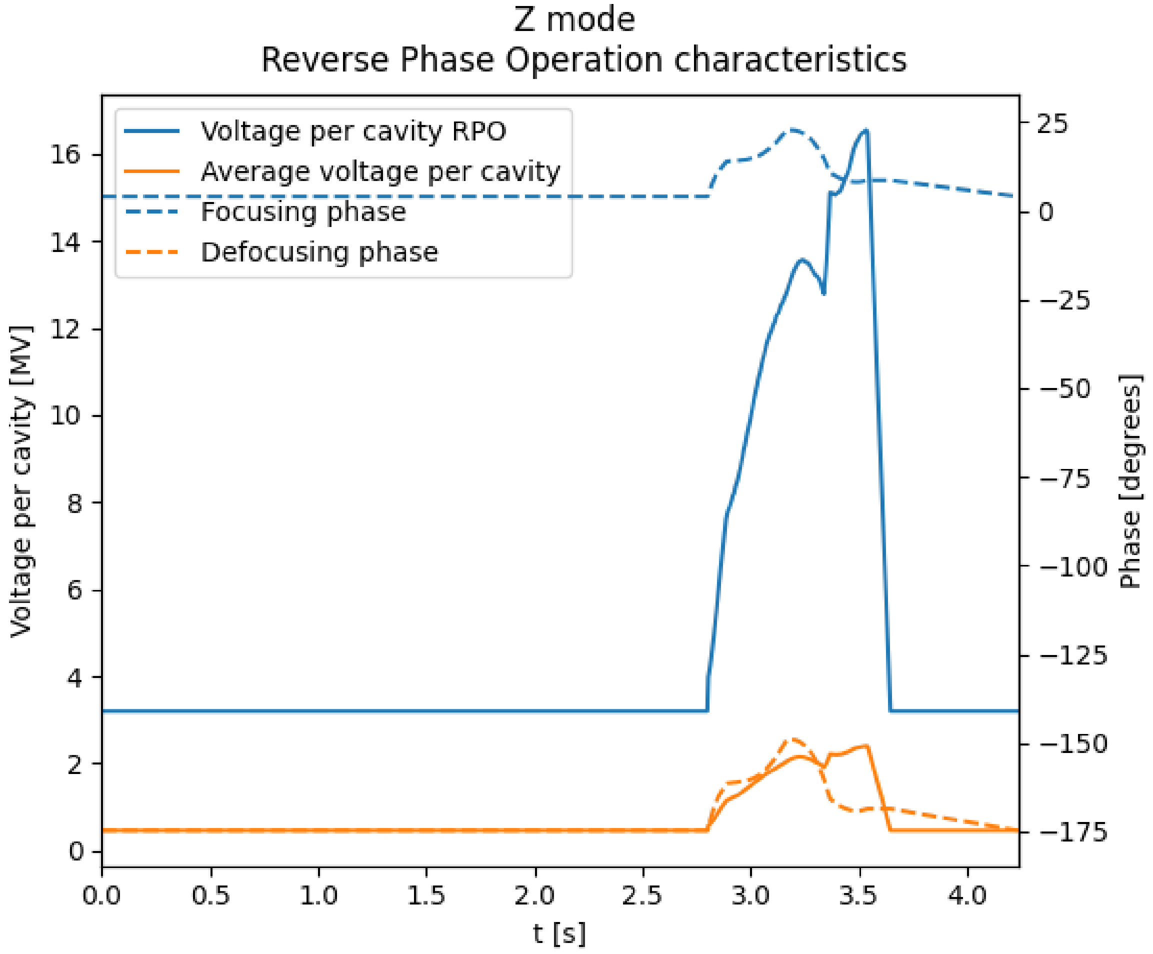
Clamp at 50kW per cavity (overshot to be verified dynamically)

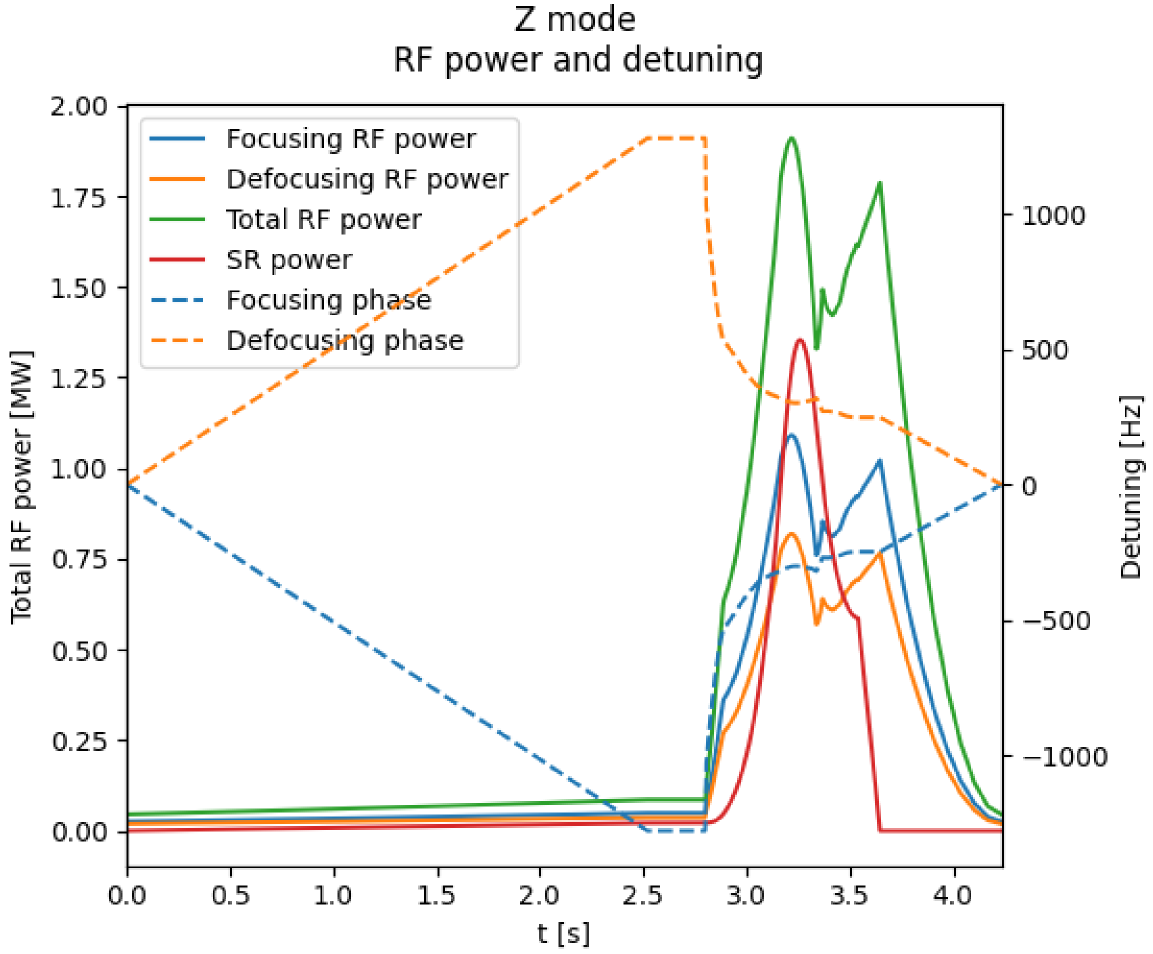




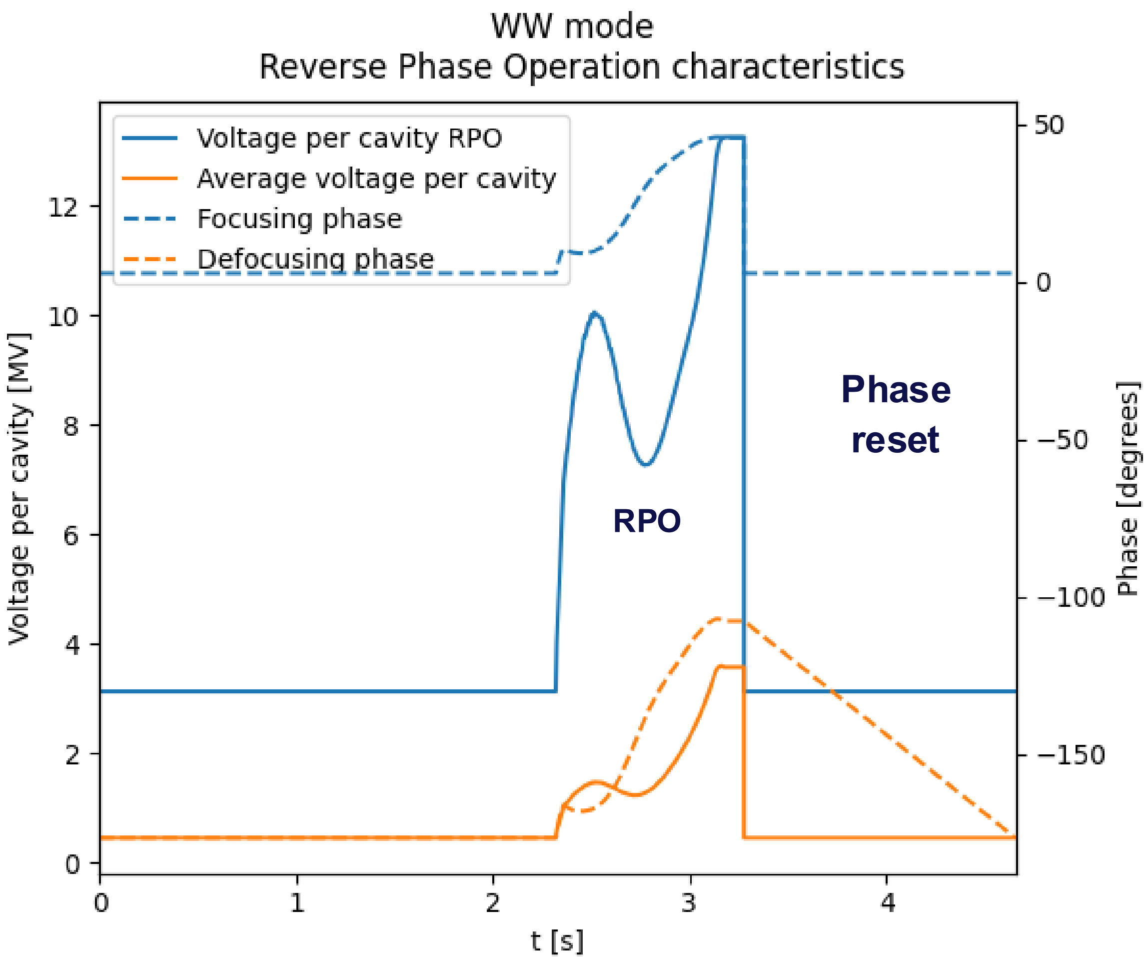
Z voltage per cavity for RPO and RF power

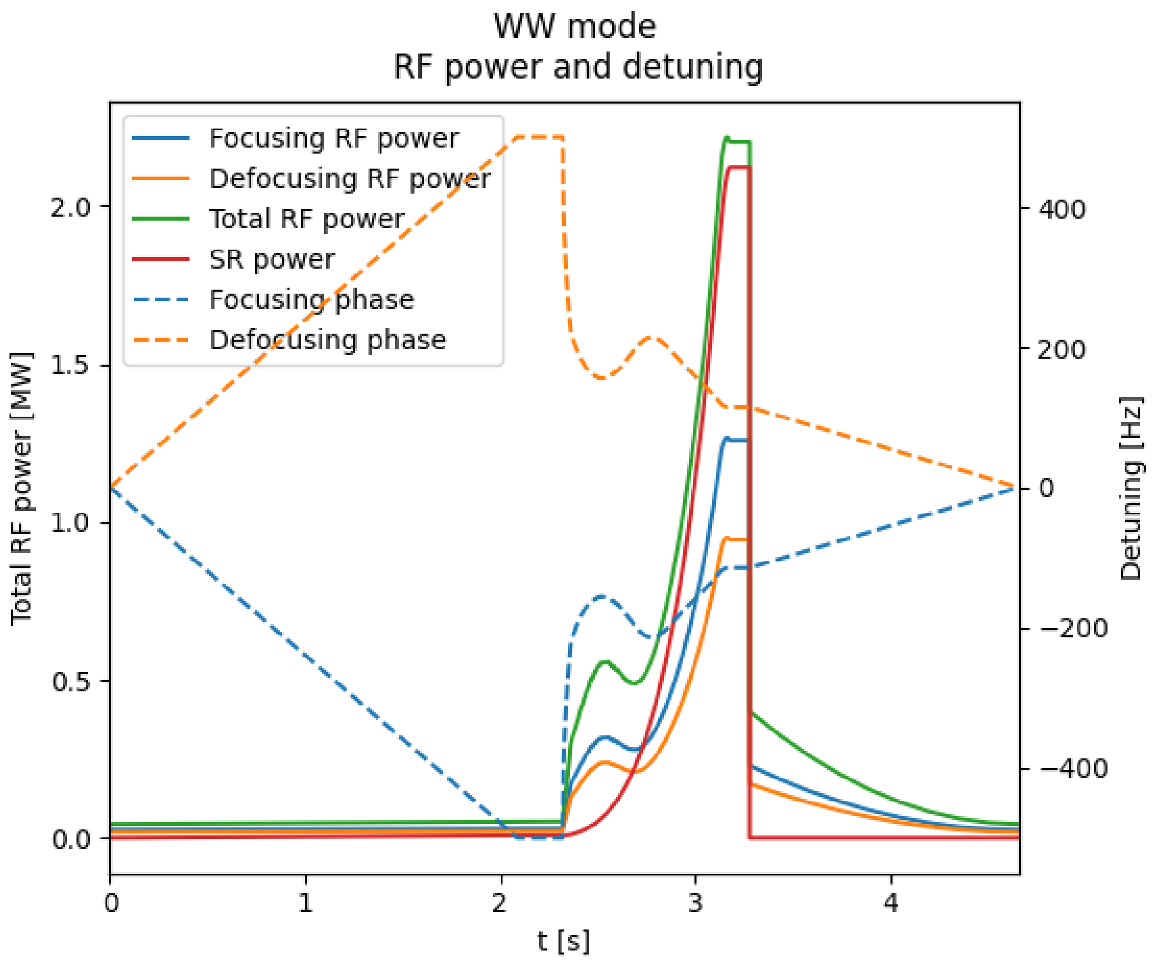
Optimized overshoot, two wigglers





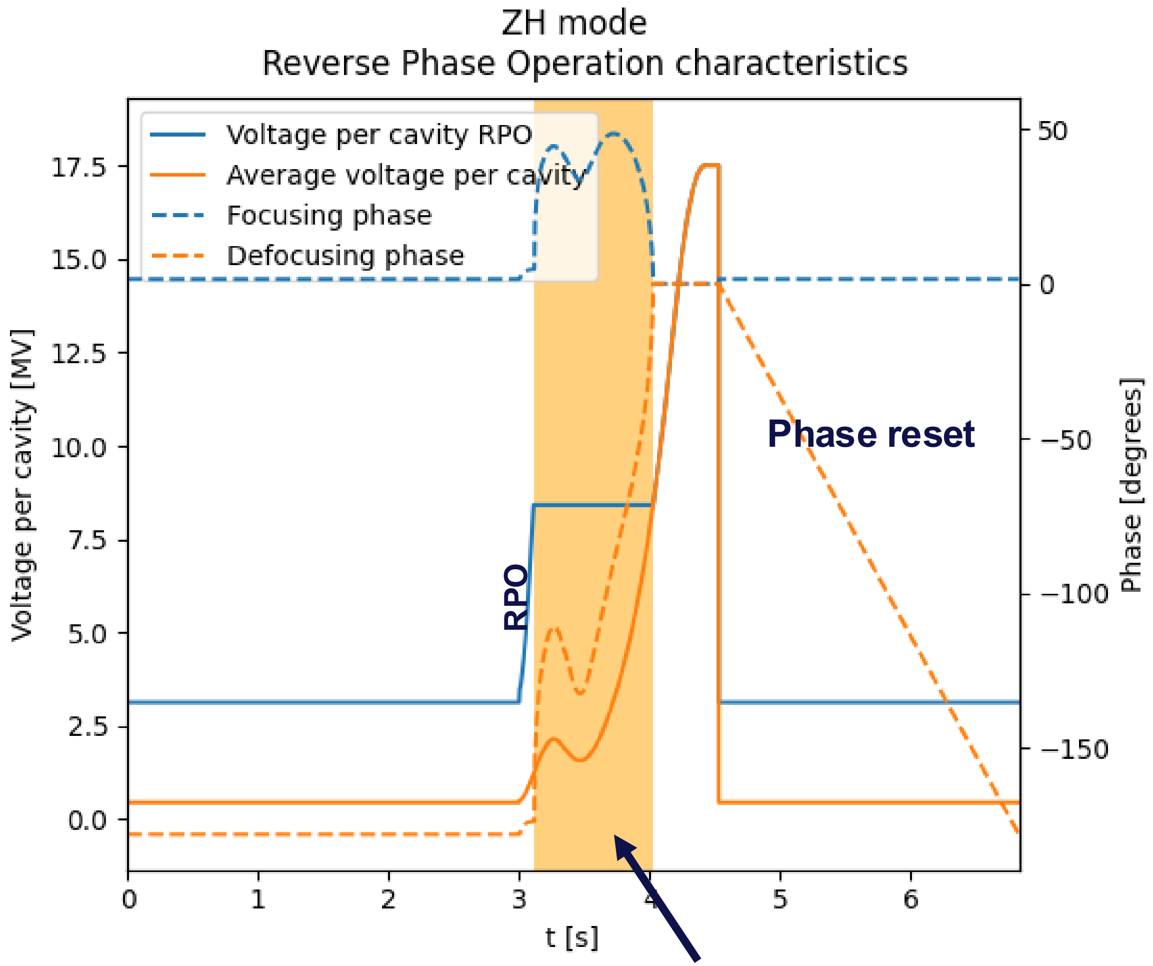
WW voltage per cavity for RPO and RF power



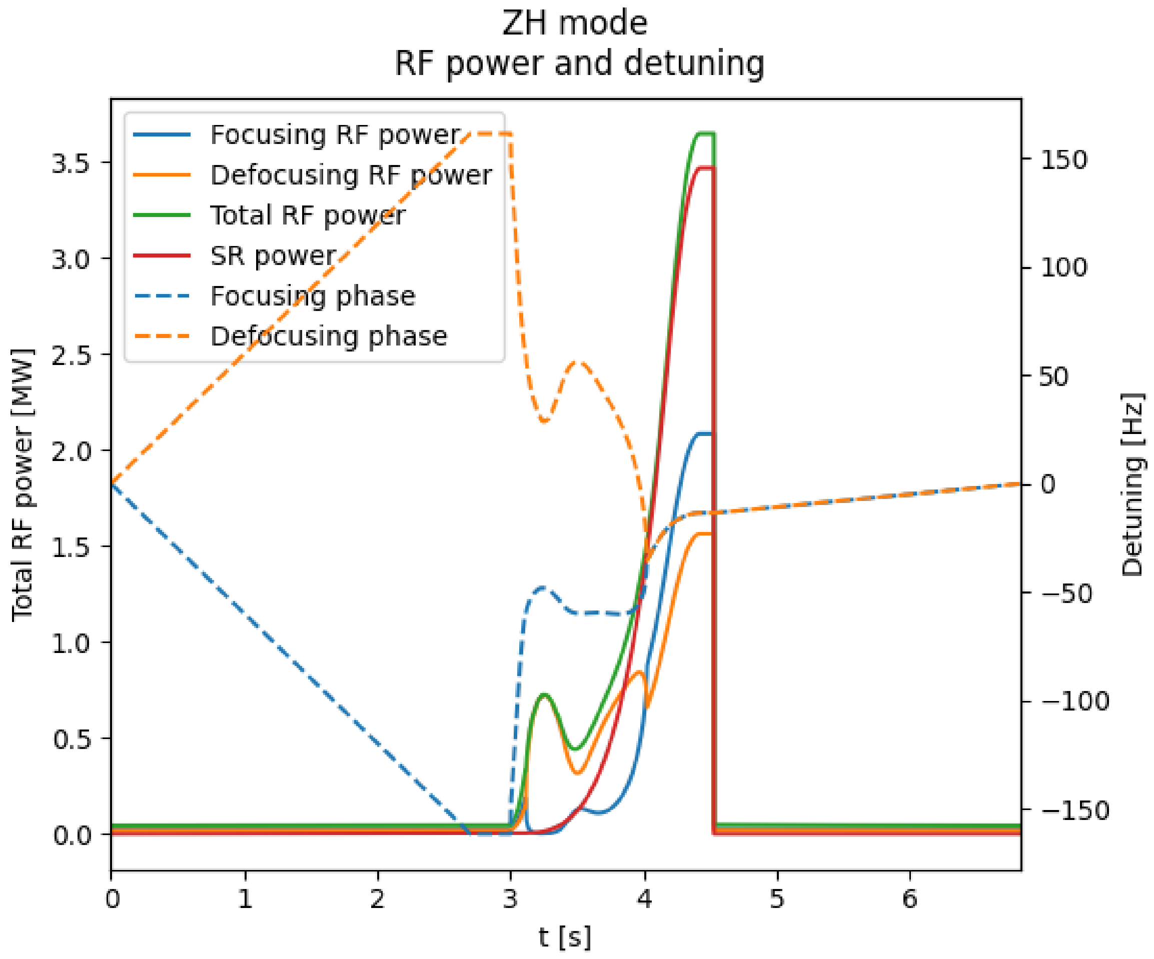


4.5% RF power overshoot at flat top

ZH voltage per cavity for RPO and RF power

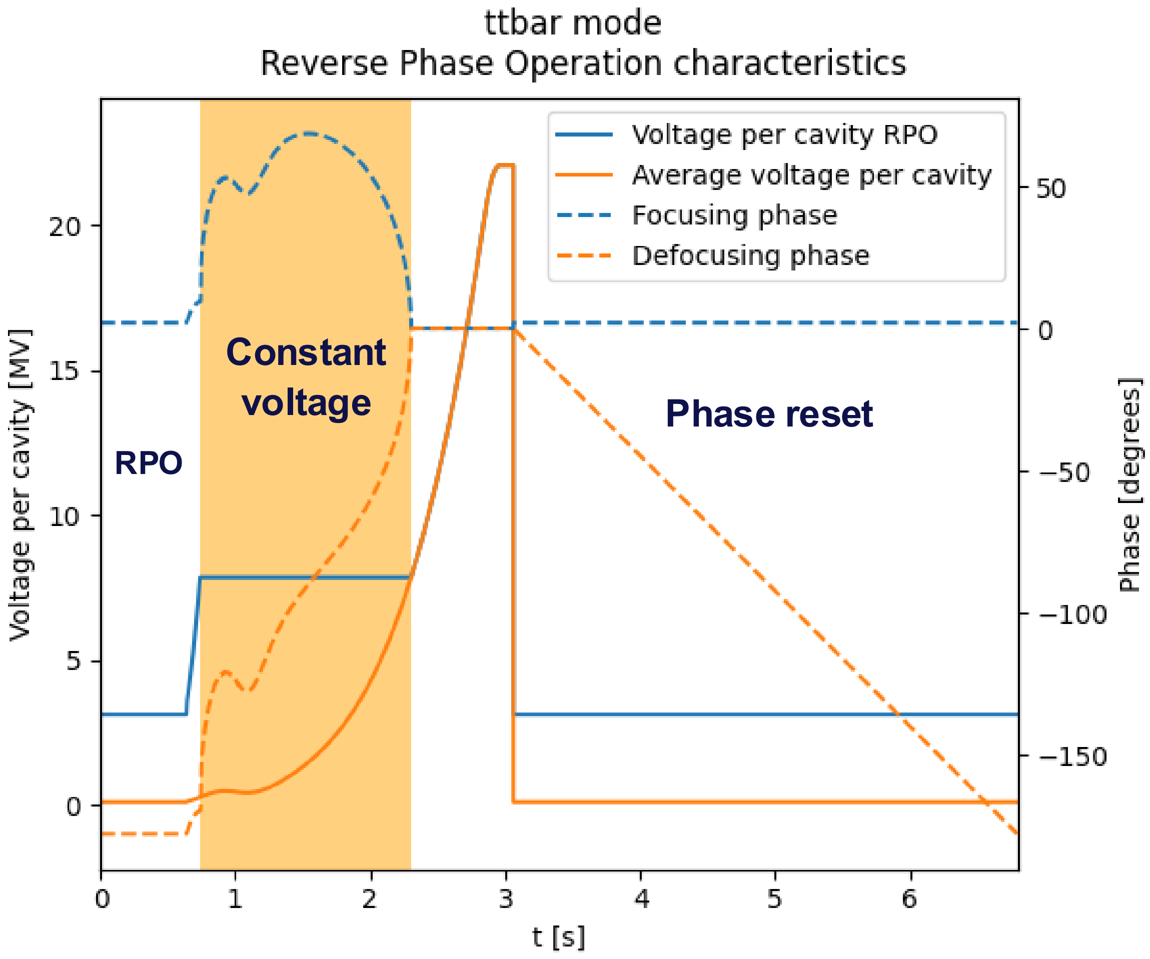


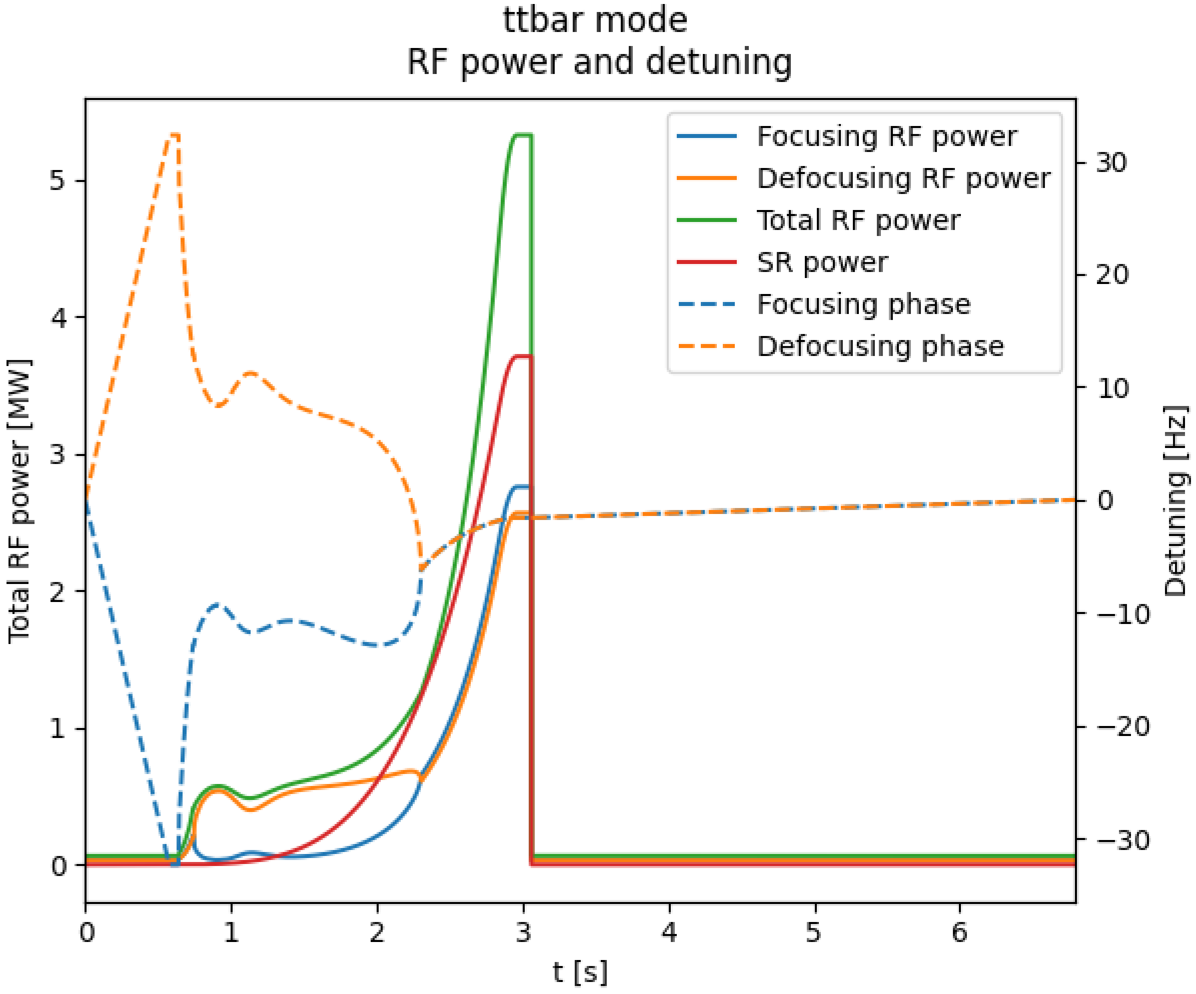
Constant voltage



5% RF power overshoot at flat top

$t\bar{t}$ voltage per cavity for RPO and RF power



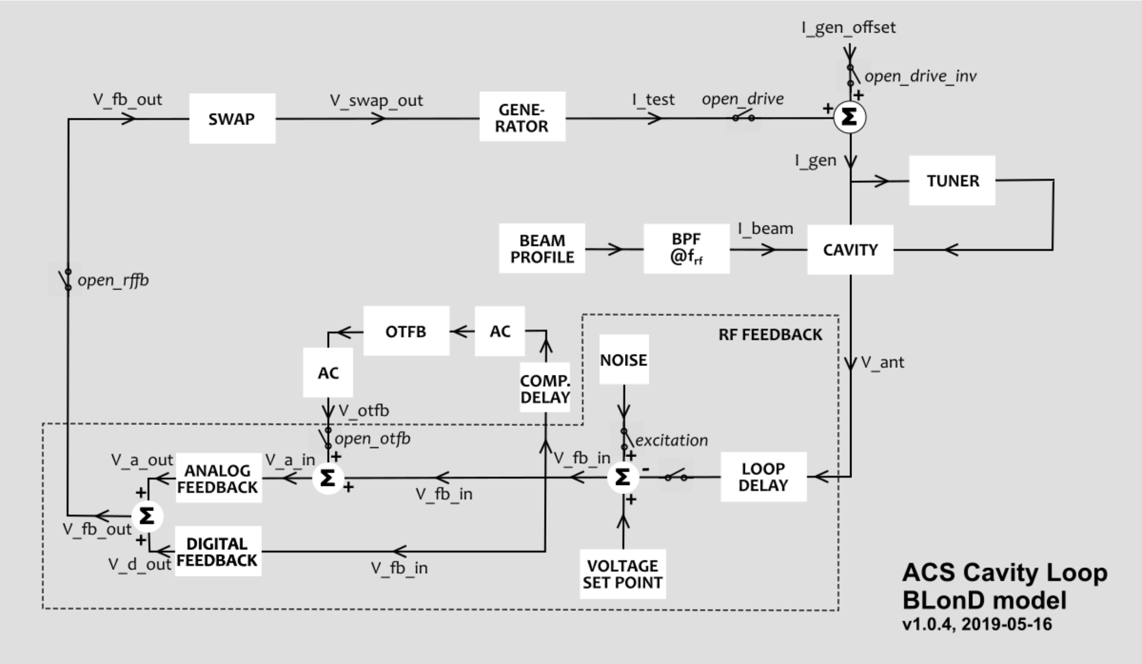


43% RF power overshoot at flat top

Power transients- appendices

RF power transients at injection using BLonD

- **Adapted LHC Cavity Loop class in BLonD**
- **Sampling time: 25ns**
- **Fixed beam in the longitudinal phase space**



Parameters of the FCCee feedback system	
Time delays	
Loop delay τ_{loop}	700 ns
Analog feedback delay τ_a	28,3 us
Digital feedback delay τ_d	66,7 us
Gains	
Maximum stable analog gain G_a^{max}	$\frac{1}{2\,R/Q\,\omega_{RF}\tau_{loop}}$
Fraction of maximum gain a	5
Analog gain G_a	$\frac{G_a^{max}}{a}$ = 90e-9
Digital gain G_d (eff. $G_a G_d$)	10
Other parameters	
Pre-detuning $\Delta\omega/f_{RF}$	0 Hz
Sampling time	25 ns
Pretracking turn number	50
Phase offset between analog and digital	- 6,7 degrees (foc.)
	+ 6,7 degrees (defoc.)