Updates of the RPO / cavity voltage studies for the FCC-ee booster

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Introduction

A common RF system design for Z, W, and ZH modes of the collider was adopted as a new baseline:
2 RF systems with 50 MW RF power and 1 GV of RF voltage

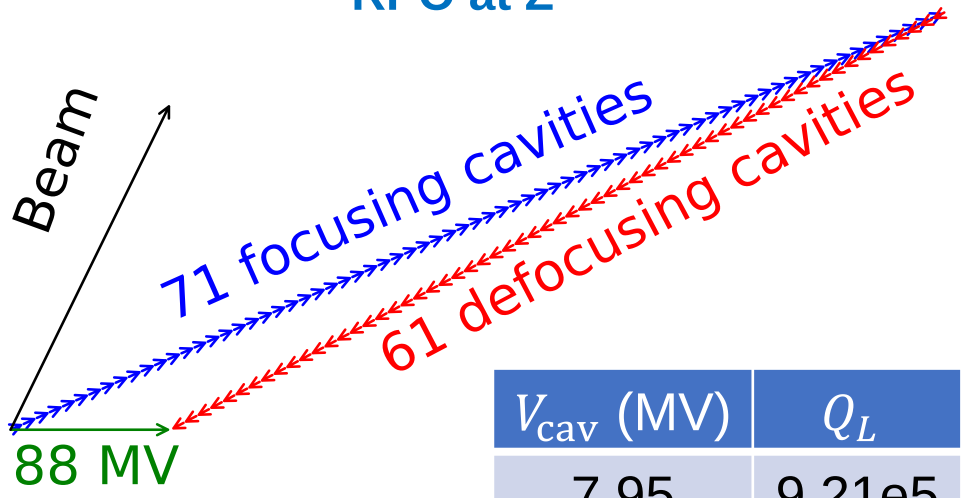
A low RF voltage for Z is achieved using Reverse phase operation mode (RPO, *Y. Morita et al., 2009*)

Splitting and combining beams in the RF straight section covers the RF voltage range for W and ZH

→ The Booster RF system requires similar flexibility to achieve a smooth switch between operational modes

	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1283	0.088
W	80	135	1.05
ZH	120	26.7	2.1

RPO at Z



V_{cav} (MV)	Q_L
7.95	9.21e5

Design constraints

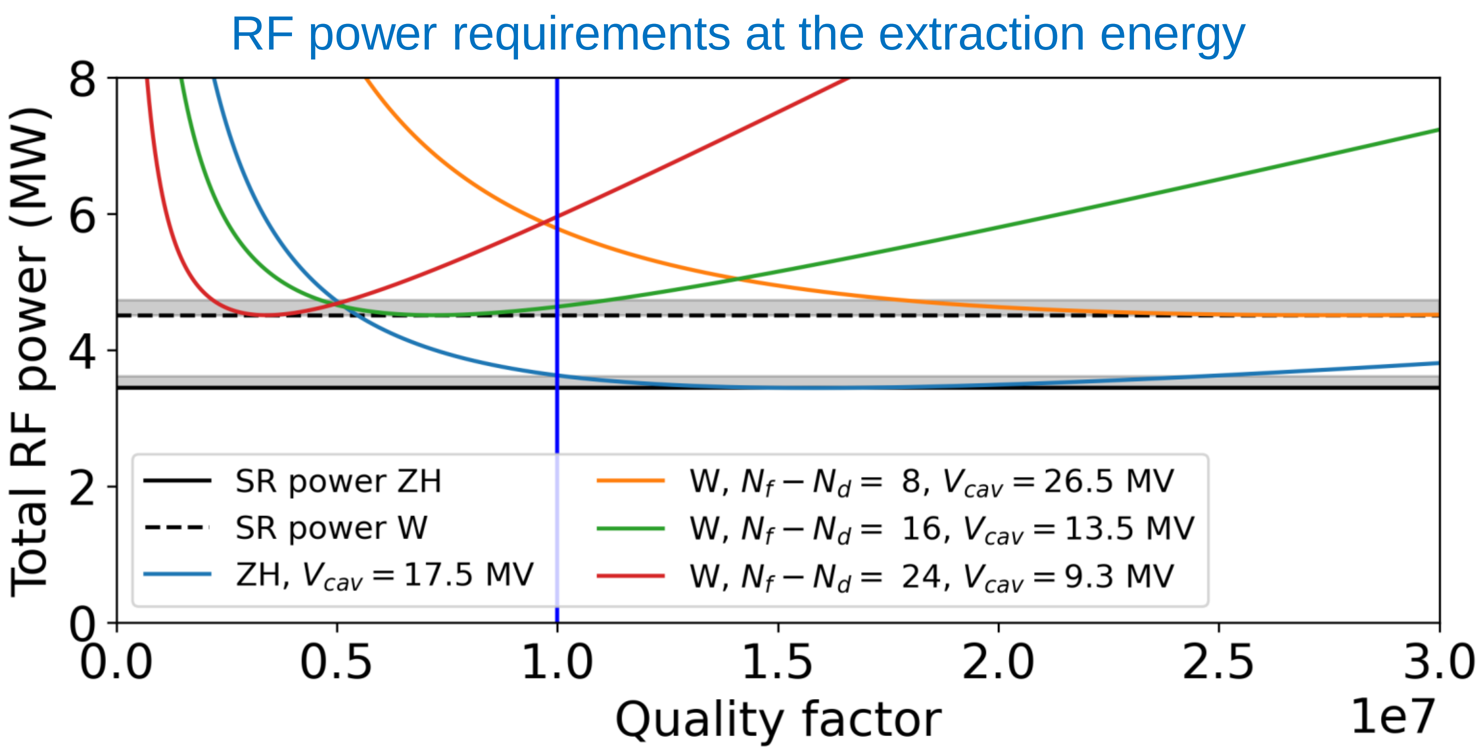
Booster RF system for Z-W-ZH modes:
→ Various RF voltages and beam currents must be covered without hardware modifications

- 112 6-cell cavities, four cavities per source (~50 kW per cavity)
- Maximum cavity voltage is defined by ZH mode (17.5 MV)
- Fixed Q_L should minimize RF power at flattop and ideally through the whole cycle
- Reverse phasing mode should be used to cover an enormous RF voltage range (50 MV→ ~2 GV)

Main RF-related parameters

	Unit	Z	W	ZH
Beam current	mA	16	13	2
RF voltage (FB)	MV	50		
RF voltage (FT)	MV	57	402	1960
Max SR power	MW	1.05	4.51	3.44

Optimal coupling: flattop considerations



RPO with four cavities per source leads to big discrete steps of the difference between the number of focusing and defocusing cavities, $N_f - N_d$

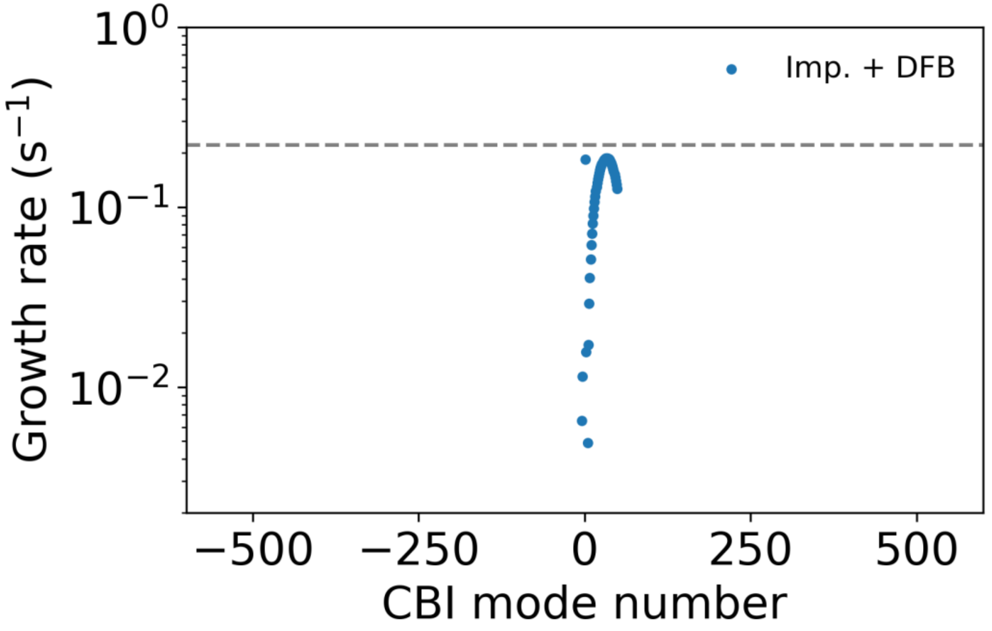
→ $N_f - N_d = 8$ is excluded due to very high RF voltage per cavity

→ $Q_L \sim 10^7$ is a reasonable compromise with less than 5% average power overshoot for W and ZH modes

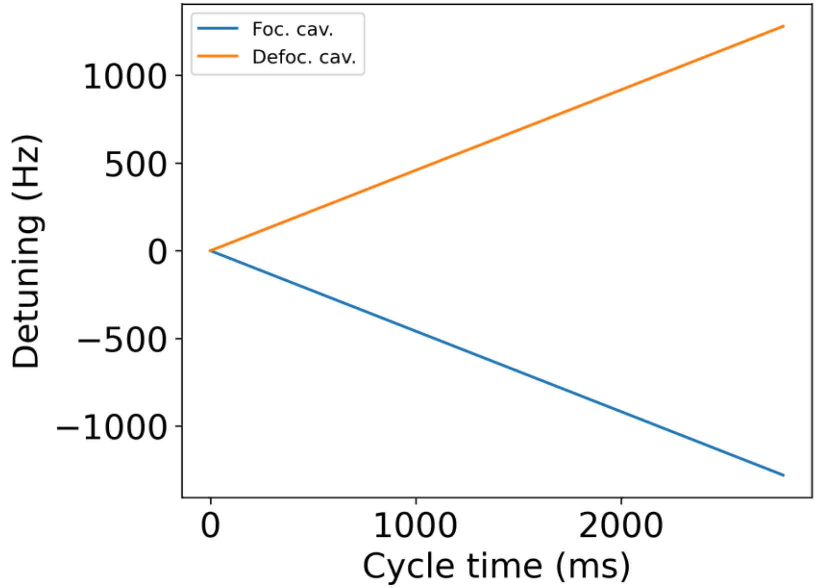
Coupled-bunch instabilities at 20 GeV

Assuming the same $N_f - N_d = 16$, we need V_{cav}~ 3.1 MV to get 50 MV at injection energy

Minimizing RF power by detuning the cavities can drive coupled bunch instabilities

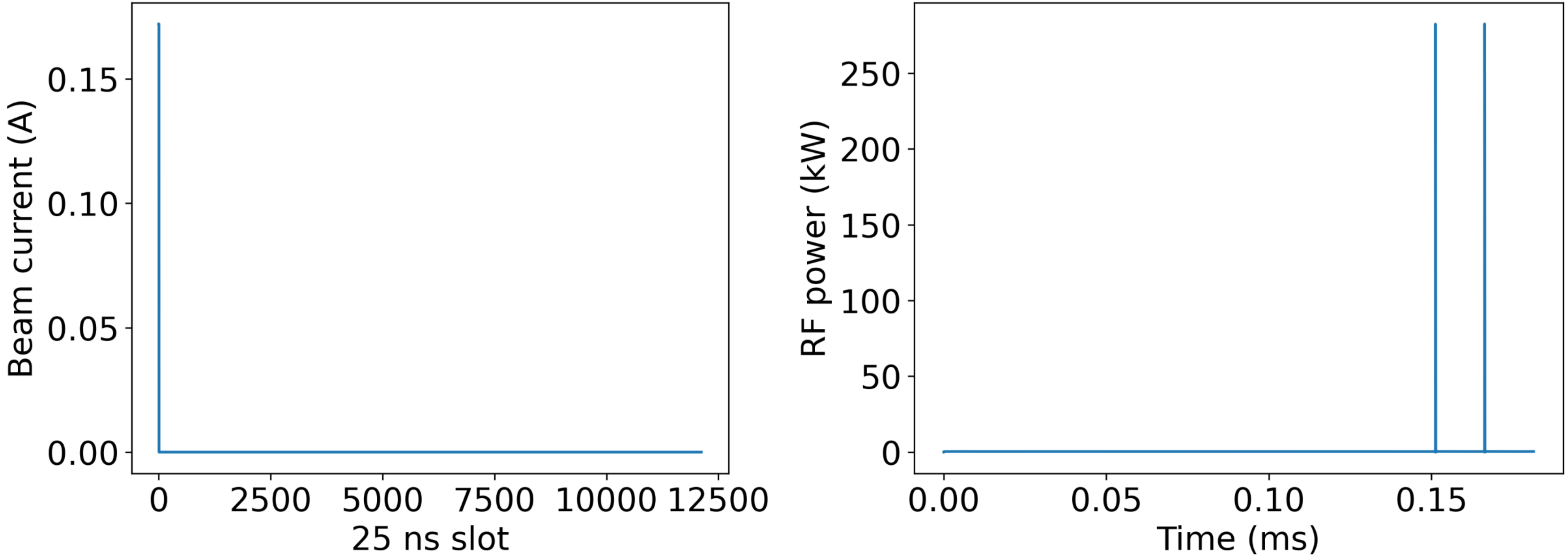


Optimal detuning during injection for Z



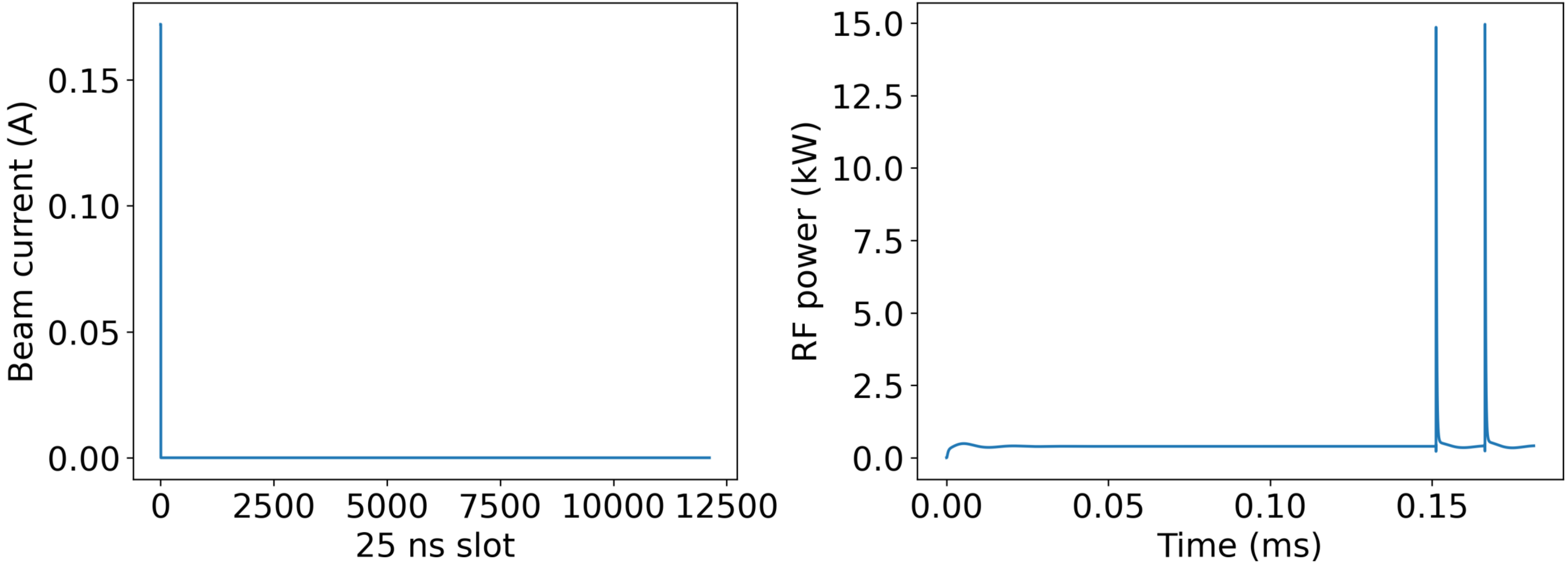
→ No margin for beam stability with direct RF feedback activated
We could profit from installing wigglers (1 wiggler → gain of 4)

RF power at injection



Large transients with the full feedback gain due to high peak beam current

RF power at injection



Reduction of gain by a factor of 5 significantly suppresses power transients
Feedback gain can be ramped up together with beam intensity
Additional margin with wigglers would be beneficial
Filling should be as uniform as possible

Conclusions

- Reverse phase operation seems feasible for the high-energy booster to avoid hardware modifications for Z, W, and ZH modes
- Beam instabilities due to fundamental mode require strong feedback
- RF feedback leads to large power transient at injection, which can be cured if additional stability margin is available (wigglers)

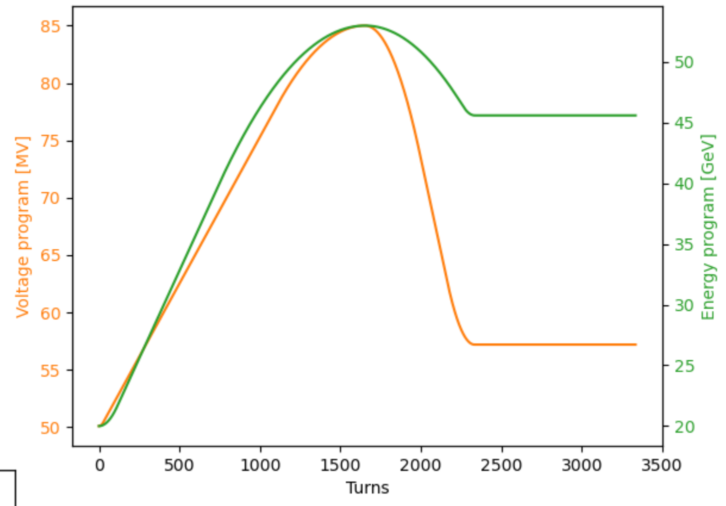
Thank you for your attention!

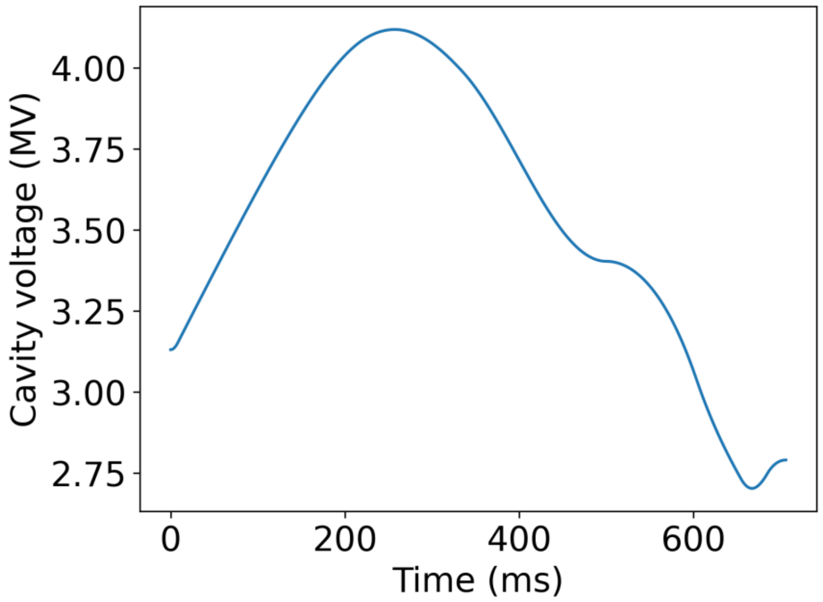
Backup slides

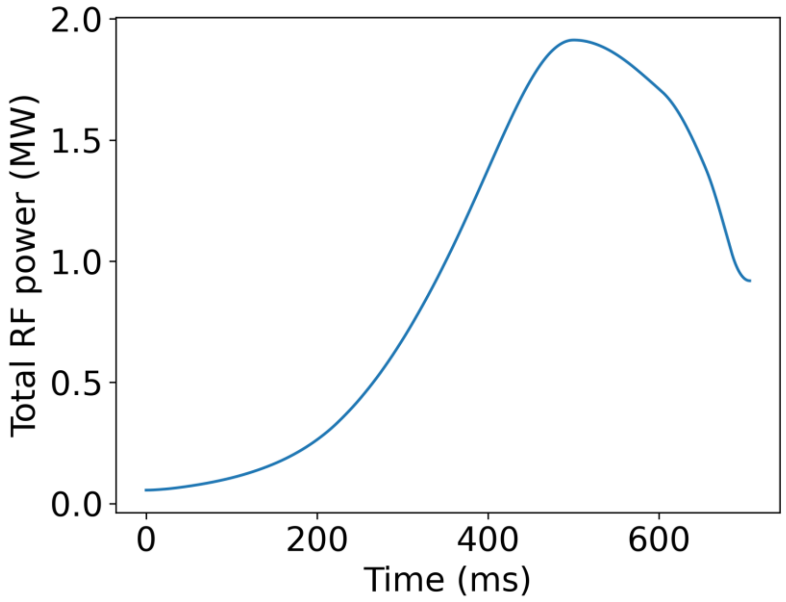
High-Energy Booster cycle

Energy ramp and RF voltage programs were initially designed for Z (*A. Vanel, FCC week, 2024*) and later for $t\bar{t}$ modes

RF voltage and energy evolution for Z

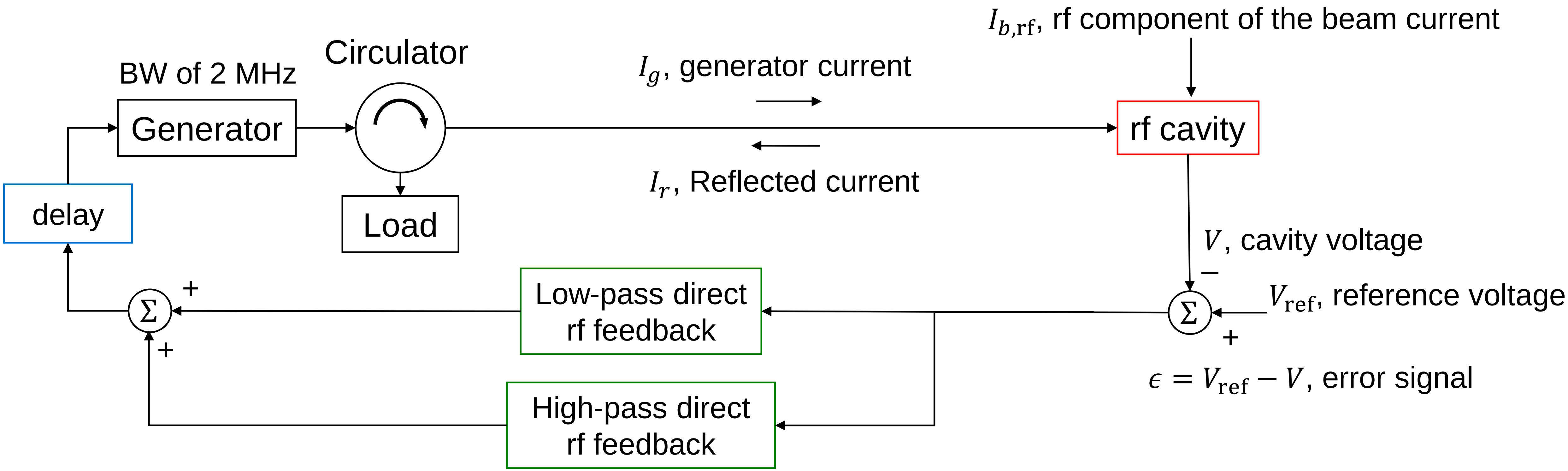




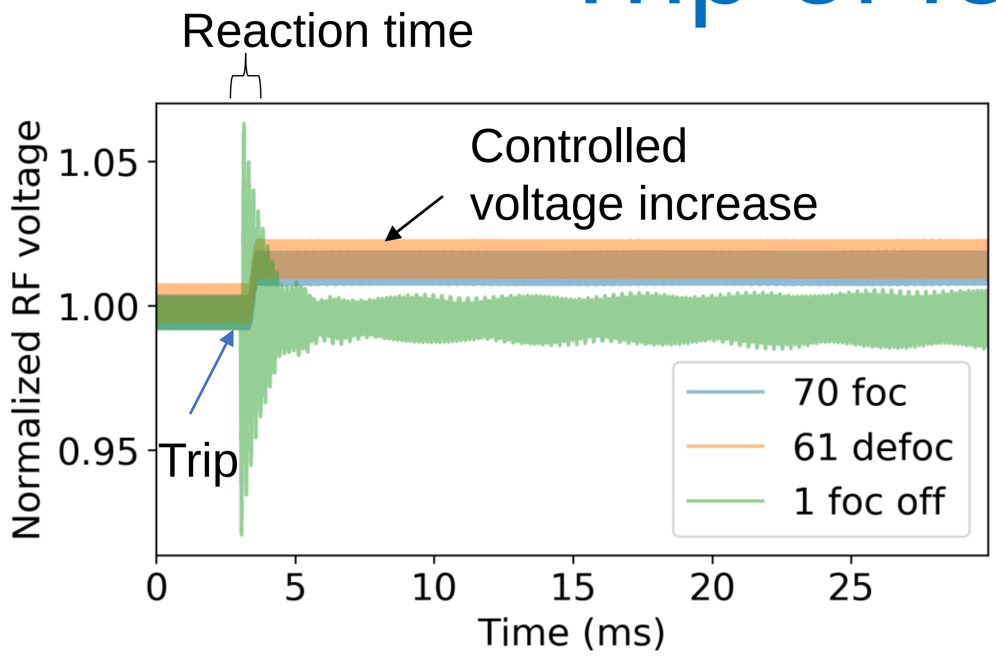


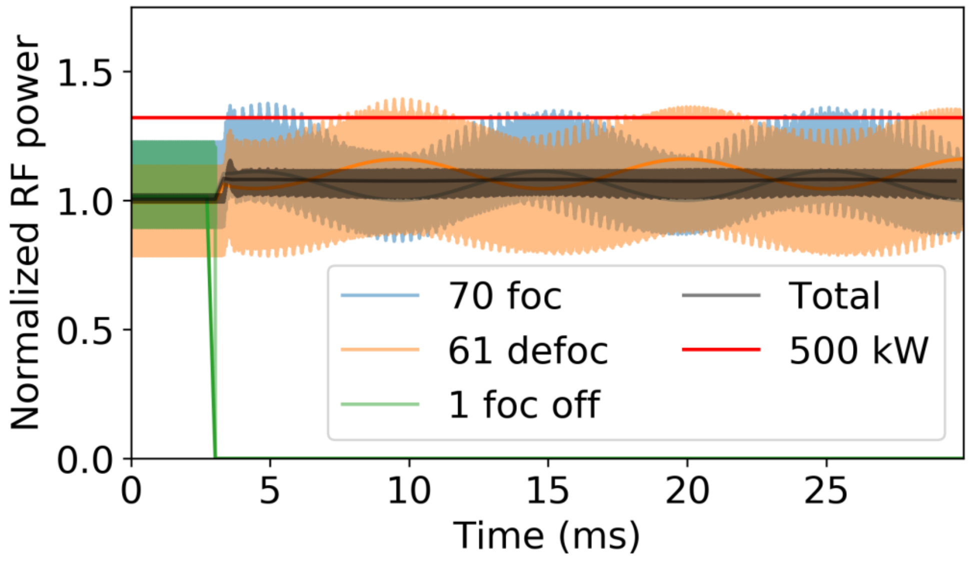
RF system block diagram

FCC feedback system assumed to be similar to one in the LHC *(P. Baudrenghien et al, 2006)*

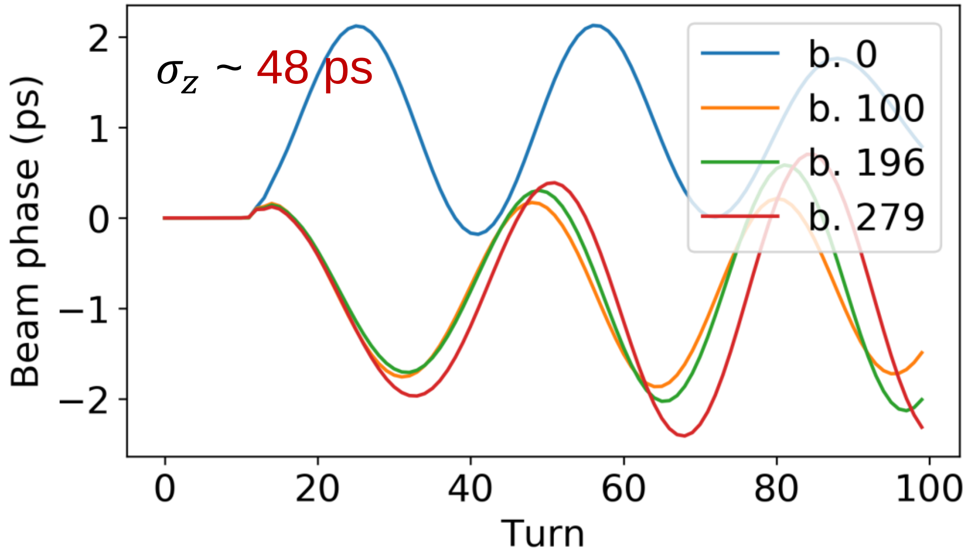


Trip of focusing cavity

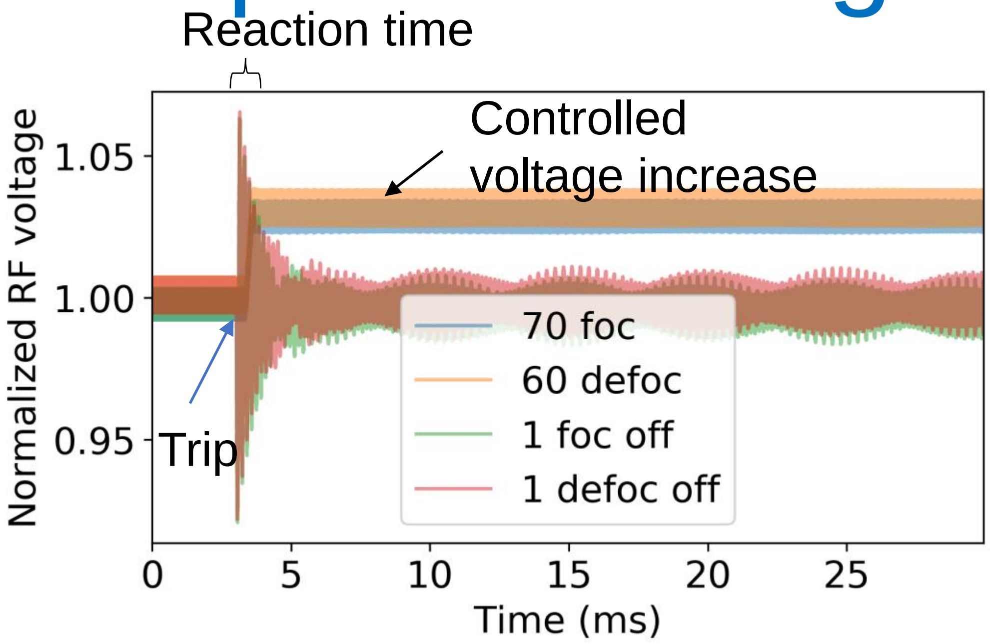


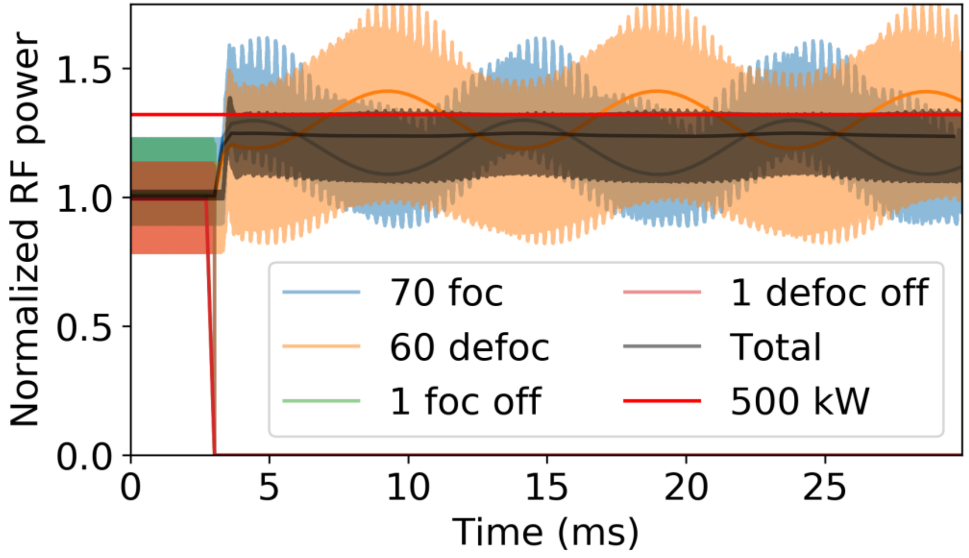


- Short RF voltage transients ~6%
- Peak power of other cavities is modulated at synchrotron frequency (avg. <15%, peak <40%)
- Initial bunch oscillation amplitude is <4% of rms bunch length



Trip of focusing and defocusing cavities





- Short RF voltage transients ~6%
- Peak power of other cavities is modulated at synchrotron frequency (avg. <45%, peak <80%)
- Initial bunch oscillation amplitude is <8% of rms bunch length