RF POWER TRANSIENTS AT INJECTION ENERGY IN THE FCC-ee HIGH-ENERGY BOOSTER

L. Valle*, I. Karpov
CERN, Geneva, Switzerland

Abstract

The FCC high-energy booster RF system consists of 112 superconducting cavities at 800 MHz for the operation modes at ZZ, WW, and ZH energies, with an additional 408 cavities for the $t\bar{t}$ stage. The first three working points require a wide total voltage range from 50 MV to 2 GV. To cover this huge range, Reverse Phase Operation (RPO) will be employed [1]. It groups the cavities into focusing and defocusing families, according to their phase. To provide beam for the relevant operation modes with the booster and provide sufficient voltage per cavity, the RF power requirements are estimated and minimized analytically assuming a defined detuning program. This includes Lorentz force detuning compensation. Additionally, transient power requirements of the RF system in the RPO operation are dynamically computed using the BLonD tracking code. The simulations are performed with sparse profiles, to limit the beam observation to the filled buckets. An LHC-like cavity feedback is adapted to the booster characteristics and allocated to both RPO families. Mitigation measures to reduce the power transients are discussed in this contribution.

INTRODUCTION

The FCC high-energy booster alternatively prepares electrons and positrons for injection into the collider. Each booster cycle includes an accumulation period at flat bottom with parameters listed in Table 1. Then, an acceleration part brings the bunches to the design extraction energy for injection into the collider. The energy ramp of the ZZ mode includes an overshoot in energy to boost radiation damping and achieve smaller beam sizes at extraction [2]. Finally, a flat top for extraction followed by a 'deceleration' mode restore the booster parameters before the following cycle. This contribution focuses on the accumulation part of the booster cycles for all foreseen operation modes.

Table 1: Parameters of the Booster Cycles for all Four Operation Modes

Mode	ZZ	WW	ZH	$t\bar{t}$
Number of bunches	1120	928	292	60
Bunch intensity [10^{10}]	2.725	1.268	1.268	1.268
Accumulation time [s]	2.8	2.32	1.92	0.6
Number of trains	40	8	2	2
Number of batches per train	7	29	146	30
Number of bunches per batch	4	4	2	2
Injection rate [Hz]	100	100	100	50

* lina.valle@cern.ch

SIMULATION FRAMEWORK

Macroparticle tracking simulations of the full accumulation period of each booster cycle has been conducted using the code Beam LONgitudinal Dynamics (BLonD) [3]. Particles are represented via macroparticles. The beam profile is obtained as a time projection of the bunch distribution in the longitudinal phase space. The time resolution is defined by slices. In the case of the FCC-ee booster, the bunches are about 60 ps-long in a 1.25 ns bucket and distributed along the 242400 buckets. Consequently, the profile object requires a large number of slices to properly resolve the FCC bunches along the 90 km high-energy booster.

Sparse Profiles and Multi-Turn Injection

Optimizing simulations for memory usage required the development of so-called sparse profiles. A sparse profile holds a finite number of continuous sub-profiles. Each subprofile covers one or multiple buckets, defined through a filling pattern. Previous implementations defined a continuous profile per bucket for beam monitoring. An update extended the sparse profiles to create a profile per bucket or batch, respectively. For instance, for 1024 slices per bucket, a significant reduction of a factor 112 and 5.6 is achieved with a sparse profiles per bucket and per batch respectively, for the initial two batches of the ZZ booster cycle. The sparse profiles only hold slices at the supposed location of the bunches, alleviating their memory allocation.

Implementation of the cavity feedback in the booster BLonD simulation called for a continuous profile over one batch, as the charge counting of the RF beam current calculation needs a profile length longer than a bucket. As such, a sparse profile per batch was implementing for accurate charge counting. Additionally, the input file of BLonD was reworked towards minimization of memory: the tracking map is prepared outside the main file, results and beam files saved at each turn for post-processing.

Cavity Loop Parameters

Each cavity must be equipped with its own feedback system. For the simulations, the LHC direct RF feedback was adapted to the FCC-ee booster characteristics [4, 5]. The gain G_a of the feedback is adjusted for each booster cycle to ensure that the RF power required for compensation of transient beam loading does not exceed the power source limit of 60 kW [6]. This contribution refers to the ratio $a = G_a/G_a^{max}$, with $G_a^{max} = 1/2/(R/Q\omega_{RF}\tau_{loop})$ as the maximum gain which ensures the loop stability [7]. The ratio R/Q is the normalized shunt impedance, ω_{RF} the angular RF frequency and the overall loop delay $\tau_{loop} = 700$ ns. The parameter a is set to 5 for ZZ to ZH and 1 for $\mathrm{t\bar{t}}$, to maintain the power transients below the RF power limit.

Minimization of the generator power during accumulation requires the detuning Δf of the RF cavities to be updated to its optimal value with each injection, according to the new stored beam current I_{beam}, following $\Delta f_{\mathrm{opt}} \propto I_{\mathrm{beam}}$. The tuning requirements for the booster cycles are detailed in [2].

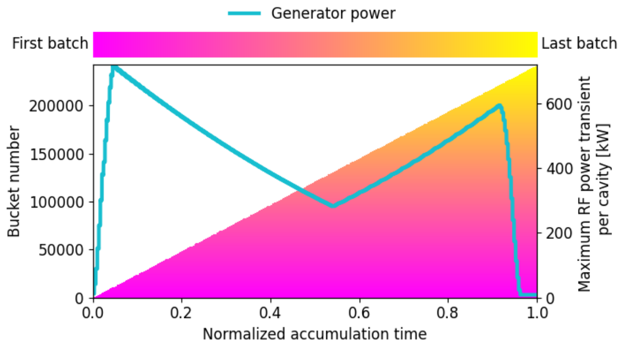
Synchrotron Radiation and Quantum Excitation

Synchrotron radiation damping in BLonD is handled by computing the energy lost per arc, the longitudinal damping time and the natural energy spread from the radiation integrals or within the isomagnetic assumption. The energy kick from radiation damping is composed of (i) the energy lost due to synchrotron radiation U_0 estimated for the synchronous particle, (ii) a radiation damping term applied to the energy offset of the macroparticles ΔE array, proportional to $\Delta E/\tau_z$ with τ_z the longitudinal damping time and (iii) a quantum excitation kick proportional to σ_E^0/τ_z with σ_E^0 the natural energy spread, applied to all particles with a normal distribution.

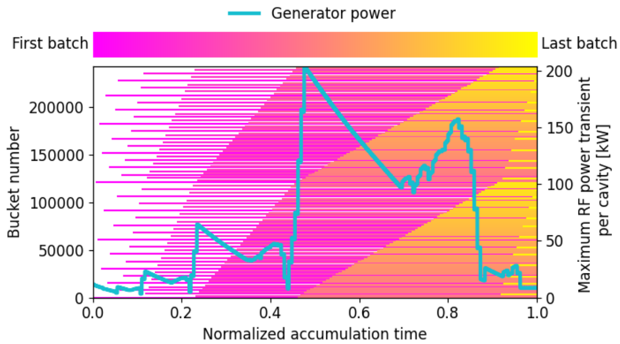
IMPACT OF THE BOOSTER FILLING SCHEME ON THE POWER TRANSIENTS

The filling scheme in the booster has an impact on the RF power transients and the compensation of transient beam loading. Accumulating batches in the same train will result in a strong dephasing at the beginning of the turn due to transient beam loading, which results in an overcompensation of the cavity voltage and phase by the feedback system. A light adaptation of the filling scheme in the booster controls the peak power requirements and contains them below the power source limit of 50 kW per cavity [6]. Figure 1 compares the impact of three different filling schemes on the generator power per cavity: (a) by injecting the new batch next to the stored beam, (b) by increasing the longitudinal distance between the injected bunches and the stored beam (exploiting the ring symmetry) and (c) by distributing the injected batches per train, and maximizing the longitudinal distance between the stored beam and the injected bunches within each train.

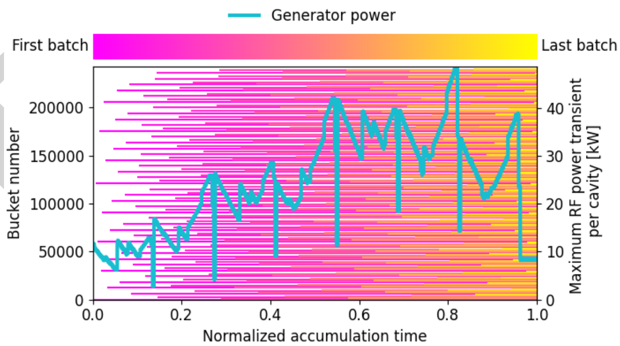
The latter results in a lower peak transients during accumulation. This filling scheme is propagated and applied to all other modes. In all cases, the power transients during the last turn, where the stored beam current is maximum, do not exceed 8 kW per cavity.



(a) Injection following the batch list.



(b) Distributing the bunches to maximize the distance between the injected bunches and the stored beam.



(c) Distributing the batches per train, and within each train, to maximize the distance between the stored beam and the injected bunches.

Figure 1: Impact of the filling scheme into the high-energy booster on the RF power transients during the accumulation period of the ZZ booster cycle. The last filling scheme is chosen to proceed with the simulation of the other modes.

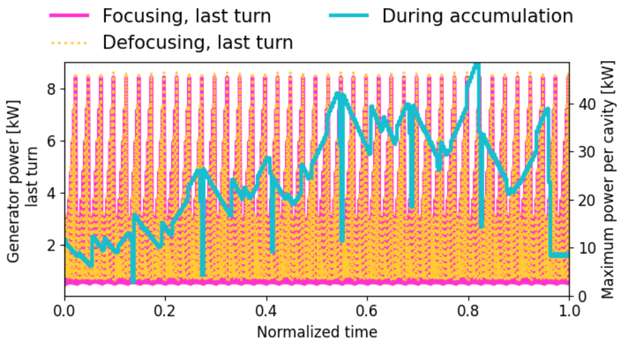
POWER TRANSIENTS FOR ALL OPERATION MODES

Power Transients for the ZZ Operation Mode

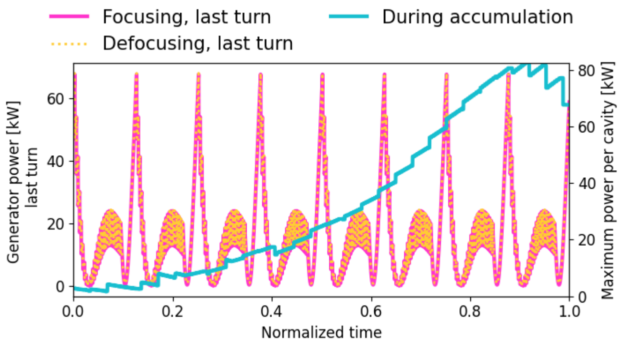
Including the evolution of the maximum peak power during the full accumulation period with the optimized filling scheme, Fig. 2(a) displays the power transients of both focusing and defocusing cavities during the last turn of the accumulation period prior to acceleration and after the last injected bunches, for an overshoot energy ramp [2].

Power Transients for the WW Operation Mode

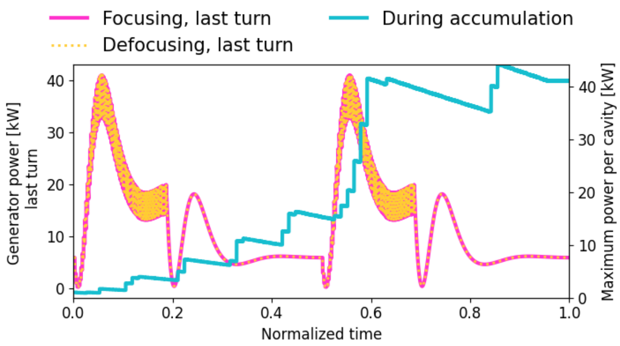
The RF power transients of the last turn of the accumulation period are displayed in Fig. 2(b) for both the focusing and defocusing cavities. On top of the evolution within the turn, the evolution of the maximum peak power during the accumulation time is displayed. The peak power reaches a maximum of 80 kW towards the end of the accumulation. Further modifications of the detuning program at the end of



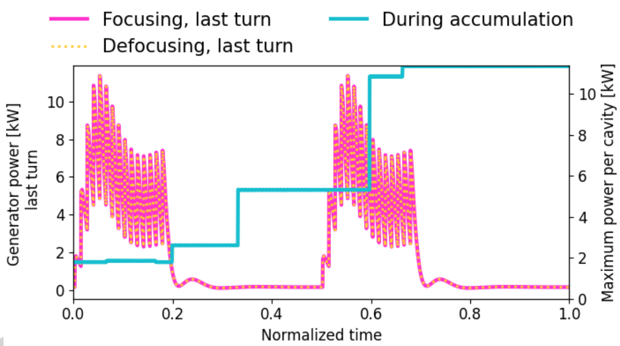
(a) ZZ mode



(b) WW mode



(c) ZH mode



(d) $t\bar{t}$ mode

Figure 2: RF power transients per focusing and defocusing cavities during the last turn of the accumulation period (pink and yellow lines respectively) and evolution of the maximum peak power per cavity during the accumulation period of all booster cycles (cyan line).

the accumulation period are required, to maintain the peak power below the 50 kW power source limit.

Power Transients for the ZH Operation Mode

The low batch current generates low power transients at the start of accumulation (see Fig. 2(c)), yet the dense trains induce a strong compensation from the cavity feedback. To keep the peak power below the source limit, the feedback gain is kept at a ratio 5 for each cavity loop.

Power Transients for the $t\bar{t}$ Operation Mode

An extra 332 cavities will be installed in the high-energy booster of FCC-ee for the $t\bar{t}$ mode. The power source envisaged for that stage are 15 kW solid state amplifiers per cavity [6]. The filling scheme does not have a big impact on the power transients for the $t\bar{t}$ booster cycle, considering the low intensity per bunch and total number of bunches (see Tab. 1). Figure 2(d) confirms the power transients for $t\bar{t}$ remain below the RF power limit including optimal detuning.

CONCLUSION

Complete and consistent simulation of the longitudinal beam dynamics in the high-energy booster of the FCC-ee required several adaptations of the code BLonD. Sparse profiles significantly reduce the simulation memory requirements and enable full simulation of the accumulation period of all booster cycles. The deployment of cavity feedback for all focusing and defocusing cavities in the RPO is required for beam stability at injection and implementation of an optimal detuning program. Compensation of transient beam loading reduces the power requirements per cavity. The RF power for all four operating modes evolution was tracked for the entire accumulation period for all booster cycles. Optimization of the booster filling scheme along with adjusting the feedback gain and detuning program brought the transient peak power below the RF power source requirements.

ACKNOWLEDGEMENTS

The authors would like to thank Birk Karlsen-Baeck, Mariangela Marchi, Leandro Intelisano, Ruben Heine, Paula Hickersberger, Leonard Thiele and Simon Lauber for fruitful conversations.

REFERENCES

[1] Y. Morita *et al.*, “Status of KEKB Superconducting Cavities and Study for Future SKEKB”, in *Proc. SRF’09*, Berlin, Germany, Sep. 2009, paper TUPPO022, pp. 236–238. https://jacow.org/SRF2009/papers/TUPPO022.pdf

[2] L. Valle, A. Chance, and I. Karpov, “Energy ramps for the high-energy booster of the FCC-ee collider”, presented at IPAC’26, Deauville, France, May 2026, paper MOP1090, this conference.

[3] H. Timko *et al.*, “Beam longitudinal dynamics simulation studies”, *Phys. Rev. Accel. Beams*, vol. 26, no. 11, p. 114602, Nov. 2023. doi:10.1103/PhysRevAccelBeams.26.114602

[4] P. Baudrenghien *et al.*, “The LHC Low Level RF”, CERN, Geneva, Switzerland, CERN-LHC-Project-Report-906, 2006. https://cds.cern.ch/record/971742

[5] B. E. Karlsen-Baeck *et al.*, “Coupling local and global rf feedback loops for macroparticle tracking simulations”, *Phys. Rev. Accel. Beams*, vol. 29, no. 3, p. 032802, Mar. 2026. doi:10.1103/bxs4-f9nl

[6] M. Benedikt *et al.*, “Future Circular Collider Feasibility Study Report Volume 2”, Rep. 19, 2025. doi:10.17181/CERN.EBAY.7W4X

[7] D. Boussard, “Control of cavities with high beam loading”, *IEEE Trans. Nucl. Sci.*, vol. 32, pp. 1852–1856, 1985. doi:10.1109/TNS.1985.4333745