

IMPACT OF POWER SUPPLY RIPPLE ON BEAM DYNAMICS IN THE FCC-ee

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Abstract

The Future Circular electron-positron Collider (FCC-ee) is a proposed next-generation lepton collider designed to deliver very high luminosities across a broad beam-energy range. The extremely tight emittance and beam stability requirements of the machine make the control of time-dependent magnetic field variations critical. Power supply ripple introduces periodic fluctuations in the magnetic field of accelerator magnets, which translate into turn-by-turn orbit and tune modulations, potentially leading to emittance growth and beam degradation. In this work, single-particle tracking simulations within the Xsuite framework are used to assess the impact of such perturbations on beam quality for the Local Chromaticity Correction (LCC) optics design, with the aim of defining power converter specifications.

INTRODUCTION

Power converters are a major cost-driver for the construction of the FCC-ee [1–3] accelerator. Their specific design and parameters are under development and are closely related to beam performance requirements. In practice, their output is not perfectly constant but contains ripple components [4] that can degrade the beam performance and limit the luminosity reach. Through the impedance of the magnet circuit, a voltage ripple at the power converter output generates a current ripple in the magnet (chain), which in turn produces a periodic modulation of the magnetic field seen by the beam. As the beam traverses the magnets turn after turn, this periodic perturbation acts as a resonant excitation that can drive tune modulation, emittance growth, and ultimately particle losses [5].

The magnetic field modulation experienced by the beam depends on the frequency f and can be expressed by a transfer function, such that:

$$B(f) = T_{B_m \rightarrow B_b}(f) \cdot T_{I \rightarrow B_m}(f) \cdot T_{V \rightarrow I}(f) \cdot V(f), \quad (1)$$

where $V(f)$ is the voltage ripple of the power supply, $T_{V \rightarrow I}(f)$ is the admittance of the circuit as seen by the power converter, $T_{I \rightarrow B_m}(f)$ is the transfer function from the circuit current to the magnetic field, and $T_{B_m \rightarrow B_b}(f)$ is the magnetic transfer function from the field generated by the magnet to the field experienced by the beam [6, 7]. For the FCC-ee, these transfer functions are still under development. In this work, a worst-case scenario is assumed in which voltage ripple is directly translated into magnetic-field ripple (i.e. all transfer functions are set equal to one). This conservative assumption provides first estimates of the required tolerances.

Ripple components are expected mainly at 50 Hz and at higher harmonics extending well into the kHz range [8] but are not yet strictly defined [9]. Frequencies close to betatron tunes or their harmonics are of particular concern, as they can resonantly excite the beam. The goal of these studies is therefore to quantify, through beam dynamics tracking simulations, the threshold below which power supply ripple has negligible impact on beam quality, and to translate this into power converter specifications [10].

Following the comprehensive FCC-ee optics comparison exercise carried out at the end of 2025 [11], the Local Chromaticity Correction (LCC) lattice has been recommended as the preferred baseline optics. All studies presented here are therefore performed for the LCC design at the Z operating point, corresponding to a beam energy of 45.6 GeV.

SIMULATION FRAMEWORK

Magnet Circuits

The FCC-ee ring contains several families of magnets, each powered by dedicated power converter circuits. For the purpose of these studies, four main families are simulated in the LCC optics: the arc dipoles, the arc focusing quadrupoles (QF), the arc defocusing quadrupoles (QD), and the final doublet (FD) quadrupoles.

Arc dipoles all belong in the same magnet family and they can be powered in series in each arc. This requires eight circuits in total, one for each arc.

In terms of optics, arc quadrupoles are grouped into one family for focusing and one family for defocusing quadrupoles. The number of required circuits is two times eight, 16 in total per beam for all arc quadrupoles. However, due to power converter voltage limitations the amount of total circuits is increased to 32 per beam, one for each half arc [11].

The magnet circuits for the final focusing quadrupoles are still under development. In the scope of this work we consider that they are connected in series and influenced by the same ripple. This amplifies its effect but it gives a first estimate on the sensitivity of the final doublet.

For each family, a scenario is considered in which all elements in all arcs experience identical ripple in amplitude, frequency, and phase. This likely represents a worst-case configuration for two reasons: in practice, magnets belonging to the same family are powered by separate circuits which can experience different ripple levels, and even within a single circuit the current ripple is progressively attenuated along the transmission line. Nevertheless, it provides a useful first step for assessing the sensitivity of the lattice under critical conditions.

Xsuite Ripple Model

Power supply ripple perturbations are studied with tracking simulations implemented within the Xsuite framework [12]. The ripple is simulated by inserting a `xtrack.Exciter` beam element into the lattice at each magnet location of the selected family. The `xtrack.Exciter` object models a time-dependent thin multipole, providing a sinusoidal modulation of the magnet strength of the form:

$$f(t) = A \sin(2\pi ft + \phi), \quad (2)$$

where $A = \Delta k_n$ is the excitation amplitude ($n = 0$ for dipole field ripple, $n = 1$ for quadrupole gradient ripple, etc.), f is the excitation frequency, and ϕ is the initial phase.

Simulations

To simulate and study the impact of power supply ripple on the beam, Gaussian particle distributions are generated and tracked through the lattice model for 5000 turns. The optics version used is the same as the comparison report — LCC v106.1 — and the final lattice used for tracking is optimized using the xutil framework [13]. All the tracking simulations include quantum synchrotron radiation, weak-strong beam-beam interactions and beamstrahlung in all interaction points.

The emittance is then calculated from the tracked beam distribution at the end of each turn. Each simulation includes a single pair of amplitude and frequency.

RESULTS

Figures 1, 2 and 3 show amplitude-frequency scans for the different magnet families. The color-scale represents the emittance blow-up relative to the nominal case (without ripple). These scans allow the definition of a ripple threshold between the region with negligible impact on emittance (blue) and the region where emittance blow-up occurs (yellow). The left axis gives the applied ripple amplitude on the magnetic field in T (dipoles) or the magnetic gradient in T/m (quadrupoles), obtained as Δk_n multiplied by the magnetic rigidity; the same amplitude is also shown normalized to the nominal Z-mode strength. For quadrupoles, the right axis shows the corresponding tune modulation amplitude. In all plots, white lines indicate revolution-frequency harmonics, while red lines denote the transverse tune and its aliases [11].

Arc Dipoles

Figure 1 shows the amplitude-frequency scan for identical ripple applied to all LCC arc dipoles, color-coded with the horizontal emittance growth as a function of ripple frequency up to 12 kHz, as the power converter switching-frequency is expected to be in the kHz range [2, 14]. The scan reveals increased sensitivity at specific frequencies close to the horizontal tune and its harmonics (red vertical lines), appearing as narrow resonance bands. For this reason, the switching frequency of the power converters should not be close to the betatron tune as it maximizes the impact on the beam. By placing the switching frequency to values far from the

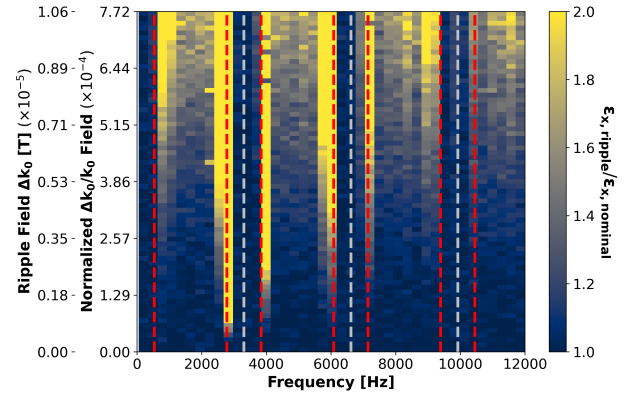


Figure 1: Amplitude-frequency scan for all LCC arc dipoles. Color-scale shows normalized horizontal emittance blow-up ratio.

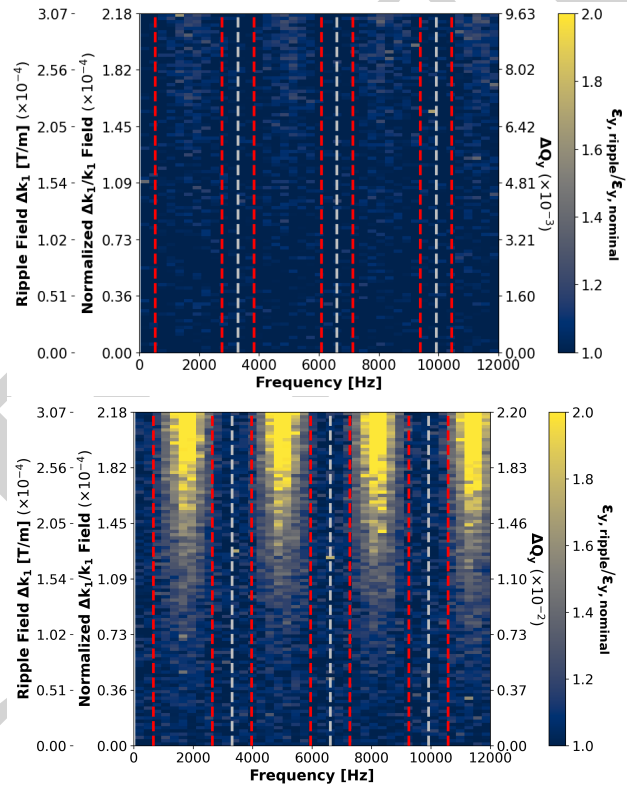


Figure 2: Amplitude-frequency scans for all LCC arc quadrupoles. Top: focusing family, normalized vertical emittance. Bottom: defocusing family, normalized vertical emittance.

betatron tune the ripple effects are minimized. Outside these frequency regions, the overall emittance impact remains small across the simulated amplitude range.

Arc Quadrupoles

Figure 2 shows the scans for the LCC arc quadrupoles, separated into focusing (top) and defocusing (bottom) families, displaying the normalized vertical emittances. The focusing quadrupoles do not have an impact for the simulated amplitudes on the horizontal emittance despite having

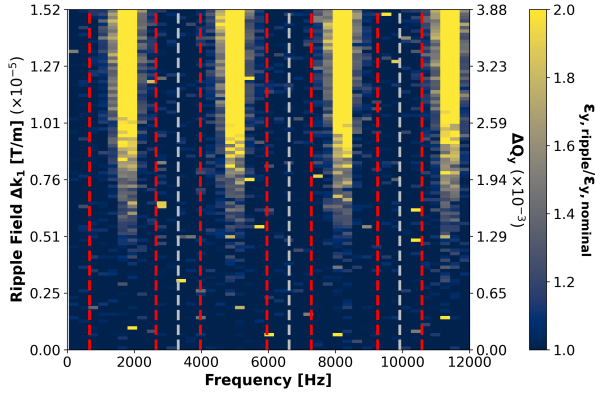


Figure 3: Amplitude-frequency scan for all LCC final doublet quadrupoles. The color-scale shows the normalized vertical emittance blow-up ratio.

a large horizontal tune modulation similar to the vertical tune modulation of the defocusing quadrupoles. However, even if the focusing quadrupoles produce a relatively small vertical tune modulation, there is a subtle impact on the vertical emittance which is much more sensitive than the horizontal one.

For the defocusing quadrupoles, emittance growth becomes significant for gradient ripple amplitudes of the order of 1×10^{-4} T/m. Since power converters are rated at the $t\bar{t}$ operating point (where they deliver maximum current), ripple tolerances must be scaled to the nominal gradient at $t\bar{t}$ rather than at Z. Normalizing the identified threshold by the nominal gradient of 11.8 T/m at $t\bar{t}$ yields a relative ripple requirement of approximately 8 ppm at specific frequencies, which is challenging to achieve with warm magnets.

Final Doublet Quadrupoles

In total, all 40 FD quadrupoles (10 per Interaction Point, four identical IPs) were modulated. Table 1 summarizes the relevant parameters for the FD quadrupoles for the interaction point A. Figure 3 shows the scan for identical ripple applied to all 40 FD quadrupoles in the LCC lattice. The vertical beta functions for the FD quadrupoles are significantly larger than the horizontal ones and as such the effect of the quadrupole ripple on the vertical plane is larger.

In contrast to the arc regions, the FD quadrupoles exhibit significantly higher sensitivity to power supply ripple. Due to the very large β -functions at the FD locations, even small field perturbations of the order of 1×10^{-5} T/m lead to large tune modulation levels of the order of 2×10^{-3} , reflecting the extreme final-focus conditions of the LCC design.

Scaling the identified thresholds to the $t\bar{t}$ reference for power converter rating, the corresponding requirement would fall in the Class 0 accuracy class [10]. However, based on current design considerations, the FD quadrupoles are expected to be superconducting. The large inductance of superconducting magnet circuits significantly attenuates high-frequency ripple components in the current-to-field transfer function, which is expected to considerably relax these requirements in practice. Nevertheless, careful con-

Table 1: Final Doublet Quadrupole Parameters for the LCC Lattice in Z Mode

Quadrupole	k_1 [T/m]	β_x [m]	β_y [m]
QF1BL	12.9	3016.5	5253.7
QF1AL	15.2	2621.1	6111.9
QD0CL	-15.0	1043.6	11750.1
QD0BL	-22.8	386.9	15167.7
QD0AL	-38.0	123.9	12565.3
QD0AR	-38.0	64.1	8228.6
QD0BR	-22.8	135.6	12984.8
QD0CR	-15.6	418.9	15066.5
QF1AR	15.2	1670.7	8781.5
QF1BR	13.8	2710.5	5739.9

sideration of the power converter design will be required, given the high sensitivity of the final doublet to small field perturbations.

SUMMARY

Single-particle tracking simulations with Xsuite have been used to assess the impact of power supply ripple on beam dynamics in the FCC-ee LCC optics at the Z operating point. Without taking into account actual transfer functions, amplitude-frequency scans of field modulations have been performed for four magnet families: arc dipoles, arc focusing quadrupoles, arc defocusing quadrupoles, and final doublet quadrupoles. The arc dipoles show limited sensitivity, with emittance growth only near tune harmonics, while the arc defocusing quadrupoles impose the strictest warm-magnet requirement of approximately 8 ppm relative ripple at $t\bar{t}$. The final doublet quadrupoles are the most critical due to their extremely high β -functions. On the other hand, they are expected to be based on superconducting technology and thus the associated large circuit inductance is expected to provide significant high-frequency attenuation in practice. The next steps include more realistic power supply ripple configurations, where individual circuits are studied, as well as integrating more magnet families both in the interaction regions and in the arcs, and developing the transfer functions.

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