LINEAR IMPERFECTION AND ORBIT CORRECTION SCHEME FOR THE PERLE ACCELERATOR [*]

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Abstract

PERLE is a multi-turn Energy Recovery LINAC, currently under construction at IJCLab in Orsay (France). It is designed to accelerate electrons of 20 mA beam current to an energy of 250 MeV through three accelerating passes followed by three decelerating passes to dump the beam at injection energy (7 MeV). The first order lattice design has emerged. Therefore, assessing the sensitivity of the optics to linear imperfections is a crucial step toward stable operation. This work investigates the impact of quadrupole misalignments on the beam orbit in both planes, accounting for the presence of horizontal and vertical dispersive sections in PERLE. The resulting orbit distortions are used to identify the most critical locations for diagnostics and correction elements. A correction strategy based on BPM–corrector pairs is implemented using the BMAD framework, and the achievable orbit restoration is evaluated with adequate correction strengths.

INTRODUCTION

Energy Recovery Linacs (ERLs) impose stringent requirements on beam stability, as the beam should be efficiently transported and decelerated to recover its energy. In such machines, even small trajectory deviations can degrade the energy recovery efficiency and potentially lead to beam losses.

PERLE [1] is a multi-turn high-current ERL, in which the same beam is transported through multiple accelerating and decelerating passes. This multi-pass configuration increases the sensitivity to lattice imperfections, as their effects accumulate over successive turns.

In this work [2], the impact of quadrupole misalignments on the PERLE single-turn lattice is investigated using BMAD [3] simulations. The resulting orbit distortions are analyzed to identify optimal locations for beam position monitors (BPMs) and corrector magnets. An orbit correction scheme is then implemented, and its performance is evaluated in terms of orbit and optics restoration.

ORBIT DISTORTION FROM QUADRUPOLE MISALIGNMENTS

In linear beam optics, a transverse displacement of a quadrupole magnet introduces an effective dipole component, resulting in a localized kick to the beam trajectory. For a quadrupole of normalized strength $k_1 = G/(B\rho)$ and magnetic length L, a transverse offset Δx generates an angular deviation given by

$$\Delta x' = k_1 \, \Delta x \cdot L. \tag{1}$$

This kick propagates along the lattice according to the linear transport, leading to orbit distortions whose amplitude scales with the lattice β-function. As a result, regions of high β are particularly sensitive to misalignments.

IMPACT OF QUADRUPOLE MISALIGNMENTS ON PERLE OPTICS

Figure 1 shows the nominal optics of the first turn [4]. The lattice is designed to be achromatic, with vanishing dispersion at the entrance and exit of each section [5, 6].

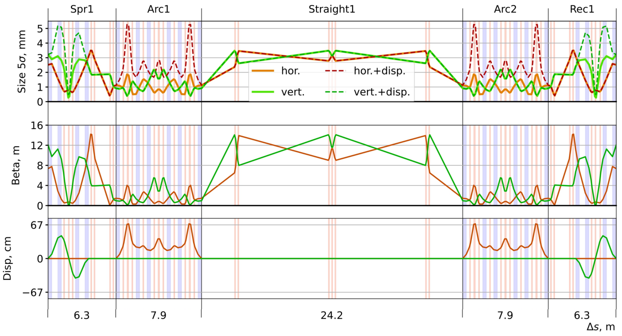

Figure 1: The 5σ beam size, the horizontal and vertical beta functions (β_x, β_y) and dispersion (D_x, D_y) along the first-turn lattice. Quadrupoles are indicated in red, while dipoles are marked in blue.

Random transverse offsets are assigned to all quadrupoles. The offsets are drawn from a Gaussian distribution with zero mean and a standard deviation of $\sigma = 0.1$ mm, consistent with typical installation tolerances. For each configuration, the transverse orbit, dispersion, and optics functions are computed and compared to the nominal design in order to quantify the effect of misalignments.

Orbit Distortion

Figure 2 shows the particle orbit along the PERLE first-turn lattice with random quadrupole transverse misalign-

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ments. In both planes, the reference trajectory is significantly perturbed by the dipole-like kicks induced by the offsets. Orbit excursions of several millimeters are observed, with the largest deviations occurring in regions of high corresponding β-function.

These results confirm the strong sensitivity of the beam trajectory to transverse quadrupole offsets in the PERLE lattice. They also provide guidance for the placement of diagnostics and correction elements.

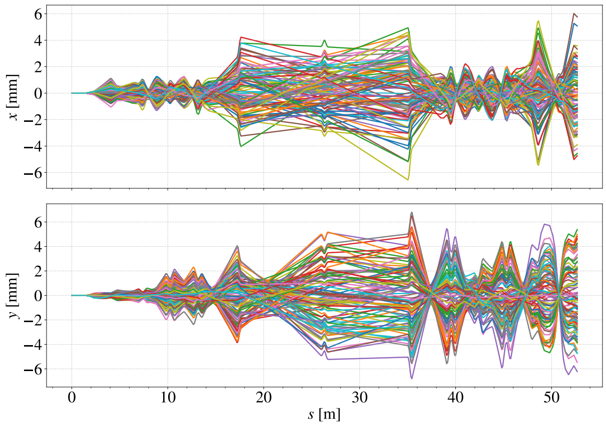

Figure 2: Particle orbit along the PERLE first-turn lattice for 100 simulations with random quadrupole transverse misalignments. The upper and lower panels show the horizontal and vertical orbit, respectively.

Dispersion and Optics Functions

The beta functions remain largely unaffected by transverse quadrupole offsets, since the quadrupole focusing strength k_1 is preserved to first order. However, the induced dipole-like fields generate non-negligible residual dispersion throughout the lattice.

Figure 3 shows the dispersion functions obtained with random quadrupole misalignments. Deviations from the nominal achromatic behavior are observed in both planes, including in the straight sections where the dispersion is expected to vanish. This demonstrates that transverse quadrupole offsets can introduce measurable dispersion growth even in nominally dispersion-free regions.

ORBIT CORRECTION SCHEME

Iterative Orbit Correction

Orbit correction is implemented in BMAD using distributed BPM–corrector pairs and the `lmdif` optimizer, based on the Levenberg–Marquardt algorithm. The correction procedure iteratively minimizes the orbit displacement at selected BPM locations by adjusting the strength of upstream corrector magnets.

BPMs are positioned near locations of maximum orbit excursion, while correctors are placed upstream in regions of high β in order to maximize the steering efficiency. At each iteration, the optimizer adjusts the kick strength until convergence toward the reference orbit is achieved.

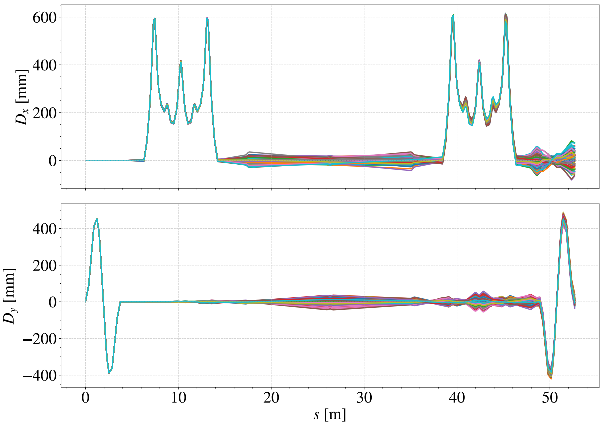

Figure 3: Dispersion functions along the PERLE first-turn lattice for 100 simulations with random quadrupole transverse misalignments. The upper and lower panels show the horizontal and vertical dispersion, respectively.

Figure 4 illustrates the correction procedure for the horizontal plane, showing the progressive reduction of the orbit distortion as BPMs and correctors are introduced along the lattice.

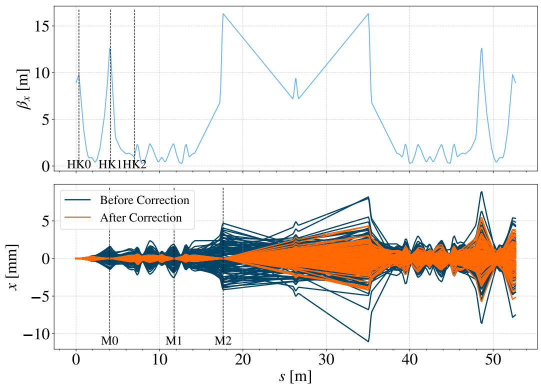

Figure 4: Illustration of the iterative orbit correction procedure in the horizontal plane. Correctors are placed upstream at high-β locations, while BPMs are positioned near orbit maxima. The orbit distortion is progressively reduced as additional BPM–corrector pairs are included.

Correction Performance

The correction scheme was applied over the full PERLE first-turn lattice using ten BPMs and seven corrector magnets. Figure 5 compares the horizontal orbit before and after correction. The correction efficiently restores the beam trajectory, reducing the orbit excursion to within the imposed 1 mm limit over the lattice.

The corresponding effect on the dispersion function is shown in Fig. 6. The residual dispersion generated by quadrupole misalignments is strongly suppressed after correction, particularly in the straight sections.

To validate the correction beyond optics functions, particle tracking was performed for a representative misalignment

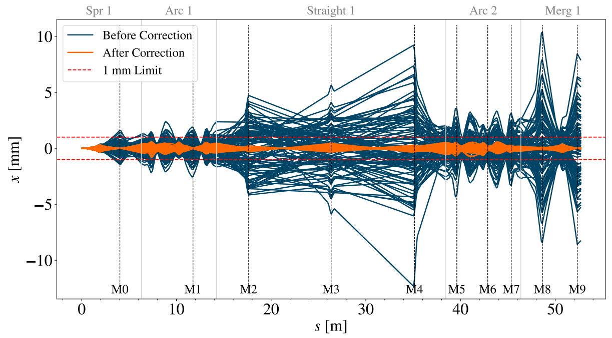

Figure 5: Horizontal orbit before and after correction for 100 simulations with random quadrupole misalignments. BPM locations used by the optimizer are indicated along the lattice. The correction restores the orbit within the imposed 1 mm limit.

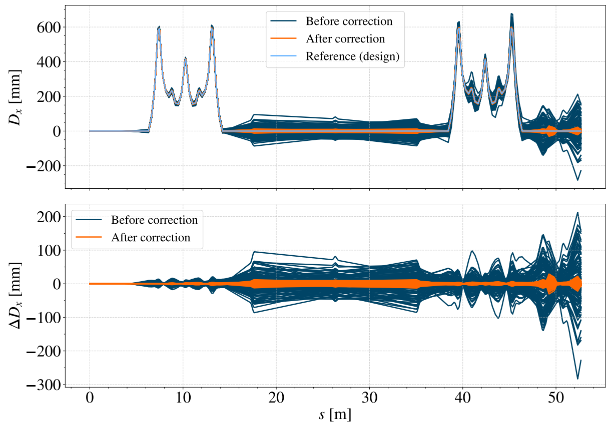

Figure 6: Horizontal dispersion along the first-turn lattice before and after correction.

configuration. Figure 7 shows the beam envelope before and after correction. The corrected beam remains close to the nominal design envelope, demonstrating the robustness of the correction strategy against transverse quadrupole offsets.

CONCLUSION

The sensitivity of the PERLE first-turn lattice to transverse quadrupole misalignments has been investigated using BMAD simulations. Random quadrupole offsets with realistic installation tolerances were shown to generate significant orbit distortions through dipole-like steering effects.

An orbit correction scheme based on distributed BPM–corrector pairs and iterative optimization was implemented and validated. The correction successfully restored the beam trajectory within the imposed 1 mm limit and strongly reduced the residual dispersion throughout the lattice. Particle tracking simulations additionally confirmed the recovery of the nominal beam envelope after correction.

These results provide a first basis for the alignment and orbit correction strategy of PERLE. Future work will extend the study to the full multi-turn ERL, including acceleration and deceleration passes, as well as additional sources of imperfections.

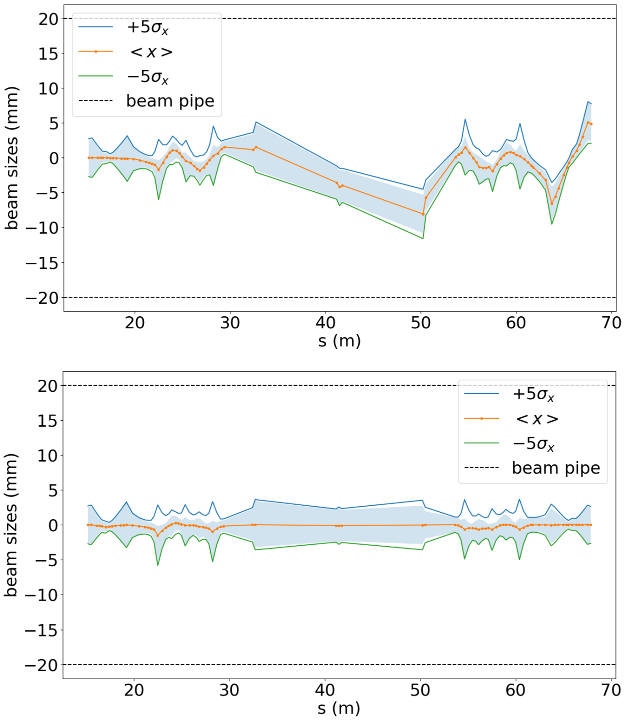

Figure 7: Beam envelope obtained from particle tracking for a representative misalignment configuration: (top) before correction and (bottom) after correction.

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