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STATUS OF THE BEAM DYNAMICS STUDIES FOR THE PERLE ENERGY RECOVERY LINAC

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On behalf of the PERLE collaboration†

Abstract

PERLE (Powerful Energy Recovery Linac for Experiments) is a three-turn, high-power Energy Recovery Linac under construction at IJCLab, France on the pathway to the realization of the LHeC and will serve as a hub for the validation of several technical choices and exploration of a broad range of accelerator phenomena in an unexplored operational power regime (up to 10 MW in its final version, for a 500 MeV, 20 mA beam). Up to now, the lattice design and phasing has been finalized. Current studies focus on non-linear effects and longitudinal dynamics. In addition, the commissioning scheme is under development. We will present the status of the beam dynamics studies of the project, and highlight some of the ongoing studies.

INTRODUCTION

Energy Recovery Linacs (ERLs) are promising candidates for future accelerators, offering high average beam currents with excellent beam quality in continuous wave (CW) mode. Their ability to recover beam energy significantly reduces RF power requirements, making them both efficient and sustainable.

PERLE, under construction at IJCLab (Orsay), aims to demonstrate the performance and feasibility of a multi-turn, high-current ERL, in alignment with the design requirements of the proposed LHeC [1], with the same bunch charge and frequency. It will also serve as a test bench for a wide range of accelerator studies, including beam diagnostics, high-power energy recovery, and laser-Compton backscattering.

The accelerator is configured in a racetrack geometry as shown in Fig. 1, with one cryomodule and three recirculation loops. Starting from a 7 MeV injector, the beam gains 82.2 MeV per turn, reaching a final energy of 250 MeV after three recirculation passes. After a path length shift of exactly half of RF period, it is then decelerated through the same linac structure to recover the beam energy up to the final dump at 7 MeV, thereby demonstrating full multi-pass energy recovery at high current.

STATUS ON THE PERLE ACCELERATOR

PERLE is currently under construction in the IGLOO building at IJCLab in Orsay, France. The project is progressing in successive phases, each designed to validate a key step toward the full ERL operation.

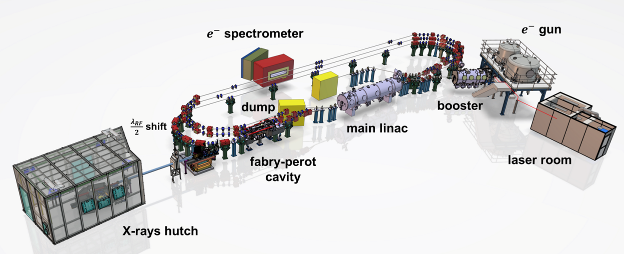

Figure 1: 3D layout of the PERLE 250 MeV ERL.

The first phase, scheduled for late 2028, focuses on commissioning the injector. This includes testing the high-current electron gun, aiming to deliver up to 20 mA of 350 keV electron bunches at a repetition rate of 40 MHz, as well as the superconducting RF booster that accelerates these bunches to 7 MeV. During this phase, the merger section and a diagnostic mirror line will also be constructed and tested to ensure that the beam properties meet the design specifications.

The next phase (Phase 1), expected to begin in 2029–2030, will establish and test the one-turn ERL loop. Key objectives of this phase include:

- Calibration of the linac and magnetic elements, ensuring full beam transport through the loop.
- Fine tuning of the beam path length using dedicated chicane tuning and/or mechanical adjustement to ensure the maximum energy recovery efficiency.
- A first energy recovery with a 89 MeV, 20 mA beam corresponding to a total beam power of 1.8 MW.

The next major phase will implement the full three-turn, 250 MeV ERL configuration. This stage is aimed at demonstrating capabilities relevant to future collider designs and conducting a first set of physics experiments with :

- Achieving 5 MW of energy recovery with 250 MeV, 20 mA beams — a power level that has not yet been demonstrated in any ERL facility.
- A demonstration of multi-pass high power energy recovery.
- Performing initial experiments involving Compton backscattering and electron scattering on radioactive ion beams.

Looking further ahead, an additional phase of the project is being considered. This upgrade would involve the installation of a second cryomodule in the second straight section,

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as originally foreseen in the conceptual design report [2]. Such a configuration would enable PERLE to explore the frontier regime of energy recovery at the 10 MW scale, using a 500 MeV, 20 mA beam. This step would not only extend the demonstration capabilities of the facility but also mark a significant milestone for future high-power ERL-based applications.

LATTICE AND OPTICAL DESIGN

The optical design of PERLE [3] has been adapted and refined for the 250 MeV configuration and has undergone continuous improvement [4]. Up to now, extensive optical and beam dynamics studies have been carried out, covering all key sections of the machine (see Fig. 2).

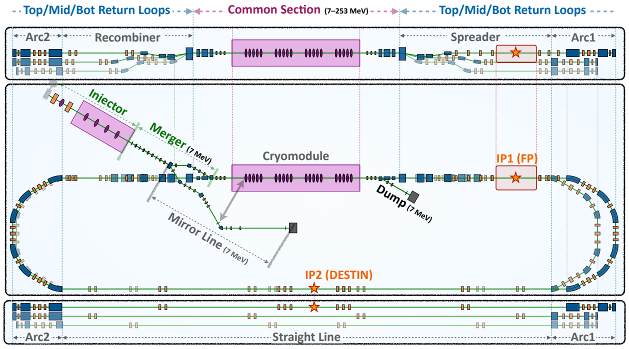

Figure 2: PERLE detailed lattice scheme, from injector to dump with a top view and both side views (linac and experiment sides).

Injection Line

Simulations have been performed using the ASTRA and OPAL tracking codes [5], from the electron gun to the exit of the SRF booster. Beam parameters have been optimized to minimize emittance and energy spread while approaching the design bunch length of 3 mm.

The merger section has been matched to the main linac for various injector tunings. Since space charge effects remain non-negligible at the relatively low energy of 7 MeV, special matching strategies are required. First, matching is performed using Twiss parameters extracted from particle tracking, rather than from the lattice model. Second, care is taken to avoid strong transverse focusing, which could amplify emittance growth due to space charge forces.

A symmetric diagnostic mirror line has also been designed to precisely characterize the beam in the linac. Due to its mirror symmetry, the beam at the end of the diagnostic line replicates the conditions at the linac entrance. This setup enables measurements of beam emittance, bunch charge, phase and Twiss parameters. Additional diagnostic elements currently under study include a spectrometer and a transverse deflecting cavity for bunch profile, energy, and energy spread measurements.

Main ERL

The main lattice comprises a linac and three return loops enabling three acceleration and three deceleration passes. The layout is also compatible with a 1-turn ERL mode by using only the high-energy (top) arc. This arc includes a $\lambda_{RF}/2$ path length extension, which allows energy recovery even in the single-turn configuration, by appropriately scaling the magnets for the 89 MeV energy.

Simulation benchmarks using ASTRA, BMAD, and CODAL [6] have been performed to study linac beam dynamics, showing very good agreement between the tools.

In addition, alignment tolerances have been studied, and the positions and specifications for beam position monitors (BPMs), correctors, and kickers have been defined to ensure robust orbit correction.

Experimental Areas

Two experimental interaction regions have been integrated into the lattice design.

The first (IP1) hosts the Fabry–Perot optical cavity for X-ray production via Compton backscattering. To achieve the required transverse beam size of approximately 100 µm RMS at the interaction point, an additional set of six quadrupoles has been implemented in this region.

The second interaction point is located in the straight section directly opposite the cryomodule and will be used for nuclear physics experiments involving an electron spectrometer. This area requires a highly parallel electron beam and still requires further dedicated optimization.

BEAM DYNAMICS STUDIES

In parallel with the lattice design, extensive beam dynamics studies have been carried out, with a strong focus on start-to-end tracking using realistic particle distributions. The low-energy section of the injector (from the electron gun to the exit of the booster at 7 MeV) is simulated using dedicated codes such as ASTRA and OPAL, while the rest of the ERL, from 7 MeV to the beam dump, is modeled primarily using the `bmad` code [7].

Start-to-end Simulations and Beam Loss Studies

Beam loss studies through start-to-end tracking have been conducted in order to dimension different subsystems such as radioprotection, collimation, diagnostics and beam pipes. Fig. 3 shows the evolution of the 5σ transverse beam envelope along the PERLE machine in its 250 MeV configuration, along with a schematic representation of the vacuum pipe geometry.

Simulations were performed for both a nominal low-charge case (black curve, up to 125 pC per bunch), where collective effects are negligible, and a high-charge, high-current case (orange curve, 500 pC per bunch), where space charge and coherent synchrotron radiation (CSR) significantly impact beam transport. Beam halo tracking (light blue area) highlights increased sensitivity to CSR in dispersive regions — in particular, around $s = 270$ m and

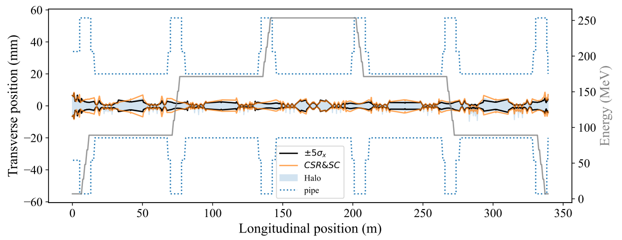

Figure 3: Beam transverse envelope along the 250 MeV (phase 2) machine. The low-current beam is represented by the black envelope while the high-current, including CSR effects and space charge is shown in orange. The beam halo, showing the extrema particles is the ligth-blue filled area. The vacuum pipe profile is shown with a dotted blue line. The beam energy (grey) helps visualize the different linac passes.

$s = 320$ m in the last deceleration arcs — where energy spread increases by nearly a factor of three.

Beam dynamics studies allowed us to determine potentially ”hot points” concerning beam losses [8]. These results will be usefull in the early future for the development and positioning of beam loss monitors and radioprotection detectors. Moreover, vacuum beam pipes dimensions have been fixed. The current aperture of the SRF linac cavities is set to 110 mm. A reduced pipe diameter of 40mm will be used in the arcs and spreader sections, where spatial constraints are tight, easing requirements on the magnet apertures in high-energy arcs.

In the merger, dump, and common transport sections — where 7 MeV beams are handled and geometrical emittance is larger — a 60 mm pipe diameter has been chosen to minimize losses due to halo and transverse beam size.

Since the common section quadrupoles operate at low energy, they can accommodate larger apertures without magnetic saturation. Moreover, the progressive transition between the 110 mm and 40 mm apertures is expected to mitigate impedance discontinuities in the system. A full impedance analysis will be conducted as part of future studies.

Longitudinal Matching

While most lattice and beam loss studies have focused on transverse dynamics, longitudinal effects must not be overlooked, as uncontrolled distortions in the time-energy phase space can lead to significant beam degradation. In addition, some experiments may impose specific requirements on longitudinal beam properties, such as reduced bunch length or minimized energy spread.

As in the transverse plane, longitudinal matching can be performed to tailor the bunch profile along the machine. At low energy — particularly in the early stages of the injector — a bunching cavity can be used to manipulate the bunch length via velocity modulation. Once the beam passes through the SRF booster, its velocity approaches the speed of light, and further bunch compression through velocity differences becomes ineffective. However, an appropriate choice of RF phases in the booster can be used to minimize energy spread.

In the main ERL loop, longitudinal beam shaping can be achieved through path length differences in dispersive regions, effectively using the R_{56} and R_{566} terms of the transport matrix. Introducing a correlated energy spread (or chirp) via off-crest acceleration in the linac enables coupling to the R_{56} term for bunch compression or decompression.

Preliminary studies have been performed to explore these mechanisms and provide a first estimation of the parameters required for such longitudinal manipulations. Artificial R_{56} and R_{566} values were introduced via Taylor maps in the lattice arcs. Fig. 4 shows initial results from these matching trials, where either the bunch length or the energy spread is minimized at the first interaction point (IP1).

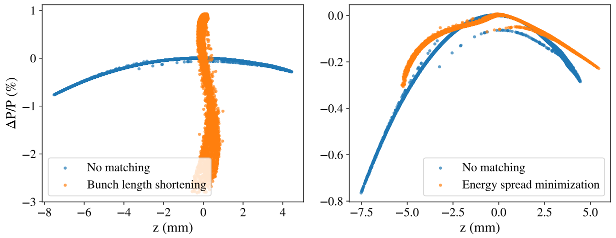

Figure 4: Preliminary longitudinal matching results at IP1. Blue: nominal phase space without matching. Left (orange): result of a bunch shortening scenario using three sets of linac phases and artificial R_{56}/R_{566} values (one per pass). Right (orange): energy spread minimization. The values explored range from $\phi_0 \in [-10°, 10°]$, $R_{56} \in [-0.8, 0]$, and $R_{566} \in [-10, 0]$.

Although these studies rely on simplified models — notably the use of artificial Taylor maps rather than realistic magnet-based optics — they provide valuable insight into the achievable ranges of bunch compression and energy spread control. They also highlight the required combinations of RF phase settings and magnet strength to reach specific longitudinal beam profiles.

Future work will focus on implementing more realistic longitudinal matching strategies using quadrupoles and sextupoles to control R_{56} and R_{566}, along with proper modeling of beam loading effects and phase shift.

CONCLUSION

Lattice design and beam dynamics studies for PERLE have been ongoing for several years, adapting to the project’s evolving requirements and design upgrades. Today, the main lattice is largely finalized, with only minor refinements to be done. Recent efforts have focused on the integration of experimental areas. Start-to-end simulations are now performed routinely, incorporating an increasing number of features and effects. This ongoing refinement contributes to a more accurate understanding of beam transport and potential loss mechanisms, providing essential input for the final stages of the machine design.

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