# PERLE - ERL Test Facility at Orsay

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July 27, 2021

*Proceedings for the XXVIII International Workshop*
*on Deep-Inelastic Scattering and Related Subjects,*
*Stony Brook University, New York, USA, 12-16 April 2021*
doi:10.21468/SciPostPhysProc.?

## Abstract

**PERLE (Powerful ERL for Experiments) [1] is a novel Energy Recovery Linac (ERL) test facility, designed to validate choices for a 50 GeV ERL foreseen in the design of the Large Hadron Electron Collider (LHeC) and the Future Circular Collider (FCC-eh), and to host dedicated nuclear and particle physics experiments. Its main thrust is to probe high current, continuous wave (CW), multi-pass operation with superconducting cavities at 802 MHz. With very high transient beam power (10 MW), PERLE offers an opportunity for controllable study of every beam dynamic effect of interest in the next generation of ERL design and becomes a 'stepping stone' between present state-of-art 1 MW ERLs and future 100 MW scale applications.**

## 1 Introduction

Next generation collider applications [2], or light sources would greatly benefit from recirculated and energy recovered linacs. They offer CW, or other high duty factor operation, high beam average current, low delivered beam energy spread, and low delivered beam emittance. CW beam acceleration with high accelerating gradient ( $>$ 20 - 30 MV/m) generally requires a multi-pass Recirculating Linear Accelerator (RLA) consisting of superconducting accelerator structures. GeV-scale RLAs at 100 mA average current would ordinarily require at least 100 MW of installed RF power merely to accelerate the beam load. Energy recovery allows the RF beam loading of the cavities to be substantially lowered. and they provide linac quality/brightness beam at storage ring beam powers. The primary motivation for the use of energy recovery is to provide beams of very high virtual power while using only minimal installed RF power. The production of high beam power with reduced RF drive represents improved electrical efficiency (it is then a 'green' technology) and it results in significant cost reductions. Particularly, the PERLE facility, to be hosted at Irène Joliot Curie Laboratory, targets the LHeC configuration and beam currents of up to 20 mA (corresponding to a 120 mA cavity load). This unique quality beam is intended to perform a number of experiments in different fields; ranging from uncharted tests of accelerator components via elastic ep scattering to laser-Compton back-scattering for photon physics [3]. Following an experiment, the CW beam will be decelerated in three consecutive passes back to the injection energy, transferring virtually stored energy back to the RF.

## 2 PERLE Facility Overview

PERLE accelerator complex is arranged in a racetrack configuration; hosting two cryomodules (containing four, 5-cell, cavities operating at 802 MHz), each located in one of two parallel straights, completed with a stack of three recirculating arcs on each side (with 45 cm vertical separation between the arcs). Additional space is taken by 4-6 meter long spreaders/recombiners, including matching sections and two experimental areas, as illustrated in Fig. 1.

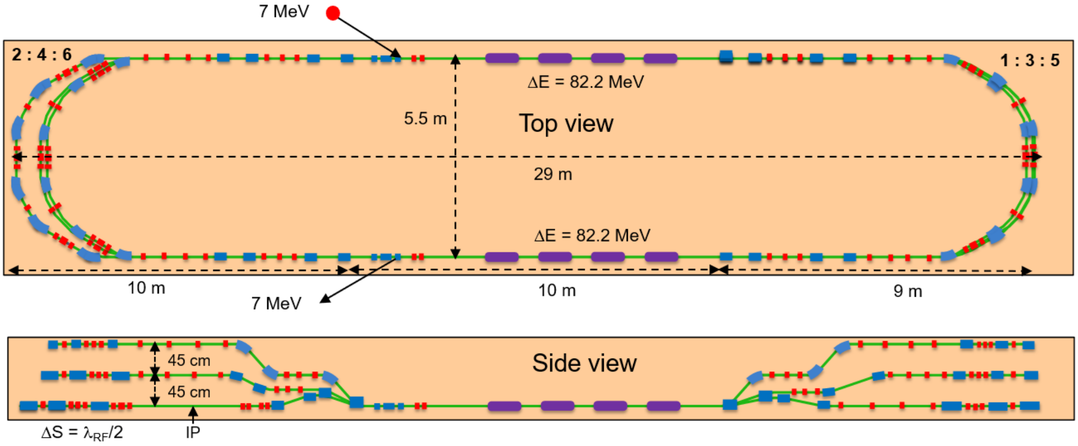

Figure 1: Top and side views of PERLE, featuring two parallel linacs each hosting a 82.2 MeV cryomodule, achieving 500 MeV in three passes.

PERLE optics features Flexible Momentum Compaction (FMC) lattice architecture [4] for six vertically stacked return arcs. Starting with a high current (in excess of 20 mA) 7 MeV photo-injector, final energy of 500 MeV can be reached in three re-circulation passes, assuming a 4-cavity cryomodules. Each of the two cryomodules provides 82.2 MeV energy boost. A summary of design parameters is presented in Table 1. The beam parameters have been chosen to match those of LHeC [5], so that it will serve as a test bed for the ERL design and SRF technology development. The bunch spacing in the ERL is assumed to be 25 ns, however empty bunches might be required in the ERL for ion clearing gaps.

Table 1: PERLE Beam Parameters

| **Parameter** | Unit | Value |
|---|---|---|
| Injection beam energy | MeV | 7 |
| Electron beam energy | MeV | 500 |
| Norm. emittance $\gamma\epsilon_{x,y}$ | mm mrad | 6 |
| Average beam current | mAmp | 20 |
| Bunch charge | pCoulomb | 500 |
| Bunch length | mm | 3 |
| Bunch spacing | nsec | 24.95 |
| RF frequency | MHz | 801.58 |
| Duty factor | | CW |

# 3 Multi-pass Linac Optics with Energy Recovery

Injection at 7 MeV into the first linac is done through a fixed field injection chicane, with its last magnet (closing the chicane) being placed at the beginning of the linac. It closes the orbit 'bump' at the lowest energy, injection pass, but the magnet (physically located in the linac) will deflect the beam on all subsequent linac passes. In order to close the resulting higher pass 'bumps', the so-called re-injection chicane is instrumented, by placing two additional opposing bends in front of the last chicane magnet. This way, the re-injection chicane magnets are only 'visible' by the higher pass beams. Layout and injection pass optics is illustrated in Fig. 2 The second linac in the racetrack is configured exactly as a mirror image of the first one, with a replica of the re-injection chicane at its end, which facilitates a fixed-field extraction of energy recovered beam to the dump (at 7 MeV).

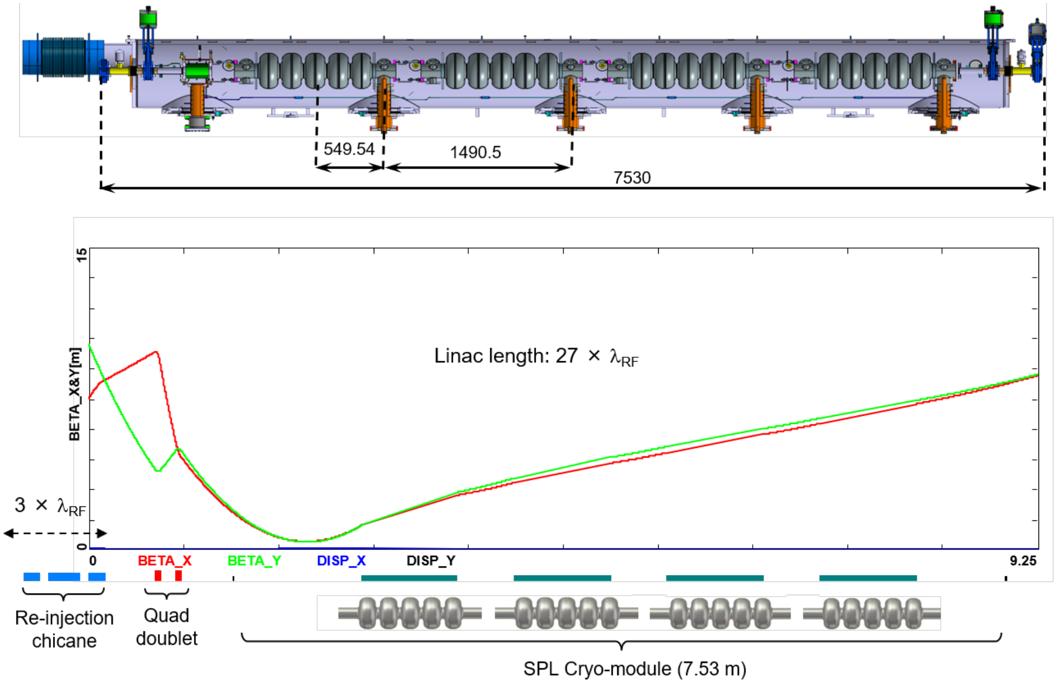

Figure 2: Linac configured with the SPL cryo-module. Injection, 1-st pass linac Optics tunable by an initial quadrupole doublet.

Multi-pass energy recovery in a racetrack topology explicitly requires that both the accelerating and the decelerating beams share the individual return arcs. This in turn, imposes specific requirements for the TWISS function at the linacs ends: the TWISS functions have to be identical for both the accelerating and decelerating linac passes converging to the same energy and therefore entering the same arc. To represent beta functions for multiple accelerating and decelerating passes through a given linac, it is convenient to reverse the linac direction for all decelerating passes and string them together with the interleaved accelerating passes, as illustrated in Fig. 3. This way, the corresponding accelerating and decelerating passes are joined together at the arcs entrance/exit, automatically satisfying the matching conditions into the arcs.

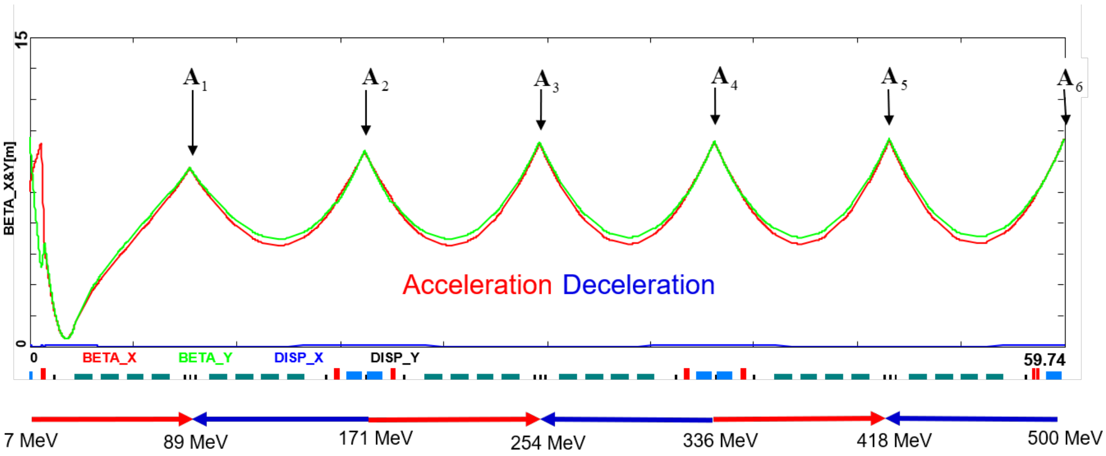

Figure 3: Multi-pass linac optics. Red/Green curves illustrate symmetrically optimized horizontal/vertical beta functions across different passes through the linac; Red/Blue arrows indicate the accelerating/decelerating passes.

## 4 Recirculating Arc Architecture

The spreaders are placed directly after each linac to separate beams of different energies and to route them to the corresponding arcs. The recombiners facilitate just the opposite: merging he beams of different energies into the same trajectory before entering the next linac. Each spreader starts with a vertical bending magnet, common for all three beams, that initiates the separation. The highest energy, at the bottom, is brought back to the initial linac level with a chicane. The lower energies are captured with a two-step vertical beam line. The vertical dispersion introduced by the first step bends is suppressed by the three quadrupoles located appropriately between the two steps.

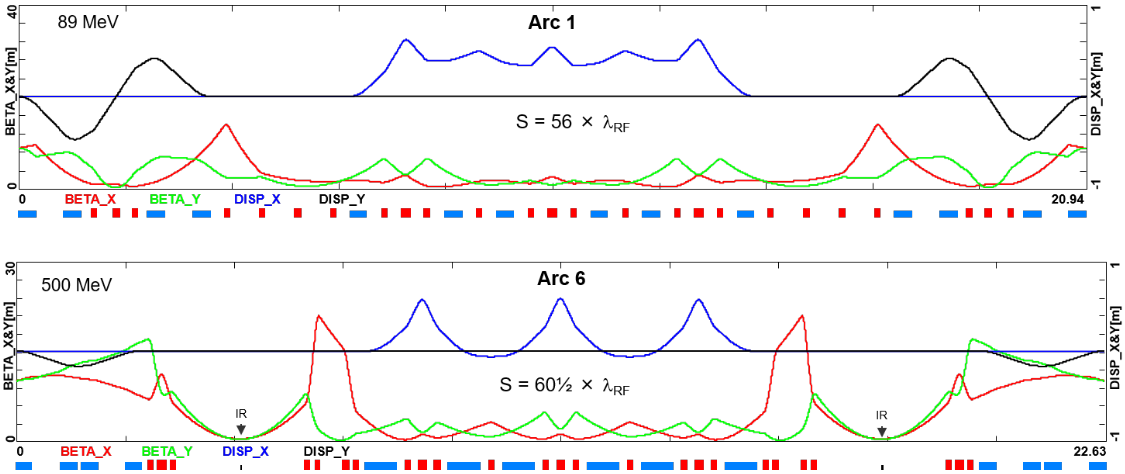

Figure 4: The lowest and highest energy arcs (arc 1 and arc 6). Optics architecture based on the FMC cell. Horizontal (red curve) and vertical (green curve) beta-function amplitudes are illustrated. Blue and black curves represent the horizontal and vertical dispersion, respectively. The arc, as configured above, is tuned to the isochronous condition, of zero momentum compaction factor.

The lowest energy spreader is configured with three curved bends following the common magnet, because of a large bending angle (30 deg.) the spreader is configured with. This minimizes adverse effects of strong edge focusing on dispersion suppression for a lower energy spreader. Following the spreader,there are four matching quads to 'bridge' the TWISS function between the spreader and the following 180 deg. arc (two betas and two alphas). All six, 180 deg. horizontal arcs are configured with a FMC style optics to ease individual adjustment of the momentum compaction factor in each arc (needed for the longitudinal phase-space re-shaping, essential for operation with energy recovery). The three arcs on either side of the linacs are vertically stacked and composed of 6 dipoles instead of 4 dipoles with respect to the previous design [1]. The increased number of dipoles allow to reduce the effects of CSR [6]. The low energy implies that the energy spread and emittance growth due to incoherent synchrotron radiation is negligible in the arcs.

The lower energy arcs (1, 2, 3) are composed of six 33 cm long curved 30 deg. bends and of a series of quadrupoles (two triplets and one singlet), while the higher arcs (4, 5, 6) use 'double length', 66 cm long, curved bends. The usage of curved bends is dictated by a large bending angle (30 deg.). If rectangular bends were used, their edge focusing would have caused significant imbalance of focusing, which in turn, would have had adverse effect on the overall arc optics. Another reason for using curved bends is to eliminate the problem of magnet sagitta, which would be especially significant for longer, 66 cm, bends. Each arc is followed by a matching section and a recombiner (mirror symmetric to previously described spreader and matching section). As required in case of mirror symmetric linacs, matching conditions described in the previous section, impose a mirror symmetric arc optics (identical betas and sign reversed alphas at the arc ends). Complete lattices for the lowest and highest energy arcs (arc 1 at 89 MeV and arc 6 at 500 MeV), including a spreader, 180 deg. horizontal arcs and a recombiner, are illustrated in Fig. 4. Presented arc optics architecture features high degree of modular functionality to facilitate momentum compaction management, as well as orthogonal tunability for both the beta functions and dispersion. The path-length of each arc is chosen to be an integer number of RF wavelengths, except for the highest energy pass, arc 6, whose length is longer by half of the RF wavelength (to shift the RF phase from accelerating to decelerating, switching to the energy recovery mode). The optimal bunch recombination pattern gives some constraints on the length of the arcs.

## 5 Experimental Areas

PERLE facilitates a pair of Experimental Areas configured at 500 MeV, located symmetrically on both sides of arc 6. Their optics based on low-beta squeeze configured with a pair of doublets, is illustrated in Fig. 5.

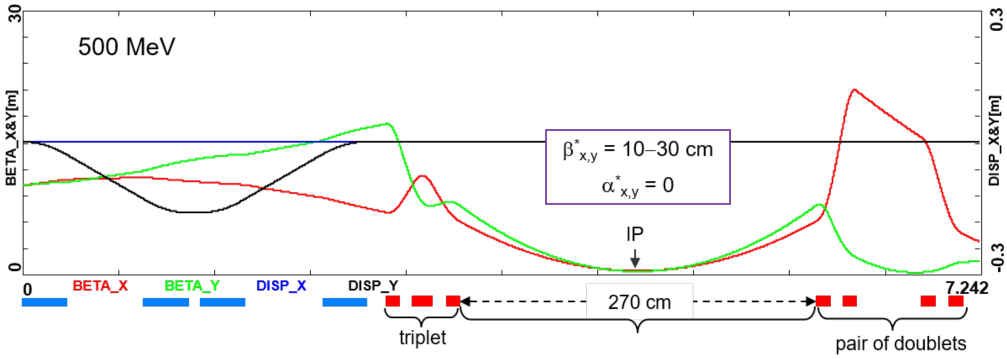

Figure 5: Optics design for 2.7 meter long Experimental Area, with a low-beta squeeze configured with a pair of doublets

## 6 Summary, Outlook

PERLE is a compact three-pass ERL test facility based on SRF technology, expanding the operational regime for multi-turn ERLs to around 10 MW of beam power. PERLE will serve as a hub for validation of a broad range of ERL accelerator phenomena, probing an unexplored operational regime and braking new grounds add developing novel ERL technology for future energy and intensity frontier machines. Innovative PERLE design expands on recently developed technological components, such as: 802 MHz Niobium cavity developed (JLab in collaboration with CERN) for the LHeC and FCC-ee, which features a high $Q_0$ of 3 $10^{10}$ and an impressive gradient of nearly 30 MV/m. The facility will initially use several in-kind contributions: a gun (from ALICE at Daresbury), a booster cryostat (from JLab) and a main linac cryostat (from CERN adapting the SPL module). The PERLE Collaboration has recently established an ambitious plan for first beam operation in the mid twenties. Several electron-scattering experiments are in the early phase of planning. We are presently launching a vigorous RD program to develop a Technical Design Report for PERLE, within the next year. To achieve this goal, we have tentatively identified the following sequence of accelerator design studies:

- Complete injector/merger design including space-charge studies
- Study momentum acceptance and longitudinal match
- Complete Start-to-End simulation with synchrotron radiation effecrs, including CSR and micro-bunching
- Optimize cavity design for HOM and test a dressed cavity
- Study multi-pass wake-field effects, BBU studies

Integration of PERLE into the European Road-map for Accelerators is quite timely, since both the FCC-ee and recently the ILC are proposed as ERL colliders with significantly increased luminosity and substantially reduced power consumption. Needless to say, PERLE is positioned as a key effort towards future High Energy Physics, Particle Physics and Nuclear Physics facilities.

## Acknowledgements

Useful discussions and conceptual input from: Kevin André, Bernhard Holzer, Max Klein, Walid Kaabi, Dario Pellegrini and Alessandra Valloni at all stages of the accelerator design process are greatly acknowledged.

**Funding information** Work at Jefferson Lab has been supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contracts DE-AC05-06OR23177 and DE-SC0012704.

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