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PERLE: A HIGH POWER ENERGY RECOVERY FACILITY

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Abstract

PERLE is a proposed high power Energy Recovery Linac, designed on multi-turn configuration, based on SRF technology, to be hosted at Orsay-France in a collaborative effort between local laboratories: LAL and IPNO, together with an international collaboration involving today: CERN, JLAB, STFC ASTeC Daresbury, Liverpool University and BINP Novosibirsk. PERLE will be a unique leading edge facility designed to push advances in accelerator technology, to provide intense and highly flexible test beams for component development. In its final configuration, PERLE provides a 500 MeV electron beam using high current (20 mA) acceleration during three passes through 801.6 MHz cavities. This presentation outlines the technological choices, the lattice design and the main component descriptions.

INTRODUCTION

PERLE facility, here presented, is being as a new generation energy recovery machine uniquely covering the 10 MW power regime of beam current and energy. It is a compact multiple pass ERL based on SRF technology, to serve as testbed for validation and testing a broad range of accelerator phenomena and technical choices for future projects [1]. Particularly, design challenges and beam parameters (Table 1) are chosen to enable PERLE as the hub for technology development, especially on SRF, for the Large Hadron Electron Collider (LHeC) [2].

Table 1: PERLE Beam Parameters

Target parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Norm. Emittance $\gamma\varepsilon_{x,y}$	mm·mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	Mm	3
Bunch spacing	Ns	25
RF frequency	MHz	801.6
Duty factor		CW

PERLE DESCRIPTION

Configuration and Lattice

The PERLE accelerator complex is arranged in a racetrack configuration hosting two cryomodules (containing four, 5-cell cavities operating at 801.6 MHz), each located in one of two parallel straights completed with a vertical stack of three recirculating arcs on each side. The straights are 10 m long and the 180° arcs are 5.5 m across. Additional space is taken by 4 m long spreaders/recombiners, including matching sections.

As illustrated in Fig. 1, the total footprint of PERLE is: 24x5.5x0.8 m³ , accounting for 40 cm vertical separation between arcs. Each of the two cryomodules provides up to 82 MeV energy boost. Therefore, in three turns, a 492 MeV energy increase is achieved. Adding the initial injection energy of 7 MeV yields the total energy of approximately 500 MeV.

Multi-pass energy recovery in a racetrack topology explicitly requires that both the accelerating and decelerating beams share the individual return arcs. Therefore the TWISS functions at the linac ends have to be identical, for both the accelerating and decelerating linac passes converging to the same energy and therefore entering the same arc.

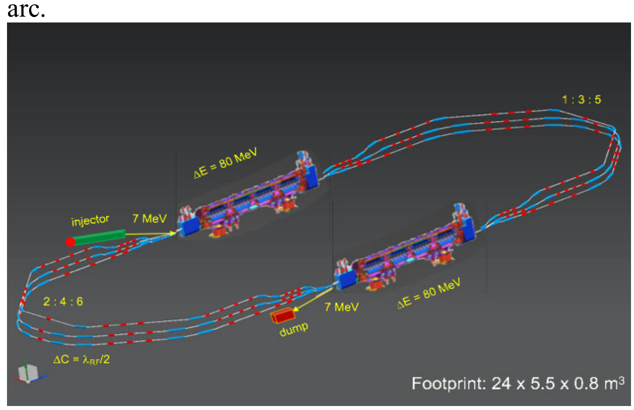

Figure 1: PERLE Layout featuring two parallel linacs each hosting a cryomodule housing four 5-cell SC cavities, achieving 500 MeV in three passes.

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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 reinjection chicane is instrumented, by placing two additional bends in front of the last chicane magnet. This way, the reinjection chicane magnets are only visible by the higher pass beams. 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 the beams of different energies into the same trajectory before entering the next linac.

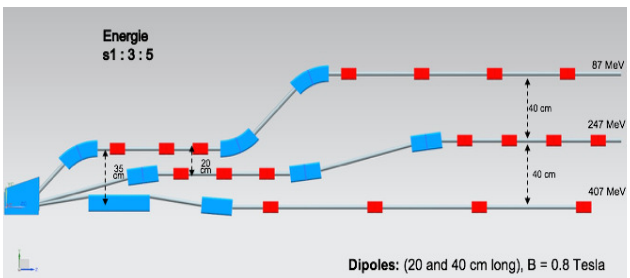

Figure 2: PERLE spreader design and matching to three circulating arcs.

The spreader design (Fig. 2) consists of a vertical bending magnet, common for all three beams, that initiates the separation. The highest energy, at the bottom, is brought back to the horizontal plane with a chicane. The lower energies are captured with a two-step vertical bending. The vertical dispersion introduced by the first step bends is suppressed by the three quadrupoles located appropriately between the two steps. The lowest energy spreader is configured with three curved bends following the common magnet, because of a large bending angle (45°) the spreader is configured with. This minimizes adverse effects of strong edge focusing on dispersion suppression in the spreader. Following the spreader there are four matching quads to bridge the TWISS function between the spreader and the following 180° arc (two betas and two alphas). All six, 180° horizontal arcs are configured with Flexible Momentum Compaction (FMC) optics to ease individual adjustment of M56 in each arc (needed for the longitudinal phase-space reshaping, essential for operation with energy recovery). The lower energy arcs (1, 2, 3) are composed of four 45.6 cm long curved 45° bends and of a series of quadrupoles (two triplets and one singlet), while the higher arcs (4, 5, 6) use double length, 91.2 cm long, curved bends. The usage of curved bends is dictated by a large bending angle (45°). Each arc is followed by a matching section and a recombiner (both mirror symmetric to previously described spreader and matching segments).

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.

PERLE Source and Injector

The PERLE injector must be capable of delivering a beam with the characteristics shown in Table 1. There is also the desire of delivering polarised beams for specific experiments. To provide both these options a DC photocathode gun based injector will be used.

The beam will be emitted with a photocathode illuminated by laser pulses with the required time structure. The acceleration of the beam up to the necessary injection energy will be done with a booster operating with a frequency of 801.6 MHz, the same frequency as the main ERL linacs. The booster being considered for beam dynamics study will consist of five SRF cavities with independently controllable phases and amplitudes. The longitudinal bunch compression will be done using a (sub) harmonic normal conducting RF buncher and the booster. Independent control of the booster cavities will allow for fine adjustment of the bunching and acceleration of the beam.

Focusing solenoids located between gun and booster will be used for transport of the beam and for emittance compensation, which reduces the projected emittance growth due to the significant space charge forces present. After the booster the beam is transported to the main ERL loop and injected with a merger. In order to linearise the longitudinal phase space the installation of an additional linearisation cavity is being considered. The polarised operation mode will require the addition of a spin rotator section between the gun and the booster.

The PERLE electron source will initially be based on the eXtra High Vacuum (XHV) DC photocathode gun with a ground pressure of better than $1 \cdot 10^{-11}$ mbar previously used on the ALICE ERL based at Daresbury and now transferred to Orsay. The required upgrade for operation with higher average current will be based on one previously designed and partially manufactured for ALICE [3]. The significantly higher bunch charge of PERLE compared to ALICE requires complete re-optimisation of the gun electrode system [4].

For unpolarised and polarised operation modes of PERLE the gun will run at different operating voltages. 350 kV for the unpolarised mode vs. 220 kV for the polarised one. Lower voltage provides longer photocathode lifetime and more effective spin manipulation. Antimonide based photocathodes will be used for the unpolarised operation mode. The polarised operation mode will require to use gallium arsenide based photocathodes as these are the only materials capable of delivering polarised beams.

Cavity Prototype and Design

Activities to optimize a bare 801.6 MHz five-cell ERL linac cavity design, to build a prototype and to validate the design in a vertical test at 2K helium temperature have been successfully completed at JLAB in 2018. The chosen high current cell contour shape aimed to balance key performance parameters with regard to RF, mechanical and beam-dynamical aspects, e.g. resulting in a rather large

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cell-to-cell coupling that considers efficient Higher-Order-Mode (HOM) damping, while keeping the magnetic and electric surface RF peak fields as well as the dynamic heat load at a given accelerating field comparably small [5]. A full set of parameters for this cavity can be found in the PERLE CDR [2].

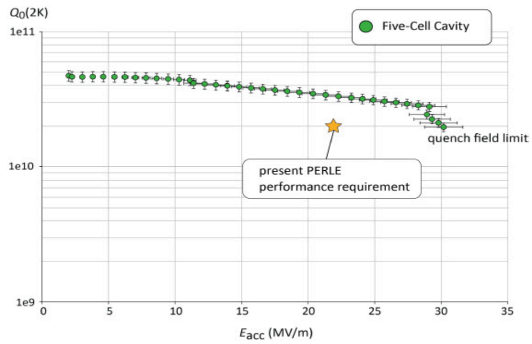

Figure 3: Vertical test result of the 5-cell 801.6 MHz Niobium cavity. The yellow star indicates the edge of the performances considered for PERLE operation.

Result for the Nb cavity - made from fine grain high-RRR Nb - is encouraging since cavity reached accelerating fields, Eacc, slightly above 30 MV/m ultimately limited by thermal breakdown. Moreover, the RF losses were rather small due to the relatively rather low RF frequency, which provides a small BCS surface resistance. This resulted in unloaded quality factors, Q0, well above 4·1010 at 2K at low fields, while Q0 values beyond 3·1010 could be maintained for the five-cell cavity up to about 27 MV/m (see Fig. 3). Standard post-processing methods were applied, including bulk buffered chemical polishing, high temperature vacuum annealing, light electropolishing, ultra-pure high-pressure water rinsing, and a low temperature bake-out. The vertical test results indicate generous headroom for a potential performance reduction once a cavity is equipped with all the ancillaries and installed in a cryomodule.

Cryomodule Design

The PERLE layout is integrating two superconducting RF cryomodules, one per linac, containing 4 superconducting 801.6 MHz 5-cell elliptical cavities each. Several challenging requirements are specific to PERLE operating mode. The most important one is linked to the CW operation of the cryomodules, where dynamic heat loads are much larger than static ones. Thus, reaching high quality factors for the SC cavities is a main objective. Besides specific optimisation on cavity design and preparation, the cryomodule has to provide a very low residual magnetic field environment to the cavity. Thus, both stringent optimisation of the magnetic shielding (material, layers number, active and/or passive shielding) and careful choices of the non-magnetic material for components close to the cavities are required. Even the cooling-down process has to be carefully studied to allow proper rejection of residual magnetic field in the superconducting material. Another important constraint is linked to the rather high power to be extracted by the HOM couplers. The cryomodule has to provide the capacity to efficiently evacuate the HOM thermal load not to degrade the cryogenic performances of the cryomodule. For PERLE use, we have chosen the cryomodule layout developed by IPN Orsay and CERN for the Superconducting Proton Linac (SPL) [6], for its capacity to fulfil the requirements in terms of dimensions, cryogenic performances and cavity requirements (Fig. 4).

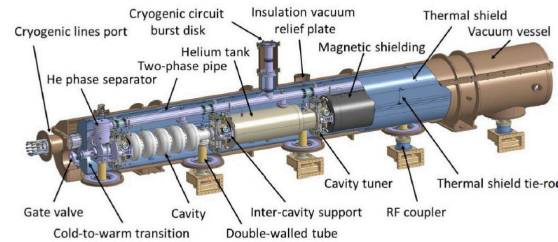

Figure 4: General assembly view of the SPL cryomodule considered to be adapted for PERLE.

In this cryomodule, the cavity string is directly supported by the power coupler with dedicated inter-cavity support features. Moreover, it integrates a full length demountable top lid, enabling the cavity string assembly from the cryomodule top. These two specific features allow an easier assembly process of the cavity string inside the module as compared to other cryomodule designs. The thermal shield is made of rolled aluminum sheets, and is composed of four main parts assembled before the vertical insertion of the string of cavities. The shield, wrapped with multi-layer insulation, is suspended to the vacuum vessel via adjustable tie rods in titanium alloy which also cope, by angular movements, with its thermal contractions. The cavity stainless steel helium tanks are connected by a 100 mm-diameter two-phase pipe placed above the cavities. This pipe ensures liquid feeding to the cavities by gravity, and is also used as a pumping line for gaseous helium. The cavities are protected by individual magnetic shields made of 2 mm thick CryopermTM sheets. The shields are made of 2 half-shells mounted around the helium tank and fixed to it on the tuner side. This allows the residual magnetic field to be kept bellow 1 μT. The cryomodule provides a dedicated 6 mm circuit supplies 4.5K vapor helium for cooling of the RF coupler double-walled tubes.

The SPL R&D program already provided design and experimental results on this type of cryomodule, and the mechanical capability of the module with the PERLE cavities has been checked requiring minor adaptation. Additional studies have to be performed, once detailed designs of some parts (like the HOM couplers) will be finalized.

CONCLUSION

Several proposals exist worldwide for ERLs that are currently beyond the state-of-the-art. PERLE lattice design, its technical choices and beam parameters, presented in this paper, occupy a unique place in parameter space such that it serves to bridge the gap between current and future facilities. Further beam dynamic studies, component prototyping and tests will still be required to validate the lattice and confirm some technical choices.

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