PERLE: A NOVEL FACILITY FOR ERL DEVELOPMENT AND APPLICATIONS IN MULTI-TURN CONFIGURATION AND HIGH-POWER REGIME*

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The development of ERLs has been recognized as one of the five main pillars of accelerators R&D in support of the European Strategy for Particle Physics (ESPP). The ERL Roadmap Panel recognized the PERLE project as "a central part of the roadmap for the development of energy-recovery linacs", with milestones to be achieved by the next ESPP in 2026. PERLE at Orsay is a project aiming at the construction of a novel ERL machine for the development and application of the energy recovery technique in multi-turn configuration, large current, and large energy regime. It will operate in a 3-turns mode, first at 250 MeV, then upgraded to 500 MeV with 20 mA beam current. Such challenging parameters make PERLE a unique multi-turn ERL facility operating at an unexplored operational power regime (10 MW), studying and validating a broad range of accelerator phenomena, paving the way for the future larger-scale ERLs. The PERLE machine opens a new frontier for the physics of "the electromagnetic probe". It will be the first ERL dedicated to Nuclear Physics for studying the eN interaction with radioactive nuclei. PERLE is also the necessary demonstrator for the future HEP machine (LHeC/FCC-eh) (the same technological choices and beam parameters). PERLE could also host elastic ep scattering experiments and experiments on Nuclear Photonics using inverse Compton scattering gammas. In this paper, we will present the PERLE project focusing on the challenges of accelerators physics and presenting the possible physics applications. We will also show the project structuration in an international collaboration and a timeline for the TDR phase and the following staged construction steps toward the PERLE machine at its nominal performances.

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1. General introduction

In a time when energetic sobriety is a keyword, and in societies where energy sustainability is critical, keeping energy consumption as low as reasonably possible is an unavoidable challenge for future accelerators. Energy-Recovery Linacs (or ERLs) offer one of the main options to lower the energetic consumption of accelerators and to enhance their efficiency.

ERLs share many characteristics with ordinary linacs, as their six-dimensional beam phase space is largely determined by electron source properties. However, in common with classic storage rings, ERLs possess a high average-current-carrying capability enabled by the energy recovery process, and thus promise similar efficiencies. The efficient recovery of power, to re-excite cavities from a used beam, was first suggested in 1965 by Tigner [1], and experimented only twenty years later by Stanford [2] and LANL [3] for facilities accelerating beams at rather low power. The concept becomes really viable thanks to the major advances in SRF technology within the last decades (quantified by cavity quality factors $Q_0 > 1010$) enabling a high average current operation, in addition to the consideration of multi-pass recirculation allowing high beam energy in a relatively compact machine. These two aspects have paved the way to a new generation of powerful machines with a relatively compact footprint.

PERLE is a compact three-pass ERL project based on the SRF technology, being a new generation machine targeting the 10 MW beam power regime [4]. Apart from the experiments it could host thanks to its beam characteristics, PERLE will serve as a hub for the validation and exploration of a broad range of accelerator phenomena in an unexplored operational power regime serving for the development of ERL technology for future energy and intensity frontier machines. While the concept and promise of ERLs has been kick-started by demonstration machines based on existing accelerator technology, PERLE is meant to be the first machine designed from the ground up to use fully optimized ERL-specific designs and hardware. To attend this goal, an international collaboration is formed around the project, involving today CERN, JLAB, STFC, University of Liverpool, Cornell University, An-Najah University, ESS-Bilbao, and IJCLab-CNRS (collaboration with BINP-Novosibirsk being suspended). It should be noticed that ESS-Bilbao and An-Najah University joined in the last months. All collaborators are leading laboratories on accelerator physics with experience in ERL development and operation for some (JLab, STFC, and Cornell University). IJCLab is leading the collaborative effort towards the realization of the project.

In this document, we situate the PERLE initiative in the current scientific context for accelerators, pointing its impact in the ERL landscape. The PERLE design and beam parameters, the lattice and the main components are briefly presented in an introductory style with indications on the work to be performed. The project organization, available resources, and estimation of the needs will be expressed also. The Phasing strategy that will be adopted will also be detailed in this document.

2. Scientific context of the project

ERLs are just beginning to assert their potential as game-changers in the field of accelerators used in synchrotron radiation sources, high-energy electron cooling devices, electron–ion colliders, and other applications in photon science, nuclear and high-energy physics. Their unique combination of linac-like beam quality, extremely flexible time structure, and unprecedented operating efficiency open the door to previously unattainable performance regimes. In addition, the consideration of multi-pass recirculation allowing high beam energy in the relatively compact machine is paving the way to a green generation of high energy, high brightness, and high average current electron beams.

The 2020 Update of the European Strategy for Particle Physics (ESPP) clearly stated that ERLs are among the innovative accelerator technologies that deserve a vigorous R&D effort in the upcoming years. In his final report [5], the ERL Roadmap Panel recognized the PERLE project as "*a central part of the roadmap for the development of energy-recovery linacs*". It was clearly stated that three main actions are necessary to succeed the ESPP Accelerator Roadmap as far as the ERL is concerned:

— The Realisation of PERLE as a high-intensity, multi-turn ERL ($3+3$ passes), 20 mA beam current;

— Upgrade bERLinPRO towards the First ERL Facility to operate 100 mA in a single turn with FRT control;

— Develop a key technology R&D program for next-generation ERLs.

At the national level, the Particle Accelerators & Associated instrumentation working group stated in its report for 2020–2030 French Strategic Plan that: "*ERL is a very promising technology for future electron accelerators. The ambitious PERLE@Orsay initiative should be strongly supported, provided that an adequate international participation to the project can be settled*".

For IJCLab, it constitutes a unique opportunity to become the headquarter of a very promising technology (ERL) which could have a strong impact on accelerator physics facilities in the future. Due to the presence of many of the necessary skills to conceive the machine, the international collaboration has recognized IJCLab as a natural place to install PERLE. It is clear that PERLE — as another European project — cannot be done without a solid and compact international collaboration and strong support from the CNRS and the University. The benefit is thus to have a central and very ambitious project which can catalyze the consolidation of the skill needed for PERLE and, at the same time, that could be useful for other present and future projects. PERLE will render IJCLab attractive and a central place in Europe for accelerator development in phase with the ESPP.

In addition, PERLE could host a unique facility for a pioneering experiment in nuclear physics. It will be the first ERL dedicated to Nuclear Physics for studying the eN interaction with radioactive nuclei. Also, thanks to that, IJCLab will be attractive to the nuclear physics community.

To meet all these expectations and challenges, and in order to develop and acquire expertise in the design, studies, and later construction and operation of ERLs, IJCLab is today leading an international collaboration around PERLE. The collaboration involves today CERN, JLAB, STFC, University of Liverpool, Cornell University, Al-Najah University, ESS-Bilbao, and CNRS (LPSC + IJCLab), the collaboration with BINP-Novosibirsk being suspended. Four of these international partners have been pioneering the development of ERL technology, the others are leading laboratories on SRF technology and accelerator physics. The collaboration is, of course, open to newcomers.

3. Importance of PERLE in the ERL facilities landscape

The global landscape of ERLs projects (*cf.* Fig. 1) shows an exhaustive list of past, planned, and potential future ERL facilities around the world. It summarises the survey for the superconducting ERL facilities on a double logarithmic scatter plot showing the facilities' maximum beam energy and beam current. It is worthwhile underlining that only two superconducting ERL facilities are currently operational: The S-DALINAC ERL at Darmstadt University, Germany [6] and c-ERL at KEK-Japan [7], and that all past and currently operated superconducting ERL facilities feature only one acceleration and one deceleration passage through the SRF system. The only multi-turn ERL facility features normally conducting RF systems is NOVO FEL at BINP-Novosibirsk [8] and offers therefore only limited feedback for new-generation machines.

Colliders in the ERL configuration initiatives were recently proposed: the CERC (alternative approach of FCCee) [9] and the ERLC (alternative approach of ILC) [10]. The two proposals were analyzed by the ERL expert panel mandated by the Laboratory Directors Group (LDG) in the framework of the accelerator roadmap for the European strategy. A report was delivered with recommendations for further R&D to make these initiatives viable [5].

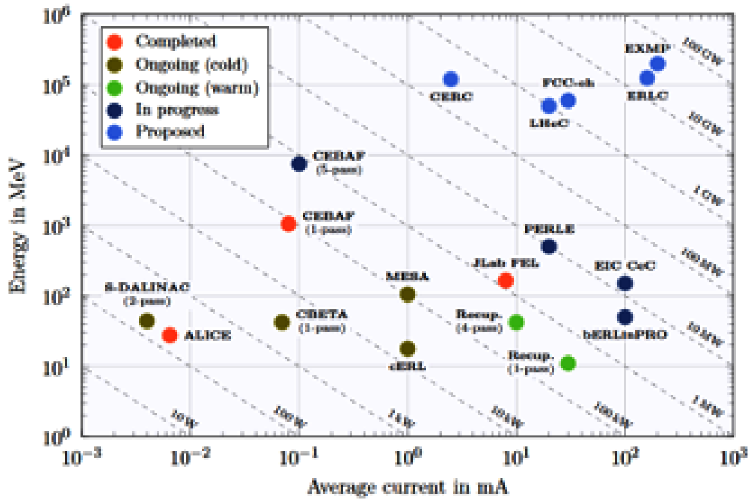

Fig. 1. (Colour on-line) Scatter plot of past (orange), operational (olive green (SC), and green (NC)), planned (dark blue), and potential future (light blue) superconducting ERL facilities on a double logarithmic scale with the maximum beam energy on the vertical and the maximum beam current on the horizontal axis. The dashed diagonal lines indicate the beam power regimes in the scatter plot.

The LHeC (Large Hadron Electron Collider) is a proposed multi-turn ERL reaching 50 GeV in three turns, providing electrons that collide with the HL-LHC protons [11]. It features 3 acceleration and 3 deceleration circulations, implying a maximum beam current in the SRF system that is 6 times higher than the target beam current at the LHeC Interaction Region (IR). Thus, the LHeC will push the ERL beam power frontier by 3 orders of magnitude as compared to the current record holder, the JLab IR facility [12], operated in the early 2000 and push the beam energy frontier by 2 orders of magnitude beyond that of the current record holder, the JLab CEBAF-ER demonstration, operated in 2003 [13]. This important transition in magnitude requires additional tailored demonstrator facilities at an intermediate power range.

There are currently 3 planned ERL facilities bridging the gap of power between the current record holder (CEBAF-ER) at 1 MW and the targeted performances of LHeC (1 GW) by exploring an intermediate operational power regime (around 10 MW):

— The bERLin-Pro facility [14] in Germany will be the first facility pushing the injected beam current above 100 mA and will approach the 10 MW beam power regime in ERL operation. It will feature one acceleration and one deceleration loop.

— The EIC electron cooler (USA) [15] aims also to feature the 100 mA beam current in a single turn ERL at a beam energy slightly higher than bERLinPro. Both machines will operate in CW mode.

— The PERLE facility targets the LHeC-specific aspects by featuring a 3-turn acceleration and 3-turn deceleration recirculation, 802 MHz SRF system and beam currents of around 20 mA (*e.g.* $2 \times 3 \times 20$ mA = 120 mA in the SRF cavities), and pushing the operational regime for multi-turn ERLs around the 10 MW beam power level.

All of the 3 projects share the same concerns: the high beam average current handling, the low beam energy spread, and the low beam emittance. Their realisation and success will provide valuable input and crucial validation for the future energy and intensity frontier machines.

Furthermore, PERLE will be the facility that offers the possibility to uniquely demonstrate and validate multi-turn ERL operation with a high beam power and beams of different energies in the same SRF system. This would pave the way to a new generation of compact but powerful ERLs for applications requiring high-energy beam and/or high total current (*e.g.* photon generation by the Compton back-scattering, high-energy cooling source for ions, electron–ions collider).

4. PERLE design and main beam parameters

The PERLE accelerator complex (*cf.* Fig. 2) 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. Additional space between the straights and the arcs is taken by long spreaders/recombiners, including matching sections. 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. 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. All six, 180° horizontal arcs are configured with the Flexible Momentum Compaction (FMC) optics to ease the individual adjustment of M56 in each arc (needed for the longitudinal phase-space reshaping, essential for operation with energy recovery). Each of the two cryomodules provides up to 82 MeV energy boost to the high average current electron beam (20 mA). Therefore, in three turns, a 492 MeV energy increase is achieved. Adding the initial injection energy

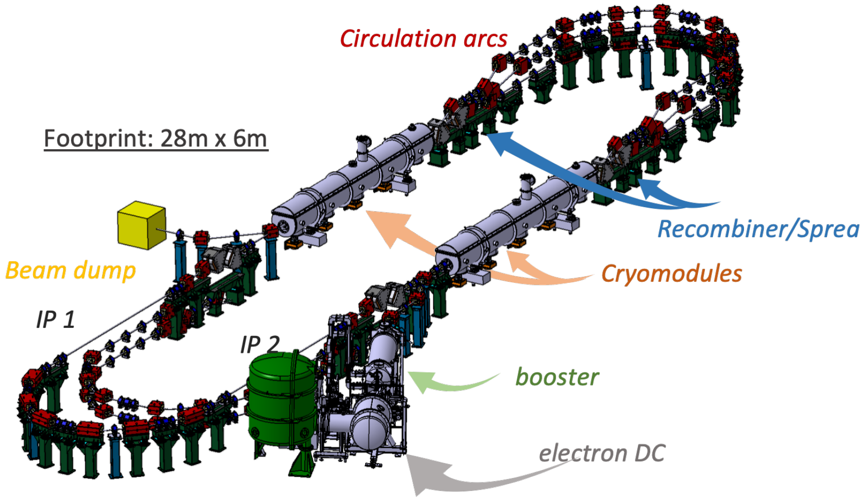

Fig. 2. PERLE layout featuring two parallel linacs, each hosting a cryomodule housing four 5-cell SC cavities, achieving 500 MeV in three passes.

of 7 MeV yields the total energy of approximately 500 MeV. The beam is then used for its intended purpose (*e.g.* photon generation by the Compton back-scattering, a cooling source for ion beams or collision with ions). This process may increase the energy spread or the emittance of the electron beam, but the major part of the beam power remains. The beam is then again sent back through the accelerators, this time roughly 180° off the accelerating RF phase, to be decelerated through the same number of passes and its energy is deposited into cavities allowing for the acceleration of newly injected bunches, thereby effectively cancelling the beam loading effects of the accelerated beam. The remaining beam is sent to a dump at around the injection energy. Several benefits accrue from this manipulation:

— The required RF power is significantly reduced (the investment cost also) to that required to establish the cavity field and make up a minor losses;

— To dump the beam at low energy to minimize the radioactive activation of the materials in the beam dump and, therefore, minimize the environmental impact of the accelerator throughout its life cycle;

— Experiments could benefit from the fresh beam with the required characteristics at the interaction point, as the used beam is sent to the beam dump after recovering its energy.

The main beam parameters of the PERLE facility are summarized in the following table.

Table 1. PERLE beam parameters.

Target parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Norm. emittance $\gamma\epsilon_{x,y}$	mm $\times$ 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

5. PERLE phasing strategy: From design to full construction

5.1. The Technical Design Phase (TDR) — 2020–2023

The initial and crucial phase of the PERLE project that should lead to the publication of a Technical Design Report (TDR) is expected by the end of 2023. The studies planned within this phase are:

— Consolidation of the PERLE design by performing optic lattice and beam dynamics studies of the injection line, the 250 MeV and 500 MeV versions of the machine;

— Design of the main systems and components of the machine (Buncher, Magnets, HOM couplers, full dressed cavity, power couplers, new CM, IP, dump ...);

— Studies of the adaptation and upgrade possibilities of the foreseen in-kind equipment (DC Gun, Cryomodule, booster);

— Definition of the needs on Diagnostics, Cryogenics, CC, LLRF, Shielding, machine interlock system, infrastructure ...;

— Identifying the possible experiments with PERLE beam and their specific needs and impact on the footprint.

Further required studies and design of some systems could of course be continued beyond this phase. Test results of some prototypes, planned in the preparatory to-build phase, could also be included in the TDR if available.

5.2. The Preparatory to Build Phase (P2B) — 2022–2025

The current phase of the PERLE project is characterized by a number of important/essential additional and complementary objectives to the TDR that must be met before construction can begin. We call this phase Preparation to Build: P2B. The objectives in question are:

— The commissioning of the in-kind received from the international partnerships: Installation of the DC gun and its upgrade to PERLE performances;

— The realization of critical prototypes that are needed and must be done before the start of the construction. The choice of the time being has been concentrated on prototyping cavities for the main loop cryomodule and for the booster as well as HOM fundamental power couplers;

— The preliminary work on infrastructure;

— The work related to the administrative classification of PERLE (ASN authorisation).

A clear consequence is that the objectives and timing of the TDR will not need to be changed. The TDR could eventually include "P2B deliverables" at the time of publication which is foreseen at the end of 2023. This phase will run up to the beginning of the construction of the main systems (by 2025).

5.3. Construction phasing

The PERLE configuration shown in Fig. 2 entails the possibility to construct PERLE in stages. We defined three main phases of construction with their objectives and timelines:

— Phase 1: Installation of the injection line (2022–2027) with a beam dump at its end: The injection line includes the DC gun, the load lock photocathode system, solenoids, buncher, booster, merger, and required beam instrumentations to qualify the generated beam. The commissioning of the injection line will require the installation of cryogenics, RF power source, power supplies for the optics, photocathode laser, beam dump, control command, vacuum systems, site shielding, safety control system, fluids, *etc.* Many of these installations must be already sized according to the final configuration of PERLE.

— Phase 2: 250 MeV version of PERLE (2024–2028): Installation of a single linac in the first straight and installation of beam pipe and complete return arcs. The switchyards have to be chosen according to the beam energy at each end (energy acceptance ratio: 1:2:3 for the spreader and combiner). This version of the race track is connected to the injection line built in Phase 1, via the merger. This intermediate step will allow in the relatively short term and lower expense to test with beam the various SRF components, to prove the multi-turn ERL and high-current operation, and to gain essential operation experience with ERL. This version of PERLE will be extensively studied in the TDR.

— Phase 3: 500 MeV version of PERLE (2028–2031): the realisation of PERLE at its design parameters, as a 10 MW machine. This will imply the production of a dedicated further cryomodule and switchyards at the required acceptance ratio need to be installed on both sides of the second cryomodule. By this choice, we give PERLE the opportunity to test later a cryomodule hosting further energy-saving technologies currently under development, once they reach the required maturity.

6. Studies and technical developments

In this section, we will describe the main systems of the machine and detail the needed studies and technical developments that will be performed towards TDR preparation and the P2B phase.

6.1. Optics lattice

Multi-pass energy recovery in a racetrack topology (*cf.* Fig. 2) 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.

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. The spreader design (Fig. 3) consists of a vertical bending magnet, common for all three beams, called the B-COM magnet, that initiates the vertical separation of beams. The highest energy, at the bottom, is brought back to the horizontal plane with a chicane. A second B-COM magnet was introduced (entry of this chicane) in an updated version of the spreader design to avoid the cross-talk between two dipoles proposed in the initial design. 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. In the preliminary version of the lattice, the lowest-energy spreader is configured with three curved bends following the common magnet due to the large bending angle (45°) the spreader is configured with. This minimizes the adverse effects of strong edge focusing on dispersion suppression in the spreader.

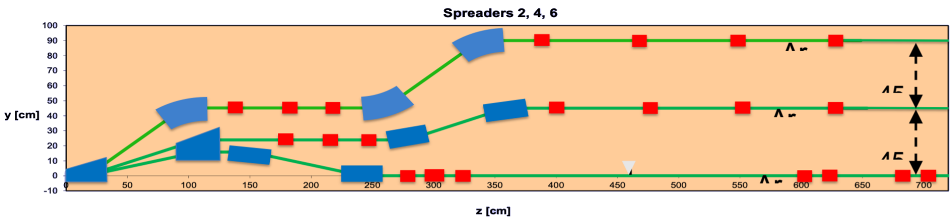

Fig. 3. PERLE spreader design and matching to three circulating arcs.

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 the Flexible Momentum Compaction (FMC) optics to ease the 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 six 33 cm long curved 30° bends and of a series of quadrupoles (three triplets and two singlets), while the higher-energy 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°). If rectangular bends were used, their edge focusing would have caused a significant imbalance in focusing, which in turn, would have had an 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 (both mirror symmetric to the previously described spreader and matching segments). As required in the case of identical linacs, the resulting arc features mirror symmetric optics (identical betas and sign reversed alphas at the arc ends).

The presented arc optics with modular functionality facilitates momentum compaction management (isochronicity), as well as orthogonal tunability for both 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 description of PERLE first-order lattice design having been done, to optimise the lattice and consolidate it, the following studies are targeted in the TDR phase:

- ERL design: For both versions of PERLE: the 500 MeV and 250 MeV machines:
  - Design of the linear lattice,
  - Linear lattice optimisation with initial magnet specs,
  - Optimisation of bunch-filling pattern,
  - Momentum acceptance and longitudinal match studies,
  - Correction of nonlinear aberrations with multipole magnets,
  - Final magnet specifications,
  - Final lattice proposal,
  - Design of the B-COM and arc magnets (dipoles and quadrupoles),
- Beam dynamics studies:
  - Start-to-End simulation with CSR & micro-bunching,
  - BBU studies,
  - Space-charge studies at the injection,
  - Merger beam dynamics consideration,
  - Multi-particle tracking studies, error effects and halo formation,
  - Impedance analysis and the Wakefield effect mitigation.

6.2. Electron source and injector

The PERLE injector (see Fig. 4) must be capable of delivering a beam with the characteristics shown in Table 1. 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 the beam dynamics study will consist of five SRF single-cell cavities with independently controllable phases and amplitudes. The longitudinal bunch compression will be done using a normal conducting RF buncher at 802 MHz 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 the gun and booster will be used for the 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.

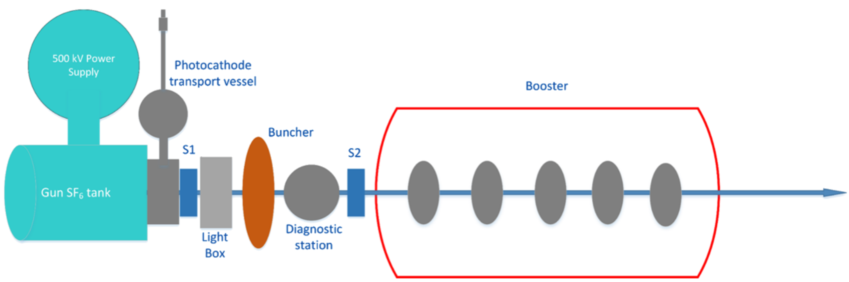

Fig. 4. The layout of the unpolarized injector.

The injector for PERLE will reuse the DC electron gun previously used on the ALICE ERL-Daresbury and now transferred to Orsay. The required upgrade for operation with a higher average current will be based on the one previously designed and partially manufactured for ALICE [16]. The significantly higher bunch charge of PERLE compared to ALICE requires complete re-optimisation of the gun electrode shape [17].

The PERLE gun will run at an operating voltage of 350 kV. Antimonide-based photocathodes will be used. These materials have high quantum efficiency in the wavelength range where lasers with sufficient power to provide the required average current are available. Another major upgrade will require the design and manufacturing of a load lock system allowing photocathode replacement without breaking the vacuum.

Optimization of injector design (photocathode shape, buncher cavity conceptual design, and the merger design) and beam transportation through it was performed in the framework of a Ph.D. thesis common between the University of Liverpool and IJCLab. Further studies and design optimisation of the injector are currently undertaken at IJCLab and a second Ph.D. thesis in collaboration with the University of Liverpool on this subject is also ongoing.

The following studies are targeted in the TDR phase:

- Conceptual design of the injection line:
  - Electron gun optimisation;
  - Injector layout optimisation;
  - Merger scheme optimisation;
- Buncher design;
- Definition of the needs on injector diagnostics.

For the P2B phase:

- Installation, commissioning, and upgrade of the DC gun:
  - Installation of the HV vessel and the DC gun;
  - Vacuum system specification and purchase;
  - Laser system specification and purchase;
  - Dielectric gas system specification and purchase;
  - Installation of beamline and diagnostics (solenoids, steerer, ICT, BPM ...);
- CC and LLRF development for the injection line;
- Design of the booster;
- Design of the beam dump;
- Prototyping of booster single cavity.

Some installation work has been already started as shown in Fig. 5.

Fig. 5. Sequences of the installation of the photo gun (from top left to bottom right) from March to December 2022. Installation of the high voltage tank with the leak tests; Assembly of the HV columns; tests and modifications to the HV; pre-positioning of the gun; cleaning and test of the anode chamber.

6.3. Cavity design and prototype

Activities to optimize a bare 801.6 MHz five-cell ERL linac cavity design, to build a prototype, and 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 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 [18]. A full set of parameters for this cavity can be found in the PERLE CDR [19].

The result for the Nb cavity — made from fine grain high-RRR Nb — is encouraging since the cavity reached accelerating fields, Eacc, slightly above 30 MV/m ultimately limited by the thermal breakdown (quench). Moreover, the RF losses were rather small due to the rather relatively low RF frequency, which provides a small BCS surface resistance. This resulted in unloaded quality factors, Q_0, well above 4×10^{10} at 2K at low fields, while Q_0 values beyond 3×10^{10} could be maintained for the five-cell cavity up to about 27 MV/m (see Fig. 6). Only standard interior surface 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. While the vertical test results indicate generously headroom for a potential performance reduction once a cavity is equipped with all the ancillary components installed in a cryomodule, clean cavity assembly procedure protocols must be established for the cryomodules to minimize the chance of introducing field-emitting particulates.

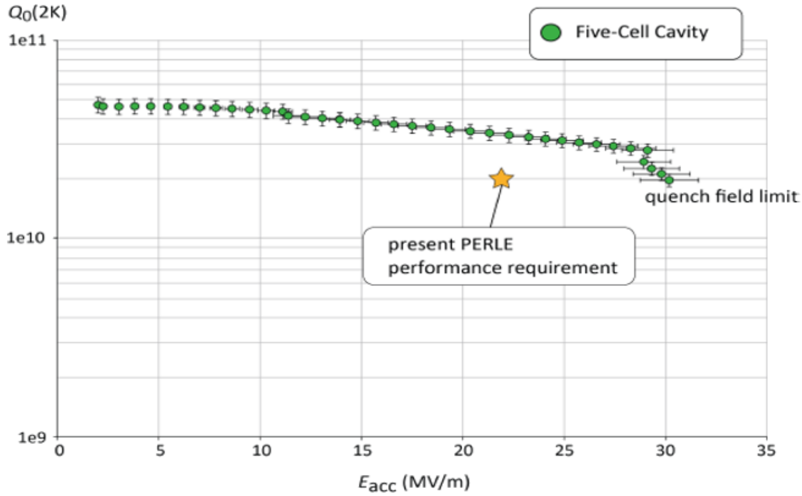

Fig. 6. (Colour on-line) Vertical test result of the 5-cell 801.6 MHz niobium cavity. The star indicates the edge of the performances considered for PERLE operation with a typical CW gradient optimum around 20 MV/m.

The effort is now made on HOM damping, an important issue for high current, multi-turn ERL, that highly impacts the beam stability and machine functioning. The aim is to obtain the first full-dressed cavity for PERLE, equipped with HOM coupler(s) and tested for the TDR. Also, the existent power coupler (made for SPL cavity at CERN) will be adapted to PERLE needs and RF conditioned.

For the TDR phase, the following studies are foreseen:

- HOM damping studies and HOM coupler design (RF and thermal);
- Optimisation of the damping scheme and design of the cavity end group;
- Cryogenic requirement for PERLE full-dressed cavity.

For the P2B phase:

- HOM couplers prototyping;
- Fundamental power couplers prototyping;
- 5-cell Cu cavity fabrication for HOM measurements and end group optimisation;
- 5-cell Nb cavity prototyping.

6.4. Cryomodule design

The PERLE layout is integrating two superconducting RF cryomodules, one per linac, each of them containing 4 superconducting 801.6 MHz 5-cell elliptical cavities. In addition to the classic constraints of an SRF cryomodule, several requirements are quite specific for the ERL operating mode posing several challenges. 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 (low cryogenic losses) for the SC cavities is the main objective. Besides specific optimization on cavity design and preparation, the cryomodule has to provide a very low residual magnetic field environment to the cavity. To achieve that, both stringent optimization of the magnetic shielding (material, numbers of layers, active and/or passive shielding) and careful choices of nonmagnetic material for components located 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 (the so-called magnetic hygiene). 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 the PERLE purpose, we will work on the adaptation of the ESS cryomodule design shown in Fig. 7. Its design offers several advantages, such as a large internal available space, easy cavity string insertion and its mechanical support, and easy access to the other components (tuner, cryogenic distribution). On top of that, 30 cryomodules have been assembled and are presently being validated with great success before their installation into the ESS tunnel.

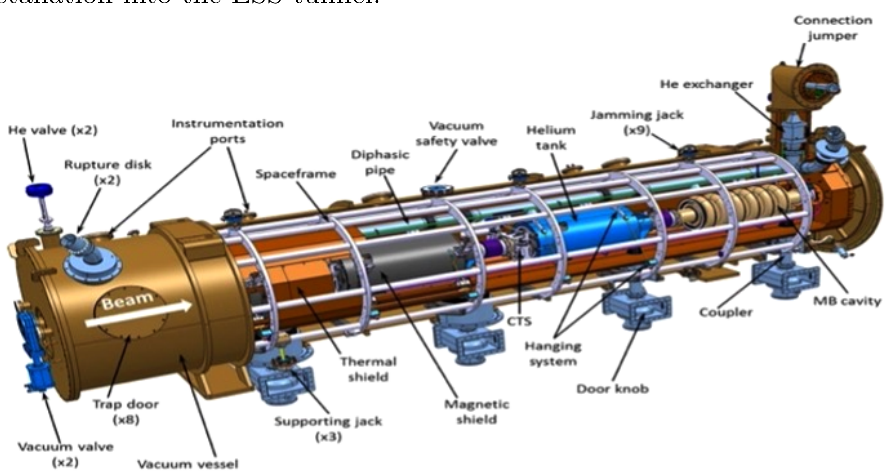

Fig. 7. General assembly view of the ESS cryomodule considered to be adapted for PERLE.

The retrofitted cryomodule will then be adapted to the ERL high current operation. This could be made possible by adapting the initial cryomodule design to integrate a string of PERLE cavities equipped with FPCs and the optimised HOM damping scheme allowing for efficient HOMs extraction and damping. The overall cryogenic distribution of the cryomodule will be adapted to the requirements of those new components (FPC and HOM couplers), mainly driven by the number of needed HOM couplers, their cooling requirement and the power extraction that will be optimized to lower the global heat loads. We keep also in mind the possibility to integrate a fast reactive tuner to mitigate the cavity detuning caused by microphonics. This may need a modification of the cryomodule design that could be implemented later (the 2^{nd} cryomodule of PERLE) once the technology came to maturity.

The following studies are targeted in the TDR phase:

— Design adaptation of ESS cryomodule to PERLE;

— Cryogenic requirement estimation;

— RF power system dimensioning.

For the P2B phase:

— Dimensioning and design of the cryo-plant.

6.5. The site

According to the lattice design (*cf.* Fig. 2), the footprint of this facility occupies a rectangle of 28×6 m^2. This area should be enclosed by shielding at a sufficient distance to allow passage and maintenance operations. We estimate the required passage and half thickness of the accelerator component to be 2 m. Concrete shielding is assumed here to stop photons and neutrons produced by halo electrons. A detailed study of the radiation generated by the impinging electron will be necessary at the following stage and will be included in the TDR. An increase in the shielding required could be alleviated by the use of denser materials (see Fig. 8).

Furthermore, the PERLE operation at the design beam parameters (Table 1) had required an in-depth study of the machine failure scenario to estimate the power left in the machine during operation after beam losses and how to handle and control it. The study aimed at investigating if the PERLE facility will be classified as INB (Installation Nucléaire de Base) or not, in respect to the French radioprotection and nuclear safety rules. The outcomes of the study showed that PERLE could not be considered as INB, even if the beam parameters are quite impressive. It was proved that for several failure scenarios, once the injection is interrupted by the laser shutter,

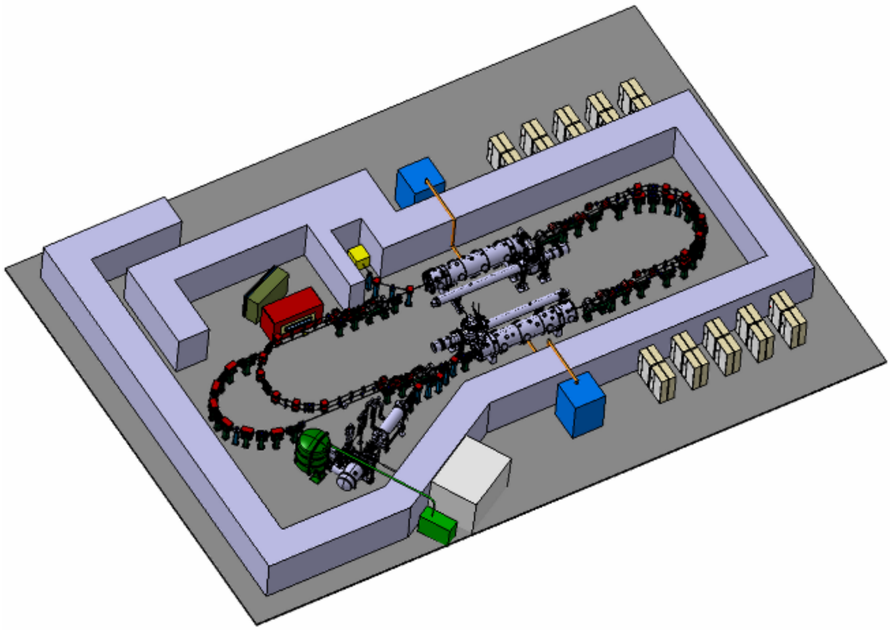

Fig. 8. PERLE layout with its bunker.

the energies of the beams in the ERL could be brought back to the injection energy and safely dumped within tenths of a micro-second, thanks to the recovery mode. For other scenarios (losses during functioning), beam loss monitors all around the machine, hard interlocks, and the machine safety system should be fast enough to manage the situation. The complete report on this study has been delivered by the IRSD team at Orsay.

Besides the central area required for machine implementation, space needs to be allocated for the auxiliary systems (power converters for magnets, RF power sources, water cooling, cryogenics, electron source, dump). One has also to consider a sufficient area for experiments that may use the PERLE beam. As a rough estimate, one would need to triple the area of the accelerator itself to accommodate all services shielding included. We are considering two possible sites at IJCLab that would host this version of PERLE: The Super ACO hall (*cf.* Fig. 9). It is equipped with cranes and electricity. The ground of the building is made of concrete slabs with variable ground resistance. A complete infrastructure study will be carried out to evaluate the ground capacity to support the machine and mainly the shielding load. The building gives the possibility to install the RF source and the power supplies at a different level than the accelerator. An existing control room that overlooks the experimental hall could be used for PERLE. A cryogenic plant is still to be built.

Fig. 9. View of the Hall Super ACO where PERLE could be hosted.

Another site that could be of interest to PERLE is the Igloo. It has the advantage to be totally shielded, has a control room available and is equipped with electricity, crane, water cooling ... However, it currently contains another accelerator (ThomX) and the remaining available space is quite tight to install comfortably PERLE. This option will be studied carefully.

The "Contrat Plan Etat-Région" (CPER) program will support the infrastructure studies that will be carried out (2M € allocated) in the two sites and part of the needed work when decided.

The following studies are foreseen for the TDR phase:

— Radioprotection study and determination of the shielding needed;

— Definition of the machine footprint.

For the P2B phase:

— 2 Sites studies and definition of the infrastructure work needed;

— Preparation of the folder for PERLE administrative classification.

7. Conclusions

The ERL machines open a new frontier for the physics of "the electromagnetic probe" (ep, eA, eN). PERLE@Orsay is a key ERL project for HEP and Nuclear Physics communities.

PERLE@Orsay has been recognised (together with bERLinPro) as an essential pillar of the ERL ESPP strategy. It combines high current and multi-passes (high luminosity/higher energy).

PERLE@Orsay is a very challenging machine including RF CW operation, specific SFR systems, multi-bunches operation, high-power machine, complex lattice design, broad range diagnostics, beam dynamics.

The TDR should be completed by the end of 2023 and the 250 MeV version of PERLE should be completed by early 2028.

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