PERLE: A High-Power Energy Recovery Facility at Orsay

1. General introduction

Energy-Recovery Linacs (or 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 suggested first in 1965 by Tigner [1], and experimented only twenty years later by Stanford [2] and LANL [3] for normal conductive facilities accelerating beams at rather low power. The concept become really viable thanks to the major advances in SRF technology within the last decades (quantified by cavity quality factors $Q_0 \geq 10^{10}$) enabling high average current operation, in addition to the consideration of multi-pass recirculation allowing high beam energy in relatively compact machine. These two aspects have paved the way to a new generation of powerful machines with relatively compact footprint.

PERLE is a compact three-pass ERL project based on SRF technology, being as 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 ERL's 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 optimised ERL-specific designs and hardware. To attend this goal, an international collaboration is formed around the project, involving today CERN, JLAB, STFC-Daresbury, University of Liverpool, BINP-Novosibirsk, Cornell University and IJCLab- CNRS. All of them are leading laboratories on accelerator physics with experience of ERL development for some. IJCLab is leading the collaborative effort towards the realization of the project.

The collaboration effort is currently focused on the organization and work sharing toward the publication of a Technical Design Report (TDR) of the machine by fall 2022. This important step is the subject of the council evaluation. Nevertheless, an overview of the project next steps will be briefly described. The TDR scope includes optic lattice study and consolidation, design studies of main systems, the prototyping of most critical equipment and beam dynamics studies.

In this document, we situate 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 toward the TDR. The project organization, available resources and estimation of the needs will be expressed also. A potential experiment using PERLE beam will be described in the annex of the 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 relatively compact machine is paving the way to a green generation of high energy, high brightness, high average current electron beams.

The 2020 Update of the European Strategy for Particle Physics clearly stated that ERLs are among the innovative accelerator technologies that deserve a vigorous R&D effort in the upcoming years. It was specified that the accelerator R&D roadmap on critical technologies needed for future colliders to be developed by the European particle physics community, should consider the R&D on high-intensity, multi-turn ERL machines.

Being aware of these scientific challenges, and in order to develop and acquire expertise in design, studies and later construction and operation of ERLs, IJCLab is today leading an international collaboration around an ambitious project: PERLE. The collaboration involves today CERN, JLAB, STFC-Daresbury, University of Liverpool, BINP-Novosibirsk, Cornell University and IJCLab- CNRS. Four of these international partners have been pioneering the development of ERL technology, the other are leading laboratories on SRF technology and accelerator physics. The collaboration is, of course, open to new comers.

At the national level, the Particle Accelerators & Associated Instrumentation working group stated in its report for the 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*".

In another hand, following a first evaluation of the project by the common scientific council of LAL and IPNo (prior to IJClab creation) in June 2019, it was stated that: "… *There may be conflicts with MYRRHA, PIP-II for the availability of experts during the study and prototyping phases. Some expertise will not be available in Orsay and the participation of collaborators external to LAL and IPN will be necessary. The organisation of the project is a key issue. The scientific council recommends setting up an international organisation with official collaborations to drive the project. Project management should be strengthened. In the same spirit, a (new) attempt to extend the collaboration to CEA should be tried.*".

"A TDR would give a clear picture on the project. Hence, the scientific council recommends to achieve the phase 1.1 as described in this document. The TDR should already be elaborated with international collaborators".

Thus, regarding the recommendations and statements above, an important effort was first dedicated to organise and officialise the international collaboration through drafting and signing the PERLE Collaboration Agreement.

A Conceptual Design report (CDR) of a 1GeV version of PERLE was published in 2017 in collaborative effort [5]. It was considered as an important step toward the realisation of LHeC (more details in next section). Today, the effort of the PERLE collaboration is focused on the TDR preparation of a smaller version defined as: an ERL accelerating a high average current electron beam (20 mA) through 3 passes to the maximum energy (500 MeV) in the superconducting RF CW linear accelerators, then decelerated through the same number of passes once the beam used for its intended purpose. The technical details of the project and its organization will be detailed in the following sections.

2. Importance of PERLE in the ERL facilities landscape

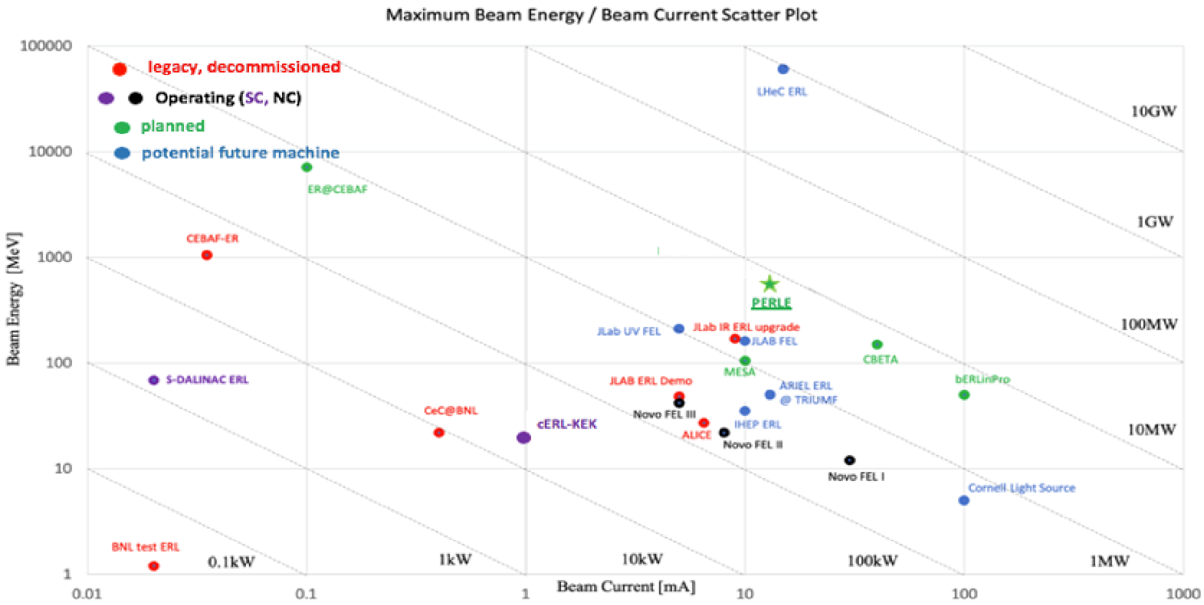

Figure 1: Scatter plot of past [red], operations [violet (SC) & black (NC)], planned [green] and potential future [blue] superconducting ERL facilities on a double logarithmic scale with the maximum beam energy on the vertical and the maximum beam current on the horizontal axis. The dashed diagonal lines indicate the beam power regimes in the scatter plot.

The global landscape of ERLs projects (Cf. Figure 1) show 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 normal conducting RF systems is NOVO FEL at BINP- Novosibirsk [8] and offers therefore only limited feedback for new generation machines.

The LHeC (Large Hadron Electron Collider) is a proposed multi-turn ERL reaching 50 GeV in three turns providing electrons that collide with the LHC protons [9]. 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 [10], 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 [11]. This important transition on 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 1MW) and the targeted performances of LHeC (1GW) by exploring an intermediate operational power regime around the 10MW. The bERLin-Pro facility [12] 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. However, it will only feature one acceleration and one deceleration loop and will therefore not be able to address issues arising from the multi-turn ERL operation (mixed beam energies in the SRF, low level RF control developments etc.). The C-BETA facility [13] at Cornell University starts commissioning in 2019. It will address issues related to multi-turn (4 acceleration and 4 deceleration passages) in an ERL facility and the viability of FFAG arcs for the return arcs and also push the operational beam power beyond the 5MW level. 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. 2x3x20 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 CW operation, the high beam average current handling, the low delivered beam energy spread and the low delivered beam emittance. Their realisation and success will provide valuable input and crucial validation for the future energy and intensity frontier machines, especially PERLE that have the possibility to uniquely demonstrate and validate some key points:

- Efficient multi-turn ERL operation at high energies with high SRF cavity gradients;
- Efficient multi-turn ERL operation with a high total beam current of about 120mA in the SRF system;
- Efficient multi-turn ERL operation with high total beam power and beams of different beam energies in the same SRF system.

Furthermore, PERLE could pave the way to new generation of compact but powerful ERLs for applications requiring high energy beam and/or high total current (e.g. photon generation by Compton back-scattering, high-energy cooling source for ion beams, electron-ions collider). Thus, two new proposed projects have chosen the PERLE technology and configuration: DIANA in Daresbury (a user facility for industrial applications) and DICE in Darmstadt University (for Photo-Nuclear Physics R&D, to replace the old s-DALINAC). Possibility of collaboration between PERLE and these two projects in several field was discussed with project leaders.

Last but not least, a recent proposal of an electron-Radioactive Ions collision facility (e-RI) at GANIL to obtain exotic nuclei was made in the frame work of the future of GANIL program (in the 2030's). The option of a high current ERL as electron source is strongly supported. Even if the choice today seems more oriented for a single tour, 100 mA (up to 200 mA), 500 MeV ERL (so 50 MW to 75 MW machine), possible interactions with PERLE initiative was discussed within the working group. Apart the teaching that could provide in the accelerator physics phenomenon for a high-power regime ERL (cf. next section), PERLE could host an R&D program on ion trap at lower luminosity, by adjunction of an upgraded photo-fission, SCRIT-like, device to it (cf. annex 1).

3. Challenges to overcome and impact on next ERLs

As mentioned previously, together with other ERLs in construction (CBETA and bELRin-Pro), PERLE will bridge the gap of power between the current record holder (CEBAF-ER at 1MW) and the targeted performances of LHeC (1GW) by exploring an intermediate operational power regime around the 10MW. Moreover, thanks to its conceptual design (multi-pass configuration in racetrack) and the high beam current in the SRF cavities, PERLE will provide enormous insight on multiple pass operation and common transport from full energy to next ERL generation.

BBU Threshold dependency: Up to date, existing SRF systems have demonstrated stability at only a modest fraction (<20%) of the full current targeted. Although threshold currents have been indirectly measured at higher values, there is no direct evidence that multi-pass systems will be sufficiently resistant to BBU at the order-of-magnitude higher current, nor has the sensitivity of the instability threshold to linac length, dynamic range, and number of passes been directly or systematically measured. PERLE will provide a single datum on linac length, and can directly measure the dependence on N_{pass} and the turn-to-turn transfer matrix. Thus, this can be reliably extrapolated to determine sensitivity to length dependence and the N_{pass}, energy and transfer matrix can be varied to determine sensitivity.

Dynamic range influence on optic design: The dynamic range (which is the ratio of injected/extracted energy to full energy) is a critical design parameter, in as much as it defines the sensitivity of the overall system to magnetic field errors. Errors at full energy drive phase/energy errors that are magnified by adiabatic anti-damping during recovery, and can exceed the dump acceptance should the errors be too large. Thus, the field quality needed is inversely proportional to the ratio of full energy to dump energy: that is, a very high energy machine (or one with very low dump energy) needs extremely high-quality magnets. For PERLE, the dynamic range is 70:1 (7 MeV in/out, 490 MeV full energy), this imply a need of $\Delta B/B_{dipole}$ ~ 0.001% field flatness (extrapolation from JLAB ERL needs) to recover cleanly enough. This imply tight constrain on magnet performances and impact their cost. PERLE has a very large dynamic range and a transport system with considerable symmetry and flexibility; it is therefore an appropriate tool to explore this issue and evaluate the cost implications for larger scale systems.

Halo formation: Existing systems have operated at maximum 1 MW full beam power. It is too low to demand a precise understanding and control of beam halo. Extrapolation to 10 MW will demand suppression of localized losses to, or below, parts per million. Higher power requires lower fractional loss. It is not now understood how to do this - in particular, collimation systems are not at present well-optimized for control of CW losses at rates observed in linacs. PERLE will provide a platform on which the next step in understanding can be taken. Other halo effects are visible at only the higher CW powers under consideration in PERLE (including Touschek and intra-beam scattering, beam-gas scattering, and ion trapping). These lead to scattering events that adiabatically anti-damp and result in intolerable loss in the back end of the machine, limiting dynamic range. There is no experience with these phenomena, although theoretical studies suggest they are problematic. PERLE will be the first system capable of directly exploring these issues.

Collective effects at low beam power: There are many collective effects that have already proven problematic at lower beam powers - including RF heating, resistive wall heating, THz emission heating... - that will have greater impact at both higher power and higher energy. There are at present no operating ERL systems that can study these. PERLE is the only system proposed or under construction that combines sufficient beam power with sufficient operational flexibility to study and test mitigation algorithms and methods. Absent PERLE, higher energy/power machines will have very little insight regarding these problems and no ability to test solutions.

Collective effects and preservation of beam quality: Beam quality preservation in the presence of collective effects is a significant challenge for modern machines. In particular, Longitudinal Space Charge (LCS), Coherent Synchrotron Radiation (CSR), and the microbunching instability have serious deleterious impact on performance, and can prevent a machine from producing beam consistent with user requirements - or, worse, from being able to operate at significant powers. PERLE probes the regions of parameter space where these effects are observable, and offers opportunity to benchmark models and explore mitigation methods. In fact, one of the concerns one can voice about PERLE is that it suffers from CSR and microbunching effects; given the common transport, this may result in problems during energy recovery. It is, however, well-suited to explore these phenomena and to demonstrate control of them.

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 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).

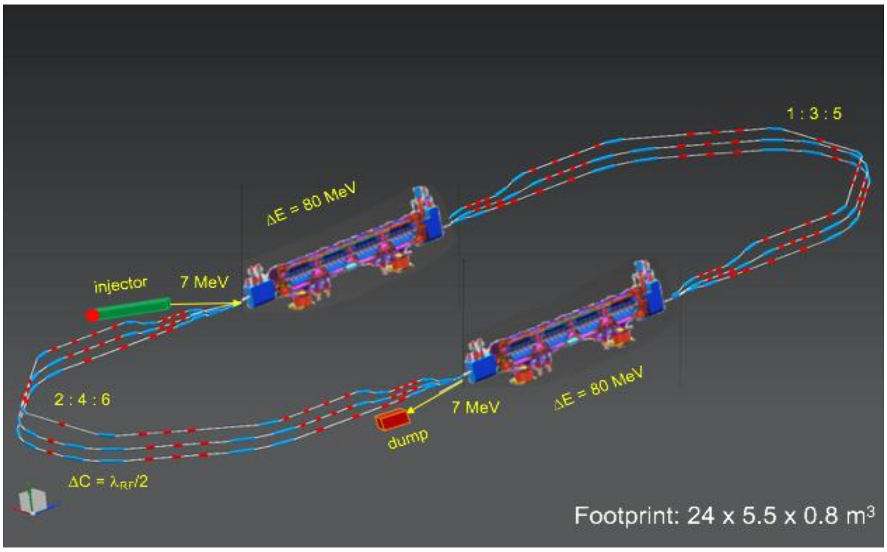

Figure 2: PERLE Layout featuring two parallel linacs each hosting a cryomodule housing four 5-cell SC cavities, achieving 500 MeV in three passes.

Each of the two cryomodules provides up to 82 MeV energy boost to the high average current electron beam (20mA). 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. The beam is then used for its intended purpose (e.g. photon generation by Compton back-scattering, a cooling source for ion beams or collision with ions). This process may significantly increase the energy spread or emittance of the electron beam but the major part of the beam power remains. The beam is then sent back through the accelerators again only this time roughly 180 degrees off the accelerating RF phase so the beam is decelerated through the same number of passes and its energy is deposited into cavities allowing the acceleration of newly injected bunches, thereby effectively cancelling the beam loading effects of the accelerated beam. Then the remaining beam is sent to a dump at around the injection energy. Several benefits accrue from this manipulation: the required RF power (and its capital cost and required electricity) is significantly reduced to that required to establish the cavity field and make up minor losses, the beam power that must be dissipated in the dump is reduced by a large factor, and the electron beam dump energy is reduced below the photo-neutron threshold so that activation of the dump region can be avoided. The main beam parameters of 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 $\gamma\varepsilon_{x,y}$	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

5. Studies and technical developments toward PERLE TDR

In this section, we will describe the main systems of the machine and detail the needed studies and technical developments that will be performed within the PERLE collaboration toward PERLE TDR preparation. Being a collaborative effort, the Work Breakdown Structure (WBS) of each task was developed and agreed upon, within the “PERLE Management Board” that we will present in the Section 6.

5.1. The optic 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.

Figure 3: PERLE spreader design and matching to three circulating arcs

The spreader design (Fig. 3) 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. In the preliminary version of the lattice, 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). In the preliminary version of the lattice, 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°). 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, 91.2 cm, bends.

Each arc is followed by a matching section and a recombiner (both mirror symmetric to previously described spreader and matching segments). As required in case of identical linacs, the resulting arc features a 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.

An upgrade of the preliminary version of the lattice (described above) is currently undertaken. The new version will take into account some raised issues relative to collective effects in the circulating arcs, dipole crowding in switchyards and the allocated space for experiments in the high energy arcs. the outcomes of this update will allow to define the final magnets specifications. and the prototyping of the most critical optic element: the common switchyard dipole by another partner: BINP-Novosibirsk.

Table 2: WBS of lattice and optics task

Task	involved parties	Task Manager	Contributer
Lattice and Optics	JLAB-IJCLab	Alex Bogacz	
Linear lattice optimization			JLAB
Arcs 1-6 (6-bend architecture)			JLAB
Spr/Rec 1-6 (two b-com switchyard)			JLAB
Matching sections 1-6 including two experimental inserts (Rec 6 and Spr 2)			JLAB
Linacs 1-2 with new cryo configuration			JLAB
Repository and data base with version control			IJCLab
Linear lattice optimization Initial magnet specs			JLAB
Momentum acceptance and longitudinal match			JLAB
Correction of nonlinear aberrations with multipole magnets			JLAB
Final magnet specs			IJCLab
Lattice design - External review			JLAB
Final Lattice			IJCLab

Once the Lattice optimised, beam dynamics studies will be performed as the following:

Table 3: WBS of beam dynamics studies

Task	involved parties	Task Manager	Contributer
Beam Dynamics	JLAB-IJCLab	Alex Bogacz	
Start-to-End simulation with CSR & micro-bunching			JLAB
BBU studies			JLAB
Space-charge studies at injection			IJCLab
Multi-particle tracking studies, error effects and halo formation			IJCLab
Impedance analysis and wakefield effect mitigation			JLAB
Beam dynamics issues - External review			JLAB

5.2. Electron 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 nuclear physics experiments in a later phase. 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 single-cell cavities with independently controllable phases and amplitudes. The longitudinal bunch compression will be done using a sub-harmonic normal conducting RF buncher (401 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 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.

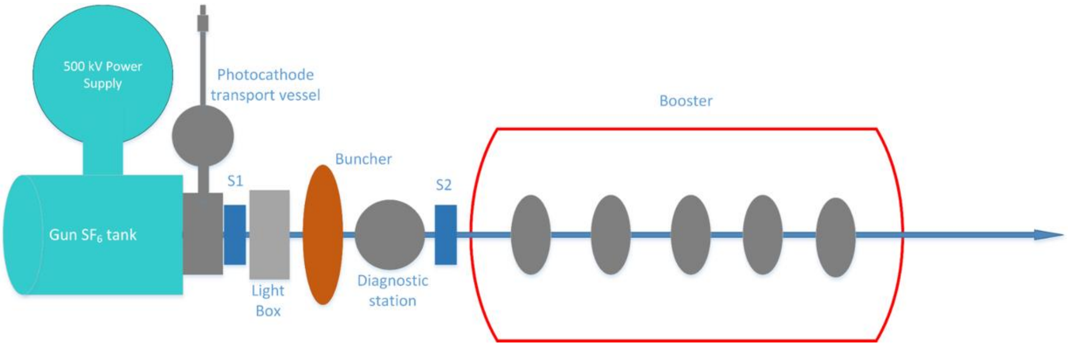

Figure 4: The layout of the unpolarized injector

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 higher average current will be based on one previously designed and partially manufactured for ALICE [14]. The significantly higher bunch charge of PERLE compared to ALICE requires complete re-optimisation of the gun electrode shape [15].

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 of PERLE. These materials have high quantum efficiency in the wavelength range where lasers with sufficient power to provide required average current are available. The polarised operation mode will require to use gallium arsenide-based photocathodes as these are the only materials capable of delivering polarised beams. Another major upgrade will require design and manufacturing of a load lock system allowing photocathode replacement without breaking the vacuum.

Optimization of injector design (photocathode shape, buncher cavity design, merger design) and beam transportation through it is performed in the framework of a PhD thesis common between University of Liverpool and IJCLab. An option to adapt and use JLEIC booster design from JLAB is under study.

Table 4: WBS of Electron source and injection line design

Task	involved parties	Task Manager	Contributer
Electron source and injection	IJCLab, STFC and UoL		
DC Gun upgrade for operation with interchangable photocathodes		IJCLab and STFC	
Review of the gun upgrade design			IJCLab and STFC
Identification of missing and additional gun upgrade components			IJCLab and STFC
Desing of transport vessel fo alkali photocathodes			IJCLab and STFC
Photocathode fabrication and load lock system design		STFC	
Buncher study and design		IJCLab	
RF design			IJCLab
Mechanical design			IJCLab
Booster studies and design		_	
Booster cavities design			_
Cryostating need and design			_
Merger		IJCLab	
Physical design			IJCLab + UoL + STFC
Mechanical design			IJCLab
Photo-injector Laser system for unpolarised regime		IJCLab	
Diagnostics need		IJCLab	

5.3. Cavity design and prototype

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 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 [16]. A full set of parameters for this cavity can be found in the PERLE CDR [5].

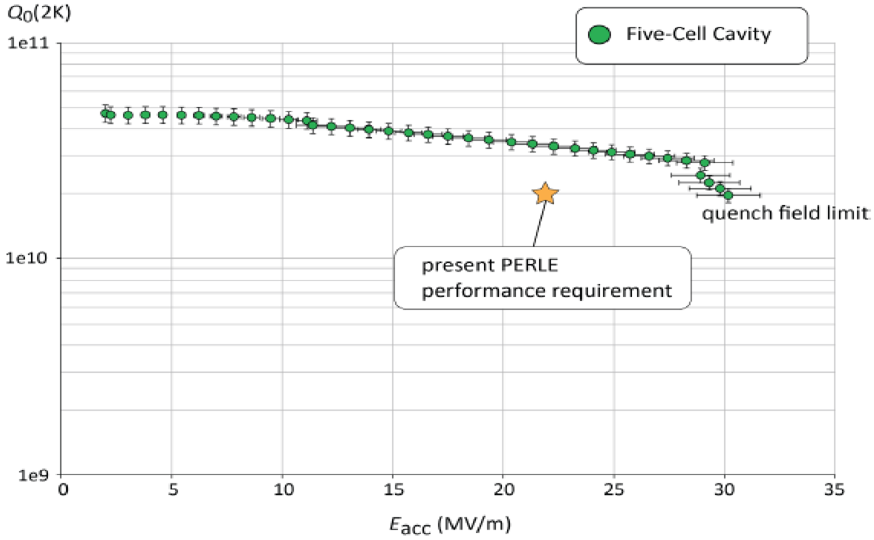

Figure 5: Vertical test result of the 5-cell 801.6 MHz Niobium cavity. The yellow star indicates the edge of the performances considered for PERLE operation with a typical CW gradient optimum around 20 MV/m.

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 (quench). 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, Q_0, well above $4{\cdot}10^{10}$ at 2K at low fields, while Q_0 values beyond $3{\cdot}10^{10}$ could be maintained for the five-cell cavity up to about 27 MV/m (see Fig. 5). 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 generous headroom for a potential performance reduction once a cavity is equipped with all the ancillary components and installed in a cryomodule, clean cavity assembly procedure protocols must be established for the cryomodules to minimize the chance of introducing field-emitting particulates.

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

Table 5: WBS of full dressed SRF cavity, Power coupler and Tuner

SRF Cavity	JLAB and IJCLab	Frank Marhauser	
RF cavity and HOMs design			JLAB and IJCLab
HOM damping needs			JLAB and IJCLab
HOM EM design			JLAB and IJCLab
HOM mechanical design			CERN
End-group design			JLAB
Fabrication & tests of first HOM couplers for first cavity			IJCLab
Fabrication & tests of first dressed cavity			JLAB
Power coupler	IJCLab and CERN		
Definition of characteristics: Qex, Pav, Pmax,			IJCLab
Adaptation of SPL coupler to 800 MHz			CERN
Design and fabrication of 800 MHz test box			IJCLab and CERN
Procurement & set-up of amplifier, LLRF, controls			IJCLab and CERN
Test and conditioning			CERN
Fast Reactive Tuner (FRT)	CERN		
Feasibility study (& integration on cavity)			CERN
Electrical & mechanical design			CERN
Pocurement & prototyping			CERN
Cold test on cavity			CERN, JLAB

5.4. 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 to 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 a 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 the non-magnetic 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.

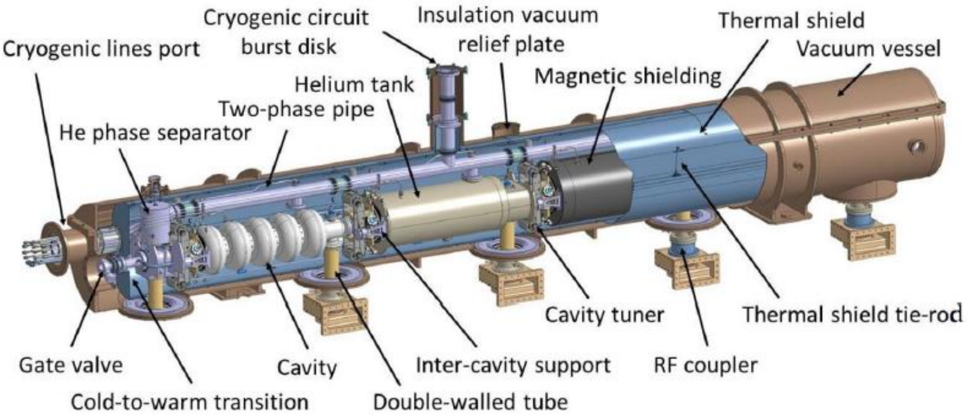

Figure 6: General assembly view of the SPL cryomodule considered to be adapted for PERLE.

Among the recent cryomodule developments made for several projects, we have chosen for PERLE to use the cryomodule layout developed by IPN-Orsay and CERN for the Superconducting Proton Linac (SPL) [17], for its capacity to fulfil the PERLE requirements in terms of dimensions, cryogenic performances and cavity requirements (Fig. 6). 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. Even if additional studies have to be performed, once detailed designs of some parts (mainly HOM couplers and their number per cavity) will be finalized, this cryomodule design is considered to be the reference for the PERLE cryomodules.

5.5. The site

According to the preliminary lattice design (cf. Fig. 2), the footprint of this facility occupies a rectangle of 24 x 5.5 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 2 m. A concrete shielding is assumed here to stop photons and neutrons produced by halo electrons. Detailed study of the radiation generated by the impinging electron will be necessary at a following stage and will be included in the TDR. An increase of the shielding required could be alleviated by the use of denser materials.

Furthermore, the PERLE operation at the design beam parameters (Tab. 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 looking if the PERLE facility will be classified as INB (Infrastructure Nucléaire de Base) or not, in respect of the French radioprotection and nuclear safety rules. The outcomes of the study shown that PERLE could not be considered as INB, even if the beam parameters are quite impressive. It was proved that for several failure scenario the energy of the beam is brought back to the injection energy and safely dumped, within tenths of micro-second, thanks to the recovery mode. For other scenario, the hard interlocks and the machine safety system are fast enough to manage the situation. The complete report of this study has been delivered by the IRSD team at Orsay.

Figure 7: View of the Hall Super ACO where PERLE could be hosted

Besides the central area required for machine implementation, space needs to be allocated for the auxiliary systems (power converters for magnets, septa and kickers, RF power, Water cooling, Cryogenics, Electron source, Dump). One has also to consider 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. The building that would host this version of PERLE is a former experimental hall, Super ACO hall (cf. Fig. 7). It is equipped with cranes and electricity. The ground of the building is made of concrete slabs with variable ground resistance. More than half of the hall area has a sufficient resistance to allow the installation PERLE. Being next to the tunnel of the old Orsay Linac and close to the "Igloo", where new accelerators are being installed currently, the building is partially shielded and some equipment (water-cooling circuits, electrical transformer) can be shared with the other machines. 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. Since all the accelerators installed nearby are based on warm technology, a cryogenic plant should be built. All the needed support for infrastructure could be assured by the "Contrat Plan Etat-Région" (CPER) program. Altogether, this appears to be a well suitable place which has the advantage to be available.

6. Project organisation and resources

6.1. Project organisation and manpower:

Being an international collaborative effort, it was decided to form the PERLE Management Board (MB) composed of experts in several accelerator field, part of the collaboration, that have a primarily technical role. This board assists the project leader to define the various project tasks, at IJCLab-Orsay and/or other collaboration sites, and to ensure the execution and monitoring of the project tasks in their respective labs. The Management Board involves these colleagues:

- Alex Bogacz (JLAB)
- Patxi Duthil (IJCLab)
- Frank Gerick (CERN)
- Eugène Levitchev (BINP-Novosibirsk)
- Frank Marhauser (JLAB)
- Boris Militsyn (STFC-Daresbury)

And

- Max Klein (University of Liverpool)- spokesperson
- Walid Kaabi (IJCLab)- Project Leader

The first task of the MB was to work on the PERLE WBS (in progress) from which we show some extraction in the previous sections.
For the time being, IJCLab is the only IN2P3 lab involved in the project. Apart the involvement of manpower from collaborators sides, here the evolution of IJCLab manpower implication on the TDR phase of the project in the past two years and an estimation for the 2 upcoming ones:

Table 6: evolution of IJCLab manpower implication over the years

Year	2019	2020	2021	2022
FTE	1.5	1.9	5	7

In 2020, we had 5 permanent staff involved (4 research engineer + 1 engineer) and 2 non-permanent staff (1 engineer + 1 PhD). The projection for the next two years is currently under discussion internally, with at least 1 additional FTE guarantied (Post-doc position to be hired).

6.2. Financial resources:

A tentative cost estimation of PERLE facility was undertaken and the global cost of the machine was evaluated at about 25 MEuros. This estimation did not include manpower cost, nor infrastructure work and related equipment (Shielding, water cooling, fluids, electrical power, safety protection system, etc.) implementation cost. If the construction of PERLE at Orsay is confirmed, a request to CPER program -Phase 2 (Contrat de Plan Etat-Région) would support the infrastructure cost. Moreover, this value did not take into account any possible in-kind contribution from the collaborators (DC gun, SPL cryomodule, possible JLEIC booster from JLab).

For the current TDR phase, the support needed is mainly on manpower (post-doc and PhD hiring), critical component prototyping (HOM coupler (s) to equip the existing bare cavity, common dipole in the switchyard), adaptation of existing components for PERLE needs before test (SPL power coupler, upgrade of the DC gun…) and on travel cost (even if the period is not favourable…)

PERLE will receive in 2021 fund from IN2P3 for 1 year post-doc (RF design profile). Also, through the European program CREMLINplus, the project received in 2020 funds for 18 months of post-doc (profile optic design and beam dynamics), and 100k€ for prototypes (Mainly magnets) to be spent in the 2 upcoming years. IJCLab contribute to the project funding by financing the common PhD position with University of Liverpool (injection line design optimisation). Table 7 summarise the fund received and their origin, with a tentative of the need estimation for next years (mainly for prototyping and test cost: HOM coupler, SPL power coupler, cavity test…). These amounts could evolve depending on the project progress and funding opportunity that we will have.

Table7: received funds and their origin over the years and estimation of the needs for 2022 and beyond.

	Year			
Fund origin	2019	2020	2021	2022-2023
IN2P3	20 k€	–	57 k€	
EU (CREMLINplus)	–	209.9 k€		
IJCLab (own fund)	–	36 k€		
Total	20 k€	245.9 k€	57 k€	A need of 80 to 100 k€

7. Staging Strategy and Timeline

Even if the evaluation concerns the TDR phase of PERLE, it is worth to show our vision for the entire project and the way we manage to realise it. The PERLE realisation starts with a design and prototyping phase that ends with the PERLE TDR, as detailed in previous sections of this document. There follow three phases of construction, commissioning and exploitation which are here sketched and will be subject to changes as the Project develops.

- **Phase 0:** Installation of the injection line 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 1:** 250 MeV Version of PERLE

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 0, via the merger.

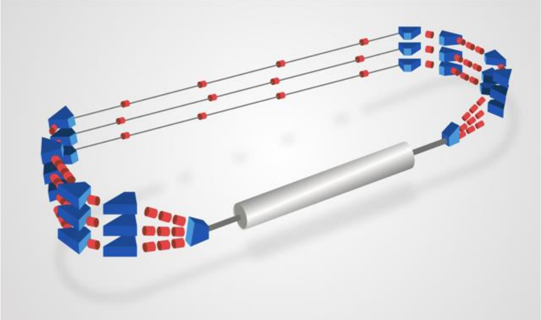

Figure 8: PERLE-Phase 1 layout featuring a single Linac in the first straight and solely beam lines in the second straight, achieving 250 MeV electron energy in three passes.

This particular staging is determined by the existence of the SPL cryomodule which will permit a rather rapid realisation of a 250 MeV machine possibly still using the ALICE gun.

- **Phase 2:** 500 MeV version of PERLE

The second phase is for the realisation of PERLE at its design parameters, as a 10 MW machine which requires the nominal electron current, i.e. the upgraded e^- gun and the completion of the production of a dedicated further cryomodule. Also, a second spreader and recombiner at the required acceptance ratio need to be installed on both sides of the second cryomodule.

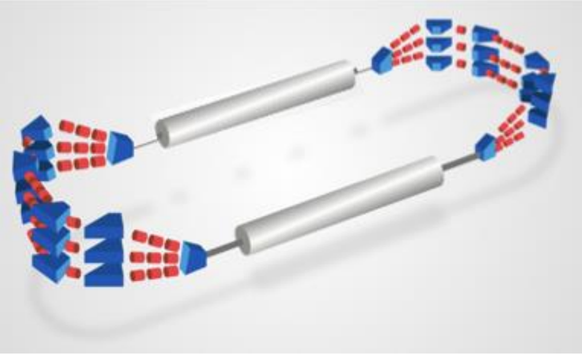

Figure 9: PERLE-Phase 2 layout featuring two Linacs, achieving 500 MeV in three passes.

The Management Board will develop a detailed time schedule for different phases as the project progress. Currently it is expected to complete the TDR by fall 2022, Phase 0 by 2025, Phase 1 by 2028 and Phase 2 by 2030. A scheme of milestones will be worked out and agreed upon with emphasis on the accelerator but including a timeline for future experiments.

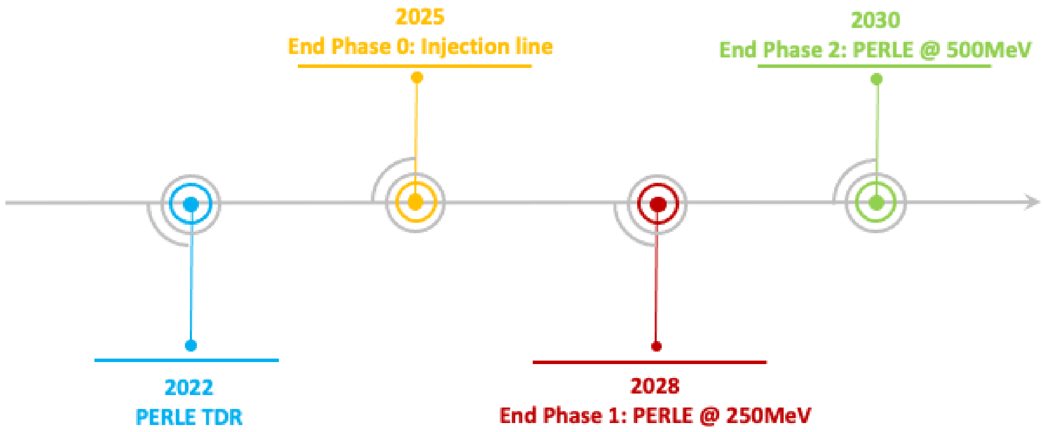

Figure 10: Time line of PERLE project toward its realisation

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Annex 1: Nuclear Physics with PERLE:

Our basic knowledge on the nuclear charge distributions was established on the stable nuclei using electron elastic scattering. Electrons of 400 – 800 MeV energy provide ideal spatial resolution scale of about 0.5 fm to study the interior nuclear charge distributions. As the electron-ion interaction mechanism is known to a high accuracy, direct expansion of the cross sections and the direct link to the charge distribution can be obtained, from which the proton distribution can be inferred. The detailed proton density profiles are needed to add constraints on the proton correlations assumed within the nuclear models, and to explore the properties of the proton densities, in particular in the case of exotic nuclei having extended or exotic nuclear shapes (halo, clusters, bubbles).

Up to now, due to the impossibility to perform ion-electron collisions with short-lived radioactive ions the knowledge on charge densities was essentially provided by extensive isotopic shifts measurements performed using laser spectroscopy techniques at ISOL (Isotopic Separation On Line) low-energy facilities. From such measurement however, the extracted information remains limited to global relative radius changes. Hence, not only the radial structure of the charge distribution of nuclei off stability remains largely unexplored, but the absolute charge radii of many key nuclei (e.g. doubly magic ones) remain beyond the reach of direct measurements.

During its recent “national prospective exercise”, the low-energy Nuclear Physics community has set among its top priority objectives the launch of an ambitious program to measure elastic scattering off radioactive ions. A first step of this long-term endeavor consists in an extensive program to measure (e,e) elastic scattering cross sections to extract directly the charge density distributions through a model-independent analysis and to compare them to theoretical predictions. Theory-wise, detailed densities are much more demanding than integrated quantities (such as root mean square radii) and encapsulate different correlation effects. As such, they offer an unprecedented test bench for state-of-the-art nuclear structure models. Their availability over a wide range of unstable isotopes would thus systematically provide model-independent constraints very complementary to information from other probes like (p,p) scattering.

The most important challenge to achieve this ambitious goal is to gather the experimental conditions in terms of production and manipulation of a population of target radioactive ions and overlapping with an electron beam of adequate energy and intensity. The scenario retained for these experiments would be that of a fixed target consisting of a cloud of trapped ions interacting with an electron beam of energy of the order of 500 MeV. A preliminary analysis carried out within the framework of the "Spiro mission" by A. Chancé, P. Delahaye2, F. Flavigny, V. Lapoux, A. Matta, V. Somà (document “Electron scattering on radioactive ions at GANIL[2] - Grand Accélérateur National d'Ions Lourds et de Leptons) has allowed to dimension the essential constraints and to highlight the main technological challenges. This study clearly shows that whatever the target/ultimate/ideal electron machine design would be, a key point is the ion capture efficiency. The more efficient the capture is, the less electron intensity is needed. An intermediary step is crucial to study and understand all processes involved, and develop and optimize an original ion trapping system that needs to be tested on a high-performance electron machine to fully explore the ion efficiency by varying some key parameters like the electron beam size. More precisely, if one is to demonstrate the ion capture efficiency, one would need benchmark tests, done at an electron machine which can deliver a beam size smaller than 0.1 mm (or similar to the target one), a sufficiently high average current (to achieve the saturation in the ion trap) and sufficiently high energy. One also need to have enough place to host the trap plus a detector.

The PERLE demonstrator in Orsay offers a unique opportunity to start a concrete program. This is the heart of the nuclear physics project at PERLE@Orsay named **DESTIN [DEep STructure Investigation of (exotic) Nuclei]** that the IJCLab Nuclear Physics community is pushing forward. The objective of this project is the realization of a complete setup including a device for the production of radioactive ion by photofission, the target trap and the electron spectrometer. The target intensities of PERLE, a few tens of mA will be sufficient for the realization of a low luminosity program, allowing for the first time to extract quantities as fundamental as the absolute charge radius of the neutron-rich doubly-magic nucleus ^{132}Sn (key nucleus of the r process). The completion of such a project - irradiating an exotic nucleus with an electron beam! - would be a resounding world first, placing us in the wake of the great pioneer Hofstadter (Nobel Prize 1961) who realized the first electron scattering off (gold) nuclei in History.