News, Interim and Towards Roadmap

Max Klein and Andrew Hutton

Meeting of ERL Panel, September 17, 2021

News

Interim Report submitted to LDG in July, unchanged. few edits by Max Bruker (thanks!), central: Nicolas Mounet.

Attached to the indico is the status 6.9. of the 5 interim reports (missing SRF). We have received compliments by the LDG Chair
The Interim Report will be sent to Science Policy Committee (SPC), restricted ECFA (rECFA) and Council.
This now overlaps in time with the roadmap convergence, the timeline is extremely tight - see below.

Presentation to European Physics Conference (EPS) 30.7. presentation of our findings and activities, attached
good coverage by summary reports from Dave Newbold (LDG Chair) and Lenny Rifkin (SPC Chair) at EPS plenary

Regular Meetings of e^+e^- Subpanel since June 9, last one on Wednesday – report today by Andrew

This is about to turn into a High Quality ERL R&D Program, complementing our 5-10 year plans
With 4K, higher Q_0, warmer HOM damping, twin cavities there is a potential for an economic ERL linear ee collider
alongside prospects for a muon collider or plasma design BUT with 10^{36} $cm^{-2}s^{-1}$ luminosity potential

2 turns with high transfer efficiency in sDALINAC – Congratulations to Norbert, Michaela (DPG Price) and team

Monthly reports given to the Lab Directors Group pushing towards final in December

Reminder of the Roadmap Content

- We promised to document:
  - The scientific drivers for R&D, and the progress needed to enable future facilities ☑
  - The current state-of-the-art, and the further steps to be taken over the next decade ☑
  - Potential deliverables and demonstrators for the next decade ☑
  - A prioritised work plan, taking into account the capabilities and interests of stakeholders
  - A range of scenarios for engagement, ranging from 'minimal investment' to 'maximum possible rate of progress', with a first estimate of resources and timeline.
- Emphasis now needs to move to the 'delivery plans'
  - Need to agree the number, time-extent and level of detail for the delivery plans
  - Need a consistent basis for presenting the plans and quantifying resources
  - Need to outline the realistic scope and resources for the delivery plans
    - It is probably not useful to propose plans that exceed European resources by a factor ten
    - Requires us to build a broad / informal understanding of the likely levels of commitment from FAs

Dave Newbold to LDG
September 8

In brief

The Roadmap report is ~40 pages.

We believe we should use the Interim Report as base, expand at places and add the genuine Roadmap (elements below).

Timeline: 30.9. presentation in a zoom "workshop" of panel chairs and deputies with LDG members. Update in an in-person workshop October 12 at CERN →

We have 2+2 weeks for the Roadmap and 4 weeks to finalise our other papers (long write-up and e^+e^-)

Interim Report → Roadmap (1. Motivation or Science Drivers)

5 pages

6.2 Motivation

6.2.1 *Sustainability*

Energy efficiency and sustainability have received a lot of attention over recent years. The concerns about climate change and global warming have to be taken especially seriously, also by the accelerator community. To quote F. Bordry : "There will be no future large-scale science project without an energy management component, an incentive for energy efficiency and energy recovery among the major objectives." It is a prime goal for the panel to evaluate the power economy of ERLs and to emphasise techniques being developed to further minimise the use of power. The accelerator community drives research and development at the cutting edge of technology for a greater purpose than just making the next accelerator better: Society expects a return from the investment in this research, which includes other applications of accelerators and further spin-offs. Innovation in accelerator technology, often linked to energy frontier physics, has been a prime attraction to new talents, the training of whom is an important part of the sustainability program followed here.

Need numbers for power economy

6.2.2 *Accelerator Development*

Energy-Recovery Linacs are an extremely efficient technique for accelerating high-average-current electron beams. In an ERL, an intense electron beam is accelerated to relativistic energies in (typically) a superconducting RF linear accelerator operating in continuous-wave (CW) mode. The beam is then used for its intended purpose, i.e., providing a gain medium for a free-electron laser, synchrotron light production, or a cooling source for ion beams. In high-energy physics, the interest is on an intense, low-emittance beam for colliding against hadrons (eh), positrons (e^+e^-) or photons (eγ). They all rely on the provision of high electron currents (of I_e up to ~ 100 mA) and high-quality cavities ($Q_0 > 10^{10}$).

Energy Recovery is at the threshold to become a major means for the advancement of accelerators. Recycling the kinetic energy of a used beam for accelerating a newly injected beam, i.e., reducing the power consumption, utilising the high injector brightness and dumping at injection energy: these are the key elements of a novel accelerator concept, invented half a century ago . The potential of this technique may indeed be compared with the finest innovations of accelerator technology such as by Wideroe, Lawrence, Veksler, Kerst, van der Meer and others during the past century. Innovations of such depth are rare and their impact only approximately predictable.

6.2.3 *ERL-based Physics Prospects*

ERLs provide maximum luminosity through a high brightness source, high energy through possible multi-turn recirculation, and high power, which is recovered in the deceleration of a used beam. It is most remarkable that following the LHeC design from 2012 (updated in 2020), all these avenues have been followed: for $\gamma\gamma$ collisions , further for eh with the FCC-eh in 2018 , for e^+e^- in 2019 (an ERL concept for FCC-ee termed CERC) and in 2021 (an ERL version of the ILC termed ERLC) and very recently a concept for the generation of muon pairs through high-energy, high-current eγ collisions .

A common task for these colliders is precision SM Higgs boson measurements dealing with a small cross section (of 0.2/1 pb in charged current ep interactions at LHeC/FCC-eh and similarly of 0.3 pb in Z-Higgsstrahlung at e^+e^-). This makes maximising the luminosity a necessity to profit from the clean experimental conditions and to access rare decay channels while limiting power. High luminosity and energy are expected to lead beyond the Standard Model and are essential for precision measurements at the corners of phase space.

At low energies, the luminosity is similarly crucial for several physics applications, such as polarised ep scattering for weak interactions, elastic form-factor measurements or dark-photon searches as are planned for MESA and had been pursued at JLab. Very high ERL intensity may permit to use internal targets, which avoids external target acceptance uncertainties. In backscattered photon scattering, the luminosity available exceeds that of ELI by a few orders of magnitude, paving the way to nuclear photonics, an area possibly comparable with the appearance of lasers in the sixties. A further fundamental interest regards the exploration of unstable nuclear matters with intense electron beams of O(500) MeV energy as is characteristic for PERLE and envisaged for GANIL in France. This follows the recognition of the field by NuPECC in their strategic plan in 2017: "Ion-electron colliders represent a crucial innovative perspective in nuclear physics to be pushed forward in the coming decade. They would require the development of intense electron machines to be installed at facilities where a large variety of radioactive ions can be produced".

Keep these sections, add high quality program to 2.2, expand the science from 1 → 5 pages

Interim Report → Roadmap (2. Impact)

3 pages

6.2.4 *Industrial and other Applications*

The range of further applications, beyond particle and nuclear physics, is very remarkable. Examples include high-power lasers, photolithography, and the use of inverse Compton scattering (ICS) . An ERL-FEL based on a 40 GeV LHeC electron beam would generate a record laser with a peak brilliance similar to the European XFEL but an average brilliance which is orders of magnitude higher than that of the XFEL.

The industrial process of producing semiconductor chips comprises the placing of electronic components of nanometre scale onto a substrate or wafer via photolithography. For advancing this technology to a few nm dimension, the FEL must be driven by a superconducting ERL. An ERL with electron beam energy of about 1 GeV would enable multi-kW production of extreme-ultraviolet (EUV) light. This would benefit the global semiconductor industry by allowing study of FEL capabilities at an industrial output level. Initial surveys and design studies were undertaken by industry some years ago. If the economic viability may be underpinned by large scale high reliability, ERLs might well reach into the market, which in 2020 was 400 B Euro.

A third example, interesting due to its applications for nuclear physics but also exotic medical isotope generation and transmutation, is the process of very intense inverse Compton scattering. An about 1 GeV energy superconducting ERL operating at high average electron current in the 10 to 100 mA range would enable a high-flux, narrowband gamma source based on ICS of the electron beam with an external laser within a high-finesse recirculating laser cavity. The production of 10 to 100 MeV gammas via ICS results in properties of the gamma beam fundamentally improved with respect to standard bremsstrahlung generation. This ICS process would be a step change in the production of high-flux, narrowband, energy-tunable, artificial gamma-ray beams. They will enable quantum-state selective excitation of atomic nuclei along with a yet-unexploited field of corresponding applications.

May think about adding here:

- Encourage + Describe stronger collaboration of Labs (Helmholtz?, PERLE, CERN involvement, global Collaboration US, Japan; Cremlin+..)
- Training of next generation of scientists (Darmstadt, Marie Curie PERLE as examples)
- Outreach (young scientists for ERL)
- What else if anything?

Perhaps better moved to Roadmap Part.?

Expand 2.4 from 1 → 2/3 pages (we have 9 pages in the Long Writeup). May move sustainability from 1) to here?

Interim Report → Roadmap (3. State of the Art)

2 pages

6.4 State of the art

6.4.1 Current Status

A long way has been paved since the first SRF ERL at Stanford. Key parameters of an ERL are the electron beam current I_e ($\propto$ luminosity) and energy E_e. The beam power is simply $P = I_e E_e$. Through recovery of the energy, it is related to the required externally supplied power P_0, which then gets augmented by a factor $1/(1-\eta)$ where η is the efficiency of energy recovery. This way, for example, the LHeC can be designed to reach $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ luminosity, for which a GW of beam power would be required without energy recovery. The current state of the art may thus be characterised by a facility overview, presented in Fig. 6.1, as an E_e vs I_e diagram with constant beam power values P drawn as diagonal lines. The plot includes three completed ERL facilities, the first European ERL facility ALICE at Daresbury, CEBAF (1-pass), which, with 1 GeV, reached the highest energy so far, and the JLab FEL, which reached the highest current, of 10 mA. Larger currents have been achieved in the normal-conducting, lower-frequency ERL facility at BINP (the Recuperator). There are three SC facilities (dark green) currently operational, S-DALINAC at Darmstadt, CBETA at Cornell and the compact ERL at KEK in Japan.

Five facilities in progress, three of which are in Europe, marked in dark blue, have complementary goals intending to reach higher energy in five turns (CEBAF 5-pass) or high current (bERLinPRO and the coherent electron cooler, CeC at the EIC), in a single pass. MESA at Mainz will serve a number of low-energy experiments, the only facility with polarised beams so far. PERLE is designed for high current (20 mA), 3-turn operation leading to 500 MeV beam energy.

Figure 6.1 also displays the parameters of the by now five design concepts for ERL applications at the energy frontier with electron beam energies between 50 (LHeC) and 200 GeV (EXMP). CERC has a low current but a rather large number of beam lines. LHeC and FCC-eh are 3-turn linacs with about 20 mA current delivered by the gun. ERLC and EXMP are single pass linacs, with possibly twin-axis cavities. There follows a common demand on SC cavities to tolerate about 100 mA current load, which is the goal of PERLE (in 3 turns) and, in a single pass, of an upgraded bERLinPRO and the CeC at BNL in its most challenging configuration.

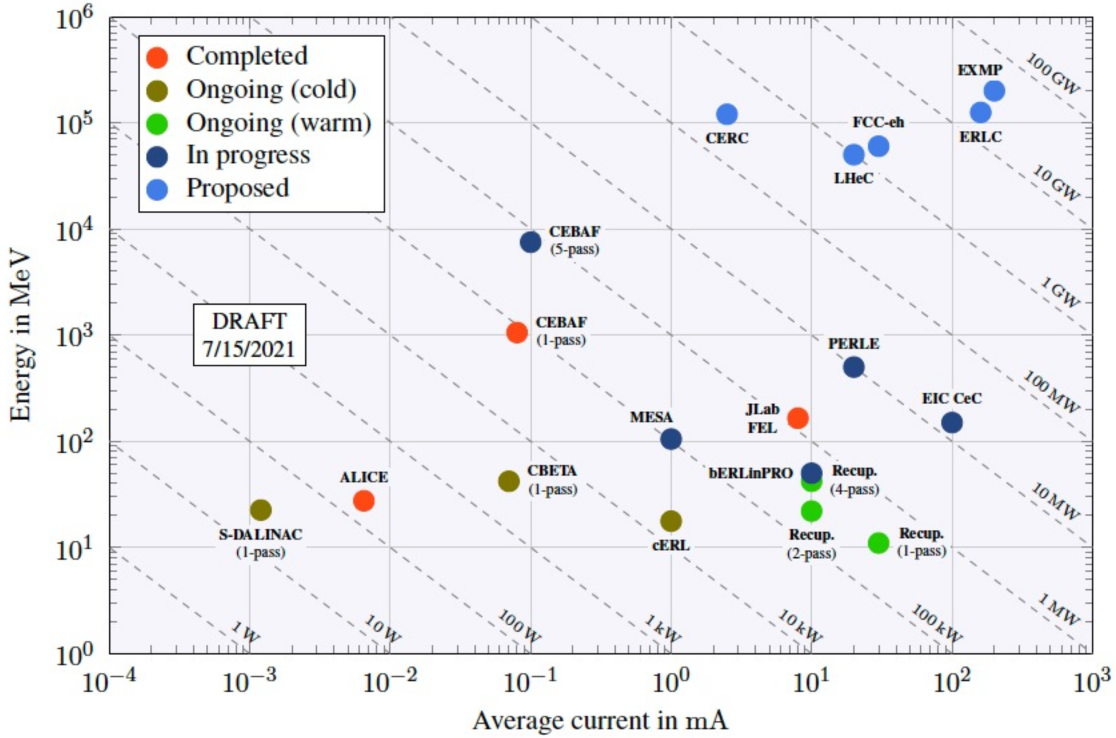


Fig. 6.1: Electron energy vs. current for ERL facilities .

Basically keep that

Interim Report → Roadmap (3. State of the Art)

4 pages

6.4.2 *Plans for the Next Years—Operational Facilities*

The existing and forthcoming facilities have specific development plans. These activities and plans underpin to quite some extent the common, main R&D objectives, which are detailed in Section 6.5.

- S-DALINAC (TU Darmstadt)
  - establishment of a multi-turn SRF-ERL with high transmission (up to 70 MeV and 20 µA);
  - quantification of phase-slippage effects in multi-cell-cavity ERLs and countermeasures;
  - characterisation of potential operating points of individually recirculating ERLs.
- Recuperator (BINP Novosibirsk)
  - The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved;
  - Plans are to install this gun in the injector, while the existing electrostatic gun will be kept there. The RF gun beamline has already been manufactured and assembled on the test setup. The beam parameters were measured after the first bending magnet and at the beamline exit.
- CBETA (Cornell)
  - improve transmission, which includes investigating better optics solutions;
  - developing improved diagnostics for the decelerating passes;
  - reducing halo by using a low-halo cathode, possibly in conjunction with beam collimation.
- bERLinPRO (HZB Berlin)
  - Present activities are focused on the high-current SRF photoinjector and associated technologies. A dedicated diagnostic line capable of handling 10 mA is installed to characterise the beam;
  - Following the upcoming booster installation, the beam can be transported through the merger to the high-power beam dump following the splitter section, allowing studies of emittance preservation, beam loss, and bunch length manipulation.
- cERL (KEK)
  - Development of a 10 kW-class powerful ERL-based EUV-FEL;
  - Realisation of 100 % energy-recovery operation with a beam current of 10 mA at cERL and FEL light production experiment;
  - Development of an irradiation line for industrial applications (carbon nanofibers, polymers and asphalt production) based on CW cERL operation;
  - Further, planning to develop a high-efficiency, high-gradient Nb_3Sn acceleration cavity to realise a superconducting cryomodule based on the compact freezer.
- MESA
  - Improving electron beam polarimetry to an accuracy of $dP/P \leq 0.5\,\%$ in order to support the first physics measurements of electroweak observables, possibly including Hydro-Moeller polarimeter;
  - Installing a second photo-source at the MESA injector with the potential to provide bunch charges > 10 pC with good beam quality;
  - Improving the cavity higher-order mode (HOM) damping capabilities, for instance by coating of the HOM antennas by layers of material with a high critical temperature.

Basically keep that (update and expand from 1 page to 4, i.e. each facility has about 10 instead of 4 lines for status and progress by 2026)
Note we shall refer to the Long Write-up (here and elsewhere)

Interim Report → Roadmap (4. Deliverables)

2 pages

6.5 R&D objectives

As the state-of-the-art section above indicates, the development of ERLs has been a complex challenge regarding several interrelated technology issues. The panel identified three key research and development objectives of particular importance: i) the provision of electron beams of high brightness, ii) the development of high-quality SRF technology designed for ERL use, and iii) the development of supportive technology including software and simulation techniques. It is characteristic for the field that its eventual progress relies on complete ERL facilities, for which a new generation is forthcoming, presented in Sect. 6.7.

6.5.1 *High-Current Electron Sources*

Injectors for high-energy physics ERLs, which require high average current in combination with complicated temporal beam structure, are typically based on photocathode guns. These guns rely on photocathodes, e.g., semiconductor materials, which for high average current are based on (multi)alkali antimonides, or GaAs-based systems for polarised beams, in combination with a photocathode drive laser and extremely-high-vacuum accelerating structure.

The quality of the photocathode is relevant for the performance of the photoinjector in terms of emittance and current, and a long photocathode lifetime is essential for photo-injector operation. Reproducible growth procedures have been developed and months-long lifetimes under operational conditions have been achieved. For high-current operation, photocathodes with high quantum efficiency are necessary and are usually developed in-house. Quantum efficiencies above 10 % at the desired laser wavelength have been achieved in the laboratory.

One critical aspect is to preserve demanding vacuum conditions ($< 10^{-10}$ mbar) on the whole way from the preparation system, via the complete transfer line to the photo-injector and the photocathode gun itself. The photocathode substrates (usually made from molybdenum) are optimised regarding their cleanliness and surface finish ($<$ 10 nm rms surface roughness) to achieve low emittance and to avoid field emission.

Especially in SRF photoinjectors, the superconducting cavity is extremely sensitive to any kind of contamination; therefore, the photocathode exchange process is very critical.

For weak interaction physics experiments, polarised electron beams are needed. These can be based on GaAs photocathodes, but their lifetime has still to be improved, e.g., by using newly developed activation processes.

Ongoing research topics in the field of photocathodes are the understanding of the photocathode materials (e.g., electronic properties), the photoemission process, and their intrinsic emittance. New growth procedures of high quantum efficiency, smooth, mono-crystalline photocathodes or multi-layer systems, and the screening of new photocathode materials are crucial for future electron accelerators.

A main research topic in the field of gun development relies on design of accelerator structure, which can provide a high cathode field in combination with extra-high vacuum conditions. Major efforts are concentrated on development of DC guns (Cornell University), VHF NCRF (LBNL), and lower- (BNL) and high-frequency SRF guns (bERLinPRO). Important insight can be gained from operating smaller facilities with high-current thermionic guns (BINP).

In brief, the field of laser systems for electron injectors, the technology of lasers with sufficient power to operate with antimonide-based photocathodes has been rather well developed. Major efforts are concentrated on the generation of laser pulses with elliptical temporal profile, which are necessary to deliver high charge bunches with ultra-low emittance.

Keep, update

Interim Report → Roadmap (4. Deliverables)

4+2 pages

6.5.2 *Superconducting RF Technology*

Superconducting RF is the key technology for energy-efficient ERLs. A vibrant global R&D program has aptly demonstrated the routine operation of SRF systems in many large-scale accelerators. Future developments must now push the technology to meet the stringent demands of next-generation ERLs while making strides in improving further the energy sustainability of the systems.

The focus for a linear collider is the high accelerating gradient, achievable in pulsed operation. CW ERLs, however, must handle very high beam currents. Simultaneously, they must balance the requirement for high cryogenic efficiency and beam availability, with the need for a reasonably compact and cost-efficient design. Presently, operation at moderate gradients (around 15–20 MV/m) provides the best compromise between these competing requirements.

Critical ERL SRF system developments must now focus on

- system designs compatible with high beam currents and the associated HOM excitation,
- handling of transients and microphonic detuning that otherwise require a large RF overhead to maintain RF stability,
- enhanced cryogenic efficiency of SRF modules.

To ensure beam stability in future ERLs operating with currents of O(100) mA, requires cavity designs and systems that minimise both the excitation and trapping of higher-order modes, facilitate HOM extraction and enables their efficient damping outside of the helium bath. Low-frequency cavities (<1 GHz) are typically favoured, having fewer cells to provide the same voltage and larger apertures. HOM damper solutions include space-efficient waveguide-coupled absorbers with high power capability or more readily implemented beam line absorbers between cavities. The ultimate efficacy of solutions must be put to the test in beam test facilities.

For CW operation, dynamic losses ($\propto E_{acc}^2$) dominate the cryogenic load and pragmatically limit the gradient. In recent years a big improvement with Nb cavities was demonstrated with novel techniques such as nitrogen doping, effectively doubling the (typically) 2 K operating Q_0. A promising approach looks at the possible use of so-called A15 materials (like Nb_3Sn) or V_3Si with higher T_c. First relevant tests with Nb_3Sn-coated cavities, which can be operated at a higher temperature (4.2 K) and thus with significantly less power consumption for cryogenics, have reached encouraging results.

6.5.3 *Supporting Technology, Simulations and Training*

There are several important technology and development items to accompany the facilities in operation and those forthcoming. We provide here a non-exhaustive list of examples, which deserve further attention.

Fast Reactive Tuners

ERL cavities are essentially free of beam loading and in theory could be operated with negligible RF power. However, beam transients and the constant microphonic detuning of the resonance requires one to operate with an increased coupling and RF power overhead that can exceed the theoretical value by an order of magnitude and more. Most of the power is reflected and dumped. A side effect is that the RF stability and hence beam stability also suffers. This waste can be avoided if one can rapidly and continuously readjust the cavity resonance. Piezo-electric tuners have been investigated for some time, and, more recently, very promising ferro-electric BaTiO3 – SrTiO3-based fast reactive tuners are under development. Their suitability and longevity with full SRF systems without and with beam must be demonstrated to capitalise on their enormous potential.

Diagnostics developments

ERLs have specific diagnostics needs because of (a) the large beam power, (b) the small emittance that is to be preserved, and (c) the low beam loading that needs to be maintained in the main linac cavities. (a) The large beam power can lead to continuous beam losses that can easily damage vacuum components, magnets, and electronics; and it can create dark current in accelerating cavities. Halo diagnostics and radiation detection in critical regions is therefore essential. While existing ERLs have developed solutions, e.g., high-dynamic-range halo monitors at the JLab FEL or continuous radiation monitors along both sides of the beam pipe in CBETA, solutions for larger beam powers still have to be developed. Once loss regions have been identified with these devices, their sources can be addressed, e.g., by collimation of the beam at low energies. (b) The small emittances of ERLs have to be preserved to high energy. While the energy is subsequently recovered, the beam size has to remain small enough to keep loss rates low. View screens can be used when setting up the accelerating paths, but only in those return-loop regions where the accelerating beams of all turns can be separated. One source of emittance dilution can be Coherent Synchrotron Radiation (CSR), which may cause a microbunching instability. Such microbunching has been observed at CBETA and will have to be monitored to avoid the resulting emittance growth. Novel diagnostics that does not interrupt the beam has to be used for the decelerating passes. Effects that occur only at large beam currents—e.g., wake effects and beam-ion interactions—also require non-interrupting diagnostics that is yet to be developed. (c) In each cavity, the energy during all accelerating turns must match the energy that is recovered during all decelerating turns. Only then can each cavity be operated by the low drive powers installed in ERLs. This balance can only be maintained when the time for each accelerating and decelerating path is closely monitored by precise arrival time monitors.

Simulation Studies and Education

Keep, more on High Quality R&D Program (4K, 10^{11}, Nb_3SN, warmer HOM damping, twin cavities – future e^+e^- collider)

Interim Report → Roadmap (5. Description of the Roadmap)

3 pages

Simulation Studies and Education

Before a facility may advance and hardware be built, it requires reliable simulations, based on collaborative efforts, experience and insight in the ERL beam physics and technology, from optimising guns through the injector, main loop onto the beam dump. Increasing beam brightness and energy requirements have to be met with advancements of simulation techniques requiring considerable CPU power. One can list a few specific beam dynamics studies related to ERLs:

- Study of CSR leading to microbunching and ultimately to beam quality degradation and emittance dilution. Simulations are instrumental in developing mitigation measures to suppress microbunching through appropriate lattice design. They are especially critical during the deceleration process, where the energy spread increases rapidly as the energy drops.
- Studies of wake fields and beam breakup (BBU) instability for multi-turn ERLs operating in CW mode, also addressing a long-standing question of BBU threshold scaling with the number of passes.
- Study of the longitudinal match to compress and decompress the electron bunch in order to optimise beam transport in energy-recovery mode. Implementation of second-order corrections to eliminate the curvature from the compressed bunch to further improve the longitudinal match without compromising the ability to transport the bunch in the decelerating passes.

The above selection of beam dynamics studies illustrates that the ERL accelerator technology represents a challenging training ground for a next generation of accelerator scientists. Many of these topics are dealt with in PhD theses, and all of the facility centres (and beyond) are engaged in forming and educating accelerator talents. The tasks to be solved are far from conventional, and the rather short time scales for building smaller facilities a plus in the attraction of young physicists.

Belongs still to previous page

6.6 Key points of roadmap

The panel is convinced that ERLs represent a unique, high-luminosity, green accelerator concept: for energy-frontier HEP colliders, for major developments in lower-energy particle and nuclear physics and industrial applications, altogether an innovative area with far-reaching impacts on science and society. With strongly enhanced performance, achieved with power economy and beam dumps at injection energy, ERLs are a most remarkable, vital contribution to the development of a sustainable science.

A peculiarity of the ERL development is that it needs operational facilities with complementary parameters and tasks to be successful. The global landscape of existing ERL facilities, including S-DALINAC in Europe, which are under further development, is rich, as has been outlined in Section 6.4.

A crucial next step towards the application of ERLs in high energy physics and elsewhere is to conquer the O(10) MW power regime with higher energy or/and high currents. This step requires to solve key technology challenges, described in Section 6.5, in particular for bright electron sources, dedicated ERL cavity and cryomodule technology ($Q_0 > 10^{10}$) as well as associated techniques. These technologies are partially available and under development for timely application and test in the existing and a forthcoming generation of ERL facilities.

The regime of high currents, in the range of 100 mA load to SC cavities, will be developed at BNL (EIC cooler CeC), KEK (cERL) and possibly HZB Berlin (bERLinPRO), and BINP Novosibirsk with normal-conducting, low-frequency RF. An order of magnitude increase in beam energy, to 10 GeV, is the goal of a new experiment at CEBAF. PERLE is the only facility designed to operate at 10 MW in a multi-turn configuration and the only one proceeding in a large international collaboration. MESA at Mainz will provide crucial insight in the handling of high beam polarisation in an ERL.

Four developments of high-energy and high-current facilities, presented in Section 6.7, are expected to provide major progress for the ERL field and a base for decisions due in the twenties on next generation HEP colliders, and their further development. For Europe, a roadmap focus will be on the utilisation of bERLinPRO for 100 mA developments and on a timely realisation of PERLE as a hub for accelerator developments and low-energy physics. These and further considerations will be the base for the European ERL Roadmap to be worked out in detail henceforth.

With appropriate financial support and enhanced attention to the European plans, complemented by the developments in the US and Asia, the road to powerful ERLs for application in energy frontier colliders, as well as for new generations of intense particle and nuclear physics experiments, can be timely followed with considerable confidence.

Keep, do not dilute, add the future e+e- considerations

Interim Report → Roadmap (6. Demonstrators – Future Facilities) 1-2 pages

- **CEBAF 5-pass** (ER@CEBAF Jefferson Lab)
  Based on the large experience at Jefferson Lab, a novel project has been approved which has the target to study an ERL at highest energy, chosen to be 8 GeV, where effects such as coherent synchrotron radiation will notably occur. For the coming 4 years, the project has the following plans, also in collaboration with the University of Brussels and STFC Daresbury:
  - engineering design for a half-lambda delay chicane;
  - install dipoles for the delay chicane and the extraction dump;
  - continue ongoing beam dynamics studies;
  - finalise the Optics design, including sextupoles;
  - develop a step-by-step experiment run schedule (2024).

- **EIC electron Cooler CeC** (Brookhaven Nation Lab)
  Coherent Electron Cooling (CeC) is a novel but untested technique which uses an electron beam to perform all functions of a stochastic cooler: the pick-up, the amplifier, and the kicker. Electron cooling of hadron beams at the EIC top energy requires a 150 MeV electron beam with an average power of 15 MW or higher. This task is a natural fit for an ERL driver, while being out of reach for DC accelerators. Currently, BNL is developing two CeC designs. The first one is based on a conventional multi-chicane microbunching amplifier which requires a modification of the RHIC accelerator to separate the electron and hadron beams. Alternatively, the second CeC design is based on a plasma-cascade microbunching amplifier. Both CeC designs require an ERL operating with parameters beyond the state of the art.

(status of Nagaitsev initiative?)

Keep US Facilities – no money request, but part of the roadmap as are the operational facilities

Interim Report → Roadmap (6. Demonstrators – Future Facilities) 2+5 pages

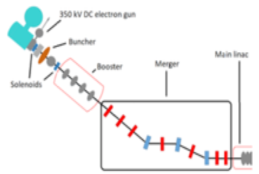
- **bERLinPro Upgrade** (Helmholtz-Zentrum Berlin)
  The beam transport and technical infrastructure for 100 mA, 50 MeV ERL operation has been set up at bERLinPro. The single-turn racetrack is closed, at high vacuum, in an underground building shielded to handle up to 30 kW continuous beam loss at 50 MeV. In 2022, the injection line will be completed and tested using an initial high-current SRF gun delivering up to 10 mA with an emittance better than 1 mm mrad. It is possible to upgrade the gun to 100 mA current and to complement the facility with a dedicated 1.3 GHz cavity-cryomodule for 50 MeV acceleration, designed to support a 2 × 100 mA load in CW operation and equipped with a Fast Reactive Tuner (FRT) system. The infrastructure at HZB exists for extensive cryomodule and FRT testing prior to installation in the ERL facility. This upgrade would transform bERLinPro into a key ERL facility providing experience with the highest current delivery and operation in the world. It will demonstrate the possibility to control the microphonic detuning of resonances leading to further, substantial power gains, and test the FRT system at currents suitable for future high-power multi-pass ERLs.

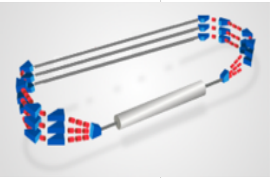
- **PERLE** (Irène Joliot Curie Laboratory, Orsay)
  PERLE is a compact three-pass ERL project using SRF technology, pushing as a new generation machine the operational regime for multi-turn ERLs to around 10 MW beam power. PERLE will serve as a hub for the validation and exploration of a broad range of ERL accelerator phenomena in a so far unexplored operational regime serving for the development of ERL technology for future energy and intensity frontier machines. Particularly, the PERLE facility targets the LHeC configuration by featuring a 3-turn acceleration and 3-turn deceleration racetrack configuration, an 802 MHz SRF system, and beam currents of up to 20 mA (corresponding to a 120 mA cavity load). A first Nb cavity, realised at JLab in collaboration with CERN for FCC-ee and LHeC, had a high Q_0 of 3×10^{10} up to a gradient of nearly 30 MV/m. The facility initially uses in-kind deliveries: of the gun (from ALICE at Daresbury), the booster cryostat (from JLab, using the module designed for JLEIC) and the main linac cryostat (from CERN adapting the SPL module). The Collaboration (BINP, CERN, U Cornell, IJClab Orsay, Jlab, U Liverpool, STFC Daresbury, with others expressing interest), has recently established an ambitious plan for first beam operation in the mid twenties. A second linac module, likely including FRT technology, and several electron-scattering experiments are in the early phase of planning.

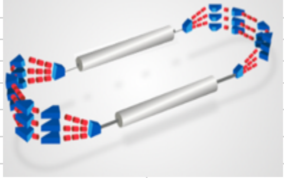
Europe to 2025+ bERLinPRO (2 pages) and PERLE (3 pages) : derive investment level, show annual milestones

DRAFT timeline of PERLE: Design, Injector, SRF, Magnets, Infrastructure, Experiments, Safety/Integration

Work Package	Task	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
		TDR Phase		PERLE-Phase 0: Injection line							
				PERLE-Phase 1: PERLE @ 250 MeV							
				PERLE-Phase 2: PERLE @ 500 MeV- 10MW							
WP2: Accelerator Design	T2.1: Lattice and Optics	Linear Lattice optimisation									
		Momentum acceptance & longitudinal match									
		Correction of nonlinear aberations with multipole magnets									
		Injection line design									
		Merger study and design									
	T2.2: Beam Dynamics	End to End Multi particle tracking studies, error effects & halo formation									
		End-to-End simulation with CSR & micro-bunching									
		Space charge studies at injection									
			Impedance analysis & wakefield effect mitigation								
			Beam Breack-Up instability								
WP3: e- source & injector	T3.1: DC gun installation preparation	Gun installation preparation	Starting gun installation	Testing DC gun	Injector Installation	Injector commisioning	Complete installation of PERLE @ 250 MeV, 4 mA, 3-turn and starting the commisioning		DC gun upgrade and operation		Complete installation of PERLE @ 500 MeV, 20 mA, 3-turn and starting the commisioning
	T3.2: Buncher & Booster design		Buncher cavity design	Buncher cavity production							
			Single cell booster cavities design	Single cell booster cavities production							
		Booster needs identification		Booster completion							
WP4: RF Systems	T4.1: Cavity & HOM design and Prototyping	HOM study and HOM coupler design	Endgroups integration into existing cavity & test	5-cell cavities production and test					5-cell cavities production and test		
	T4.2: Power coupler design and prototyping	Adaptation of SPL power coupler and RF conditioning									
	T4.3: Cryomodule	Design SPL Cryomodule completion			Completion of SPL Cryomodule and test						
				New cryomodule design					Completion and test of the 2nd cryomodule		
	T4.4: Fast reactive tuner design and protyping	Feasibility study & integration on cavity									
	T4.5: Tuner system										
	T4.6: LLRF										
	T4.7: RF power sources need										
WP5: Magnets and vacuum chambers	T5.1: Magnets	Magnet Specifications	B-Com magnet design and prototype								
	T5.2: Vacuum chambers design		Magnets & vacuum chambers design	Magnet & vacuum chambers production		Recirculator installation (arcs & swithyards)				Recirculator installation (additional swithyards)	
WP6: Instr. & diagnostics	T5.2: Beam diagnostics		Defining beam diagnostics needs	Beam diagnostics for injector							
	T5.3: Beam dump design		Dump design	Dump production							
	T5.4: Vacuum systems		Defining vacuum needs for injector	Defining vacuum needs for main loop							
	T5.5: Cryogenics	Need definition & cryoplant specification		Cryoplant design and production		Cryoplant installation & commisionni					
WP7: Experiments	T7.1: PERLE user identifaction	Potential experiment constrains									
			Fixation of Experiment program								
	T7.2: Experiment integration design			Experiment integration study						IP ingration for experiments	
WP8: Safety & integration	T8.1: Facility Administratif Classification (ASN)	Classification study and Preparation of ASN Document									
	T8.2: Radioprotection & shielding studies	Radioprotection studies		Personnel safety system (PSS) & machine safety system (MSS) design and implementation							
	T8.3: Preliminary studies of the site	Site investigations (ground, available Area, ancelleries)		Required infrastructure work							
	T8.4: PERLE footprint	Specifications & implementation design									







Principally endorsed by PERLE CB, June 2021

Walid Kaabi et al, 28.6.2021

7. Summary: R&D, Milestones and Funding – little in the interim report

LDG (Newbold) Guidance:

- A prioritised work plan, taking into account the capabilities and interests of stakeholders
- A range of scenarios for engagement, ranging from 'minimal investment' to 'maximum possible rate of progress', with a first estimate of resources and timeline.

These should be tables and itemized lists rather than text.

Group into three elements

Key Base Technology for the nearer future ~25 [essentially ongoing]
cavity (SRF, Q_0), source, and other developments – time and funding - use long writeup and interim report

New Facilities in Europe in the Twenties - in Collaboration with CERN [to be supported]
bERLinPRO m MCHF for 5 years (100 mA gun, cryomodule [1.3 GHz, FRT]) need 2 pages
PERLE n MCHF for 5 years need 3 pages

High Quality ERL Developments [for the future of the field – use 10^{36} ERLC collider for qualification]
4K, twins, 10^{11} Q_0, Nb_3SN, room T HOM damping, ..

describe where things are happening (in Europe, and embedded in global developments)

Development of Energy Recovery Linacs

A European Roadmap

1. Introduction	1	
2. Motivation	5	
3. Impact	3	
4. State of the Art	6 =	2 (items) 4 facilities
5. Objectives/Deliverables	6	
6. Roadmap Description	3	
7. Future Facilities	6 =	1 (CEBAF5, Cooler) 2 (bERLinPRO) 3 (PERLE)
8. Key Milestones and Funding	5	
9. Executive Summary	1	
Appendix: Facilities	2	sum of pages: 39

Remarks

We have a real, diverse, convincing, far reaching case and shall do the best possible to propagate + pursue it sincerely.

Using the Interim Report is proposed as the best way to establish a 40 p Roadmap document in 4 weeks

For the milestones and cost we need to meet again next week (suggest Thursday 23.9. 1-2pm CEST??).

The roadmap is a base for national Funding Agencies to invest, which requires CERN’s recognition and MTP inclusion.

Presently it is under discussion (LDG, Council, DG, ECFA), how the roadmap implementation is going to be organized.

We need to finish the Long Write Up in the next weeks, for it has to be out when the Roadmap appears.
Please check and complement your parts. Final editing to be done, may call for help. Thanks to Max Bruker.

Once agreed on how we proceed we will call for your input, help and judgement. Will open an Overleaf document.