6 Energy-recovery linacs

6.1 Executive summary

Energy Recovery is at the threshold of becoming a key 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 [1]. The potential of this technique may be compared with the finest innovations of accelerator technology such as by Widerøe, Lawrence, Veksler, Kerst, van der Meer and others during the past century. Innovations of such depth are rare, and their impact is only approximately predictable.

The fundamental principles of energy-recovery linacs (ERLs) have now been successfully demonstrated across the globe. There can no longer be any doubt that an ERL can be built and achieve its goals. The history of ERLs, and the present and future directions of development for particle, nuclear and applied physics, are summarised in a long write-up on "The Development of Energy Recovery Linacs" [2], which accompanies the appearance of this roadmap. An important, preparatory milestone was an ERL Symposium [3] held in June 2021 which, in consultation with the particle and accelerator physics communities, discussed the basis, status, impact, technology, and prospects of the field of ERLs. The technique of energy recovery in superconducting linac cavities promises a luminosity increase for physics applications by one or more orders of magnitude at a power consumption comparable to classic lower-luminosity solutions. This is a necessary step towards the future sustainability of high-energy physics, as interaction cross-sections fall at high energy scales. Much enhanced luminosities are similarly crucial for opening new areas of low-energy physics such as nuclear photonics or the spectroscopy of exotic nuclei. ERLs are also close to utilisation in several industrial and scientific applications such as photolithography, free electron lasers, inverse photon scattering and others.

The novel high-energy ERL concepts targeted at energy-frontier electron-hadron, electron-positron and electron-photon colliders, as well as other applications, require the development of high-brightness electron guns and dedicated superconducting RF (SRF) technology as prime R&D objectives. Moreover, this needs a facility comprising all essential features simultaneously: high current, multi-pass, optimised cavities and cryomodules, and a physics-quality beam for eventual experiments.

The ERL roadmap presented here rests upon three major, interrelated elements:

A) Current facilities, including crucial technological developments and operational experience. These comprise S-DALINAC (TU Darmstadt, Germany), MESA (U Mainz, Germany), CBETA (U Cornell and BNL, US), cERL (KEK, Japan) and the normal-conducting, lower-frequency Recuperator facility (BINP Novosibirsk, Russia).

B) A key technology R&D program focused on high-current electron sources and high-power SRF technology development and operation in the years ahead, including the technical target of cavity quality factors, Q_0, approaching 10^{11}. Next-generation ERLs lead to the major goal of being able to operate at 4.4 K cryogenic temperature [6] with high Q_0, also including higher-order mode damping at

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[6] The basic 4.4 K R&D program is described by the SRF panel, while for ERLs it leads to the development and beam test of a warm cavity-cryomodule in a decade hence. Operation at 4.4 K would allow universities to use small superconducting accelerators for inverse Compton back-scattering, free-electron lasers (FELs), isotope production, etc. Apart from the societal

high temperature, dual-axis cavity developments and novel means for high-current ERL diagnostics and beam instrumentation to deal with effects such as beam break-up or RF transients.

C) New ERL facilities in preparation for reaching higher currents and electron beam energies at minimum power consumption by the mid-twenties. These are, in Europe, bERLinPro (Berlin, Germany) with the goal to operate a 100 mA, 1.3 GHz facility and PERLE (hosted by IJCLab Orsay, France) as the first multi-turn, high-power, 802 MHz facility with novel physics applications. In the coming years, the US will explore ERL operation near 10 GeV with CEBAF5 (Jefferson Lab, Newport News) and develop a challenging 100 mA electron cooler for hadron beams at the EIC [4] (BNL, Brookhaven).

ERLs are the means to reach very high luminosity in the next-generation energy-frontier electron-hadron colliders, LHeC and FCC-eh [5, 6]. An ERL-based proposal has been published [7] for the generation of picometer-emittance-class muon beams by electron-photon collisions. Two concepts have been published and explored as part of this roadmap process for reaching higher luminosity at high energies: for the FCC-ee, termed CERC [8]; and for the ILC, termed ERLC [9]. A particularly interesting prospect is to design and possibly build, in the further future, an energy-efficient, ultra-high-luminosity ERL-based electron-positron collider at 500 GeV, termed HH500, which would enable the exploration of the Higgs vacuum potential with a measurement of the tri-linear Higgs coupling in e^+e^-.

The panel notes with much interest that the ERL technology is close to high-current and high-energy application, requiring dedicated and coordinated R&D efforts, with the stunning potential to revolutionise particle, nuclear and applied physics, as well as key industry areas. This comes at a time where attention to sustainability is an overarching necessity for this planet, not least big science. ERLs are therefore primed for inclusion among the grand visions our field has been generating. Adequate support for the development, in Europe and worldwide, will allow this potential to be realised.

6.2 Introduction

6.2.1 History

The idea of an energy-recovery linac traces back to Maury Tigner [1] in 1965. He was looking at ways to enhance the current in a collider for high-energy physics. Accelerating two beams, colliding them, and then dumping them is extremely inefficient. If one could recover the energy of the beams in the same cavities in which they were accelerated, then the efficiency of the machine could be greatly increased. The design of the final dump also becomes much simpler. Though the idea was sound, the implementation of an efficient solution relied on the development of reliable superconducting RF (SRF) accelerating cavities, which took place over the next decade. The first major use of SRF cavities was at the High Energy Physics Lab at Stanford University. Researchers there installed a recirculation loop with the capability of varying the path length so that the electrons in a second pass through the accelerating cavities could be either accelerated or decelerated. Both options were demonstrated. This was the first ERL with SRF cavities [10]. This type of ERL is called same-cell energy recovery. The beam was not used for anything, and the current was pulsed, but evidence for energy recovery was clearly seen in the RF power requirements during the beam pulse.

Other demonstrations of energy recovery with room-temperature cavities were carried out at Chalk River [11] and Los Alamos National Lab [12]. The Los Alamos demonstration used coupled accelerating and decelerating cavities, and it had a free-electron laser (FEL) in the beamline so the overall FEL efficiency could, in principle, be increased, but the cavity losses and the RF transport losses led to an overall increase in the RF power required, showing the advantage of SRF cavities being nearly lossless for same-cell energy recovery.

During the early development of CEBAF at what is now Jefferson Lab, the ability to recirculate beam in the newly-developed SRF cavities was tested in the Front End Test (FET) [13], where the beam

aspect, this would provide a steady demand for SRF cavities and cryomodules from industry, which would in turn benefit colliders.

was recirculated in a fashion similar to the HEPL experiment. The current in this case, however, could be run continuously, and both recirculation (two accelerating passes) and an energy-recovery configuration were demonstrated.

While all of this technology development work was taking place, several authors noted that the ERL was a natural way to increase the overall efficiency of an FEL since the FEL usually only takes about 1 % of the energy of the electron beam out as laser radiation and then dumps the rest. If one could recover most of the beam power at the exit of the FEL, one could greatly enhance the overall efficiency of the laser. The Los Alamos experiment demonstrated some of the concepts of an ERL-based FEL but was a low-average-power, pulsed device.

This led to the development of an IR Demo project at Jefferson Lab [14], based on the same cryomodules that had been developed for CEBAF. This was a resounding success, exceeding all of the ambitious goals that had been established with a 35 to 48 MeV, 5 mA electron beam producing 2.1 kW of infrared light outcoupled to users. This enabled the development of an even more ambitious goal: to increase the power levels by a factor of ten, which was then achieved by a rebuild of the recirculation arcs and an increase of the electron energy. This facility circulated 9 mA at up to 150 MeV, still the highest current that has been recirculated in an SRF ERL [15]. There was a considerable element of beam optics studies which laid the foundation for the design of later ERL facilities.

The ERLs at JLab were important demonstrations of high beam power without a large installed RF power source. The IR Upgrade ERL operated with over 1.1 MW of beam power with only about 300 kW of installed RF, thus demonstrating the most basic reason for building an ERL. Other devices were also built that pushed other frontiers. Novosibirsk has built two ERLs using room-temperature cavities [16]. While the copper losses of the cavities result in low efficiency, these machines were able to recirculate up to 30 mA of average current, still the record for recirculated current. The two ERLs are used for far-infrared FELs in a very active user program.

A group at JAERI built an ERL that used novel cryogenic cooling at long wavelengths to produce a very efficient ERL. They also pushed the efficiency of the FEL to record levels for an ERL [17]. The group at KEK commissioned a high-current ERL test machine that is designed for currents up to 100 mA and demonstrated 1 mA of beam recirculation. The photocathode gun operates at 500 kV, the highest of any photocathode gun [18].

An ERL similar in design to the Jefferson Lab ERL, ALICE, was built at the Daresbury Lab. It operated pulsed due to radiation and refrigeration concerns but demonstrated both THz production and infrared FEL operation [19]. ALICE was shut down after ten years of successful operation, having achieved its objectives.

As part of an ERL program for a light source, Cornell commissioned an injector with the highest average current demonstrated from a photocathode injector [20]. Following this, they reused the gun, booster and a single cryomodule as the basis for CBETA. The arcs that return the beam to the cryomodule used a novel technique, fixed-field alternating-gradient (FFA) transport, to demonstrate the first multi-pass energy recovery in an SRF-based ERL [21].

6.2.2 Technology

In an ERL, a high-average-current electron beam is accelerated to relativistic energies in (typically) an SRF continuous-wave (CW) linear accelerator. The beam is then used for its intended purpose, e.g. providing a gain medium for a free-electron laser, synchrotron light production, a cooling source for ion beams, or for a high-energy particle collider. The application usually creates an increase in the energy spread or emittance of the electron beam, while the majority of the beam power remains. To recover this power, the beam is then sent back through the accelerator again, only this time roughly 180° off the accelerating RF phase. The beam is therefore decelerated as it goes through the linac, putting its power back into the RF fields, and dumped with some (small) residual energy.

Three major system benefits accrue from this manipulation: the required RF power (and its capital cost and required electricity) is significantly reduced; the beam power that must be dissipated in the dump is reduced by a large factor; and often the electron beam dump energy can be reduced below the photo-neutron threshold, minimising the activation of the dump region, so the required shielding of the facility can be reduced. The cost savings associated with incorporation of energy recovery must be balanced against the need to provide a beam transport system to re-inject the beam to the linac for recovery. If significant growth in the energy spread or emittance of the electron beam has occurred in the process of utilising the beam, then this transport system can necessitate significant manipulation of the beam phase space. While these techniques are well understood by now, any new machine requires considerable care in the design phase to minimise operational problems.

There are additional benefits that accrue from the geometry and physics of such a machine. Taking advantage of adiabatic damping, an ERL has the ability to supply extremely low emittances (of approximately equal value in both planes) for the production of synchrotron light with high peak and average brightness, or for electron beam cooling. Additionally, the ERL has the advantage of being able to optimise beta functions independently without exceeding the dynamic aperture limitations that rings present. Finally, the ability of the ERL to operate at low charges with small longitudinal emittances enables the production of very short electron pulses at extremely high repetition rates. To achieve these benefits requires careful design, including answering a number of physics issues.

Several advances have been made on the hardware side to enable the potential of ERLs, most notably in the field of SRF cavity design to allow high currents, including damping of unwanted higher-order modes (HOMs) to avoid beam break-up issues. Yet, the continual improvement in ERL capability is still pushing the technology limits in several areas, including SRF. Another active research area is the development of a high-current, ultra-high-brightness, CW electron source. Extensive development efforts for CW sources have been undertaken at many laboratories, and substantial efforts are also required for appropriate diagnostics e.g. to measure multiple different energy beams simultaneously.

All relevant parameters have now been addressed at some level, but not simultaneously. In particular, it is important that the interplay of the various subsystems and beam-dynamics aspects be tested in an integrated manner in dedicated beam test facilities. It is generally believed (and history bears this out) that progress in accelerator performance usually requires steps of about a factor of ten. This roadmap is established to show how the next five to ten years may be used for ERLs to advance as a base for future electron-hadron and electron-positron colliders, as a hub for high intensity particle and nuclear physics at low energies, and with an impact on industry and other science areas. It will become clear that ERLs are to a large extent a global, pioneering project. Europe will maintain a leading role via existing and new facilities as well as with fundamental technology projects. A vision for ERLs, as will be outlined, is the development of the 4.4 K technology, to reduce the power consumption of tens-of-km-long linacs and to also support SRF technology by making it accessible to smaller labs and Universities which do not have 2 K helium cryogenics available. Following a remarkable history, a next step of ERL development is near which will underwrite ERLs relevance to energy-frontier particle physics, and thus the furtherment of the scientific goals of the ESPP in a sustainable way.

6.3 Motivation

6.3.1 Energy-frontier physics and power efficiency

Multiple decades of particle physics have passed, establishing the Standard Model (SM), a unified electroweak interaction with quantum chromodynamics (QCD) attached to it. And yet, we are in a similar situation as before the discovery of quarks: theory provides questions, but no firm answers. The SM has known, fundamental deficiencies: a proliferation of parameters, the unexplained quark and lepton family pattern, an unresolved left-right asymmetry related to lepton-flavour non-conservation, an unexplained flavour hierarchy, the intriguing question of parton confinement, and many others. The SM carries the boson-fermion asymmetry, it mixes the three interactions but has no grand unification, it needs experiments to determine the parton dynamics inside the proton, it has no prediction for the existence of a yet lower layer of substructure, and it does not explain the difference between leptons and quarks. Moreover, the SM has missing links to dark matter, possibly through axions, and quantum gravity, while string theory still resides apart. The SM is a phenomenologically successful theory, fine tuned to describe a possibly metastable universe [22].

As Steven Weinberg stated not long ago, “There isn’t a clear idea to break into the future beyond the Standard Model” [23]. It remains the conviction, as Gian Giudice described it in his eloquent “imaginary conversation" with the late Guido Altarelli, that “A new paradigm change seems to be necessary” [24] in the “dawn of the post-naturalness era”. Apparently, particle physics is as interesting, challenging, and far-reaching as it has ever been in recent history. It needs revolutionary advances in insight, observation, and technologies, not least for its accelerator base. It demands that new generation of hadron-hadron, electron-hadron and pure lepton colliders be developed and realised; a new paradigm can hardly be established with just one type of collider in the future. The field needs global cooperation and complementarity of facilities and techniques, a lesson learned from the exploration of the physics at the Fermi scale with the Tevatron, HERA and LEP/SLC.

As new phenomena may be expected to be rare and high-scale cross-sections are small, new machines have to achieve orders-of-magnitude increases in integrated luminosities compared to the colliders of the recent past. With increasing energy and luminosity, wall-plug power requirements rise to values which, even if they still could be realised, are essentially unacceptable in a world which fights for its sustainability and energy balance. To quote Frederick Bordry [25]: “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 built-in feature of energy recovery linacs that the power required for operation is an order of magnitude or more below the beam power. A prime motivation for the ERL panel has been to evaluate this aspect and its underlying technology demands as a crucial part of the ERL strategy for the coming and future years ahead. This leads to emphasis on further increased cavity quality, 4.4 K technology, fast reactive tuners (FRTs) and other key elements of the ERL roadmap described here. ERLs, for electron-hadron and electron-positron colliders, are a ‘route royale’ to high energy, high luminosity and limited power consumption. This road will not be easy to follow, but is at least now possible, building on half a century of often generic ERL and SRF R&D efforts.

6.3.2 Accelerator developments

ERLs are an extremely efficient technique for accelerating high-average-current electron beams. As described above, in an ERL, an intense electron beam is accelerated to relativistic energies in (typically) a superconducting RF linear accelerator operating in CW mode. In high-energy physics, the interest is in an intense, low-emittance e^- beam for colliding against hadrons (eh), positrons (e^+e^-) or photons ($e\gamma$). Experiments rely on the provision of high electron currents (of I_e up to $\sim$ 100 mA) and high-quality cavities ($Q_0 > 10^{10}$). As part of this roadmap, novel techniques are to be worked out and applied for monitoring beams of such high power, as is explained subsequently.

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 remarkable that following the LHeC design from 2012 [26] (updated in 2020 [5]), all these avenues have been pursued: for $\gamma\gamma$ collisions [27] using the LHeC racetrack, further for eh with the FCC-eh in 2018 [6], for e^+e^- in 2019 with an ERL concept for FCC-ee, termed CERC [8]), and in 2021 with an ERL version of the ILC, termed ERLC [9]), and very recently also with a concept for the generation of picometer-emittance muon pairs through high-energy, high-current $e\gamma$ collisions [7].

A common task for these colliders is precision SM Higgs boson measurements dealing with a small cross-section (of 0.2 pb / 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 SM and are essential for precision measurements at the corners of phase space.

A particularly interesting prospect is to design and possibly build an energy efficient, ultra-high-luminosity ERL-based electron-positron collider, which would enable the exploration of the Higgs vacuum potential with a precise measurement of the tri-linear Higgs coupling. The $e^+e^- \to ZH \to HH$ production cross-section is maximal near 500 GeV collision energy with a value of about 0.1 fb [28]. For percent-level measurements, a luminosity of 10^{36} cm^{-2} s^{-1} is required. A linear collider achieving this value must be based on novel cavity technology that exploits 4.4 K cryogenics for which pure niobium is not suited as its Q_0 drops to the 10^8 range. This sets a long-term goal of combining high gradient (> 20 MV/m), high Q_0 ($> 3 \times 10^{10}$), achieved also with dual axis cavities, 4.4 K operation, and room-temperature HOM damping to limit cost and power[7]. This goal has been translated to a long-term, high-quality ERL R&D program that has a strong link to the RF part of the Roadmap.

While these requirements, as historically, arise with particle physics, they are relevant and beneficial to general technical developments and applications. The 4.4 K technology is suited to reduce cryoplant cost and heat load for HOM extraction. This reduced both the capital and operating cost of SRF technology. Examples of industrial interest include semiconductor lithography, medical isotope production and gamma sources for nuclear industry. During previous studies of such applications with comparable scale, the capital cost of cryogenics comprised about 25 % of the full facility cost. The operating cost of electricity and maintenance again typically comprises 25 % of the full operating cost. Reducing these therefore has a significant impact on the economics of commercial deployment. Finally, at 4.4 K, SRF technology becomes accessible to smaller research labs or universities by avoiding the very special and expensive requirements posed by superfluid technology. This is expected to feed back to SRF industry, on which particle physics depends to a considerable extent.

6.3.3 Physics opportunities with sub-GeV beams

The unique beam properties of ERLs – high intensity and small emittance – enable substantial experimental advances for a variety of physics at lower energies. This is described in detail in [2].

Form factors of nucleons and nuclei are traditionally accessed via elastic electron scattering. Recently, the low-Q^2 form factor of the proton was the focus of increased scrutiny because of the proton charge radius puzzle [29], a more than 5σ difference in the charge radius extracted from muonic spectroscopy and all other determination methods. The determination of the proton form factors is limited by experimental systematics stemming from target-related background. The high beam current available at ERLs allows us to employ comparatively thin targets, for example cluster jets [30], which minimise this background, paving the way for a new generation of experiments. In a similar vein, the relatively high luminosity and typically small energies at facilities like MESA allow us to measure the magnetic form factor, only accessible at backward angles at low Q^2, with substantially increased precision in a Q^2 range highly relevant for the magnetic and Zeeman radii and where the current data situation is especially dire. Further electron scattering experiments include dark sector searches like DarkLight@ARIEL, aiming at masses of a couple of (tens of) MeV.

In backscattered photon scattering, the luminosity available exceeds that of ELI by a few orders of magnitude, paving the way to nuclear photonics, a development area possibly comparable with the appearance of lasers in the sixties. For example, the intensities achievable at an ERL allow nuclear parity mixing to be accessed. Photonuclear reactions test the theory for nuclear matrix elements relevant for the neutrino mass determination from neutrinoless double beta decay. They can be used to study key reactions for stellar evolution. Ab initio calculations of light nuclei (e.g. Ref. [31]) are advanced and need to be tested with precision measurements.

[7]Emphasis on the 4.4 K program and the recognition of the e^+e^- ERL collider potential was strongly supported during the evaluation of two recent related concepts, described and reviewed in Section 6.4.

A further fundamental interest regards the exploration of unstable nuclear matter with intense electron beams of $\mathcal{O}(500\,\text{MeV})$ 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”.

6.3.4 Industrial and other applications

The range of further applications, beyond particle and nuclear physics, is extensive. Examples include high-power lasers, photolithography, and the use of inverse Compton scattering (ICS) [2]. 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 four orders of magnitude higher than that of the XFEL plus a possible path into the picometre FEL wavelength range [32].

The industrial process of producing semiconductor chips comprises the placing of electronic components of very small scale onto a substrate or wafer via photolithography. For advancing this technology to nm dimensions with high throughput, a FEL is required, which ideally would be driven by a superconducting ERL. An demonstrator 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 the 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 is ensured by large scale high reliability designs, ERLs might well reach into the market, which in 2020 was 400 billion euro.

A third example, interesting due to its applications for nuclear physics but also for exotic medical isotope generation and transmutation, is the process of very intense inverse Compton scattering (ICS). A 1 GeV energy superconducting ERL operating at high average electron current in the 10 to 100 mA range would enable a high-flux, narrow-band 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 the properties of the gamma beam being 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.

The panel highlighted a further example of ERL impact: using high-field (15 T) bending magnets in an ERL in the energy range of 1 GeV, one can build a unique user facility with sub-picosecond X-ray pulses. Those cannot be achieved by contemporary sources [2], which have to use femto-slicing techniques [33] with very low photon flux instead. The JLab UV Demo FEL demonstrated less than 0.2 ps r.m.s. bunch duration (at an electron energy of 135 MeV and a longitudinal emittance of 50 keV ps) [34]. At higher energies it is possible to obtain 0.1 ps and less. For example, installation of 15 T bending magnets in the last orbit of PERLE at 500 MeV provides synchrotron radiation with a critical energy of 2.5 keV, leading to 7 keV photons, enough for most of the experiments that use femto-slicing today. For lower-energy ERLs, such as bERLinPro, there is a similar option with bremsstrahlung on a few-micron carbon foil. The advantage of carbon is a high fail temperature and therefore good radiation cooling of the foil, which allows a high electron current density (small spot size) at the foil. The tests of such a scheme have been started with the Novosibirsk ERL (Recuperator) at 40 MeV. ERLs have a potential to radically advance knowledge, science, and industry as these few examples illustrate.

6.4 Panel activities

6.4.1 Summary

The ERL Roadmap Panel was recruited and its membership endorsed by the LDG in early 2021. It has eighteen members from three continents, representing leading institutions and major ERL facilities (past, ongoing, or in progress), and assembles key expertise, e.g. on injectors, superconducting RF, operation and management. The panel decided early on to write a baseline paper on ERLs for publication [2] accompanying the appearance of this roadmap. That paper, written by about 50 co-authors, describes the history, status, challenges, prospects, physics, and applications of ERL technology and is intended as an up-to-date, comprehensive reference paper.

In June 2021, an extended Symposium on the Development of Energy Recovery Linacs was held [3]. With 100 participants and including an hour-long discussion, this was an important consultation with a community of interested accelerator, particle, and nuclear physicists. The talks presented there are suitable and interesting material for a quick introduction: ERL facilities (Andrew Hutton), high-current electron sources (Boris Militsyn), SRF developments for ERLs (Bob Rimmer), ERL prospects for high-energy colliders (Oliver Brüning, Low-energy physics with ERLs (Jan Bernauer), Industrial applications (Peter Williams) and Sustainability (Erk Jensen), chaired by Bettina Kuske and Olga Tanaka. Max Klein was invited to present intermediate summary reports to a TIARA meeting in June 2021 and, like the other panel chairs, to the EPS Conference at DESY (virtually) in July 2021 [35].

Over the summer, members of the panel and further colleagues in a sub-panel, were involved in an evaluation of future e^+e^- ERL collider conceptsand their implications for this roadmap. A summary of the findings of this sub-panel is given in the next section and in more detail in [2].

In the final phase of its activities, the panel's emphasis focused on the development of the actual Roadmap and this report. This was made possible through much work of the facility representatives, including ERL panel members, and further contributions and consultations with a number of colleagues worldwide, far exceeding the formal list of authors of this report. We are grateful for their efforts. What had begun as an attractive, interesting task developed to an intense process which hopefully will bear fruit. It had been motivated by the conviction to work on one of the most fascinating and promising new accelerator concepts.

6.4.2 Future e^+e^- ERL collider prospects

While the panel started to work, the ERLC concept was put forward [9] to possibly build the ILC as an energy-recovery twin collider, with the prospect of a major increase in e^+e^- luminosity compared to the ILC baseline. Similarly, the CERC concept had already been published [8] to configure the FCC-ee as a circular energy-recovery collider, with very high luminosity extending to a large collision energy of $\mathcal{O}(500\,\text{GeV})$. These potentially important developments motivated the formation of a sub-panel (see the ERL author list), to evaluate the luminosity prospects, the R&D involved, and the schedule and cost consequences for both ERL-based e^+e^- collider options. This group met frequently throughout the summer and had to deal with changes of the parameters of CERC and ERLC which partially arose in a friendly dialogue with the authors of these concepts. A brief summary of this evaluation – a topic in progress – is presented here, while a more detailed report will be available with the ERL baseline paper accompanying this report.

6.4.2.1 CERC

The Circular Energy Recovery Collider is proposed as an alternative approach for a high-energy high-luminosity electron-positron collider based on two storage rings with 100 km circumference and a maximum collision energy of 365 GeV. The main shortcoming of a collider based on storage rings is the high power consumption required to compensate for the 100 MW of synchrotron radiation power. The CERC concept aims to drastically reduce the electrical power for the RF. The sub-panel task was to evaluate whether the total power would also be reduced compared to the FCC-ee.

According to the proponents, an ERL located in the same 100 km tunnel would allow a large reduction of the beam energy losses while providing a higher luminosity and extending the collision energy to 500 GeV, enabling double-Higgs production, and even to 600 GeV for ttH production and measurements of the top Yukawa coupling. This concept also proposes to recycle the particles as well as the energy to enable collisions of fully polarised electron and positron beams.

A sketch of a possible layout of the CERC with linacs separated by 1/6th of the 100 km circumference (see Ref. [8]) shows the evolution of the beam energy for electrons and positrons in a four-pass ERL equipped with two 33.7 GeV SRF linacs. The number of interaction points and corresponding detectors is determined by the physics program. In this scheme, the luminosity can be shared between detectors; by timing, the beam bunches collide in only one of the detectors, avoiding collisions in the others. Using this scheme, the luminosity is divided between detectors in any desirable ratio, compared to the FCC-ee where the total luminosity is the sum of the luminosity in each detector. Only beams at the top energy pass through detectors, while the other beam lines bypass the interaction regions (IRs). The energy loss caused by synchrotron radiation is significant at these high energies. It makes the process of beam acceleration and deceleration asymmetric, and both the electron and the positron beams require separate beamlines for each of the accelerating and decelerating passes, meaning that the four-pass ERL would require sixteen individual transport lines around the tunnel. Whilst this adds complexity in the geometry of the accelerator, the authors propose to use small-gap ($\sim$ 1 cm) combined-function magnets and a common vacuum manifold.

The authors estimated the maximum luminosity to be in excess of 10^{36} cm^{-2} s^{-1}, which excited a lot of interest among the future user community. This was achieved by using extremely flat beams for reduced beamstrahlung energy loss (a horizontal-to-vertical ratio of 500), which the authors stated would still avoid beam loss due to high vertical disruption. A fundamental difficulty with this concept is the choice of bunch length: too short and beamstrahlung at the interaction point makes it impossible to recuperate the beams for deceleration; too long and the curvature of the RF increases the energy spread of the bunches so that they do not fit in the energy bandwidth of the final focus system. Neither of the two alternative bunch lengths suggested by the authors (2 mm and 5 cm) are viable, but an intermediate value might be acceptable. Clearly, this is a topic that needs careful simulation to move forward. Since neither parameter set was fully self-consistent, the sub-panel was unable to validate the luminosity estimate. However, the sub-panel identified several beam dynamics issues that should be studied to enable a more accurate simulation of the luminosity once a self-consistent parameter set has been developed. It is clear that the luminosity falls rapidly with increasing energy. The most important issue in the arcs is the preservation of the small vertical emittance of 8 nm over the 400 km orbit in the presence of strong focusing magnets. Emittance growth comes both from the misalignment of the combined-function magnets and ground motion, and tolerances are normally tighter for stronger focusing. Alignment of the sixteen small magnets would be a challenge, given the difficulty of access and the tight tolerances that must be achieved. The orbit correction algorithm must also be studied (the dispersion-free method, in which the beam energy is changed, cannot be used). It also became clear early on in the evaluation that 2 GeV was too low an energy for the damping rings, and the authors later stated that up to 8 GeV may be required.

The proposal was aimed at reducing the power needed for the accelerator, and the sub-panel spent a lot of effort to evaluate this claim. The sub-panel was able to confirm the reduction of synchrotron radiation and the consequent reduction in RF power required. However, there were two other effects that negated this advantage. First, the cryogenic power required to maintain the cryomodules at 2 K for the $t\bar{t}$ case was 153 MW assuming state-of-the-art SRF technology. In addition, the synchrotron radiation in the 2 GeV damping ring is not negligible and would exceed the synchrotron radiation in the 100 km arcs for the case of 8 GeV damping rings. Overall, the power consumption was estimated to be 316 MW with 2 GeV damping rings, similar to the FCC-ee. The cost of the proposal was also estimated by the sub-panel, based on the cost of the arc magnets from the eRHIC study and estimates from the FCC-ee for the rest. The total cost was estimated to be 138 % of the FCC-ee for the same configuration.

The sub-panel looked at the possibility of building the FCC-ee first and upgrading to the CERC as a later upgrade. The CERC layout is required to minimise the synchrotron radiation losses in the arcs. The FCC-ee layout, on the other hand, envisions two to four interaction points and features several 2.1 to 2.8 K SRF sections distributed around the ring. Implementing the CERC configuration inside the FCC-ee tunnel would require a redesign of the FCC tunnel layout with sufficient space for the CERC linacs next to the central interaction point. In addition, the required caverns for the detector placement are not compatible with the experimental caverns planned in the FCC-ee layout. The extent to which such a design iteration affects the FCC-ee performance reach and cost would need to be assessed.

As this report was being finalised, the authors proposed an updated set of operating parameters and gave specific choices for the linac cavity design, voltage gain and quality factor, which were not provided in the initial proposal. We had assumed a Q_0 of 3×10^{10}, the present state of the art. The authors assumed that the Q_0 would be 10^{11} as a result of future R&D. They also reduced the gradient by a factor of two. Taken together, these values would significantly lower the electrical requirements of the linac from our assessment in the $t\bar{t}$ case but would roughly double the number of linac cavities. Our simple cost model is not adequate to accurately assess these changes although an overall decrease in the cost is likely. However, the new parameters reduce the luminosity by a factor of three and do not change the large, beamstrahlung-induced bunch energy spread that brings into question the viability of this approach. With the new parameters, the CERC would still be significantly more expensive than the FCC-ee.

CERC Recommendations: The sub-panel supports the idea of designing a collider based on an ERL to reduce the energy footprint of the facility, and the CERC is an excellent first attempt. While the present proposal has several flaws due to the limited effort that the authors were able to devote to the design, the sub-panel chose to look for ways that the design could be improved rather than focus on the problem areas.

1. We strongly recommend the development of a self-consistent set of parameters with associated preliminary simulations to fully demonstrate that the idea is viable.

2. The bunch length is a critical parameter: too short and the beamstrahlung becomes excessive; too long and the energy spread from the RF curvature becomes excessive. It will be necessary to carefully optimise the choice.

3. The energy requirements of the damping rings must be integrated in the design.

4. We recommend R&D on high Q_0 cavities operating at 4.4 K, which would reduce both the cost and the power consumption.

6.4.2.2 ERLC

The Energy-Recovery Linear Collider was proposed as a high-luminosity alternative for the ILC [9]. It is based on twin-axis superconducting cavities, with the bunches being decelerated after collision to recuperate the energy (see Fig. 2 in the reference for the schematic layout). This would also permit the re-use of the bunches themselves so that the injectors only have to replace lost particles rather than the whole bunch charge. In the concept, the linacs operate with a 1/3 duty cycle, with two seconds on, four seconds off to reduce the cryogenic power needed to maintain the cryomodules at 1.8 K. The luminosity is estimated by the author to be $5 \times 10^{35}\,\text{cm}^{-2}\,\text{s}^{-1}$, a significant increase over the ILC. The sub-panel carried out an evaluation of the luminosity as well as the cost and power consumption. In addition, there were several new beam-dynamics effects which arose over the course of the study. The idea of using a 1/3 duty cycle was not endorsed by the sub-panel given the sensitivity of 1.8 K cryogenic plants to pressure variations. An additional problem with the pulsed RF is the time it takes for the RF to stabilise before the beams can be injected, and additionally, the beams have to be ramped slowly to limit the RF power required (because of the length of the linacs, it takes time for the energy to be restored in the outermost cavities). A version with full CW operation but reduced current was therefore considered as well.

The entire machine is a storage (damping) ring with an unusual insertion from the bunch compressor to the decompressor consisting of the acceleration linac, final-focus system (FFS), interaction point (IP), and the deceleration linac. The longitudinal dynamics can therefore be somewhat different from a normal storage ring due to this long insertion (the transverse plane may also be affected). The energy loss due to HOMs in the acceleration and deceleration linacs is also a large perturbation of the longitudinal dynamics. This new configuration needs careful study as it is likely to be a configuration used in other future ERL concepts.

The vertical emittance is the same as in the ILC. However, since the proposed transverse damping time corresponds to ~ 400 turns, various types of emittance increase contribute to equilibrium in contrast to the case of single-pass colliders such as the ILC. Various stochastic effects belong into this category, and these need to be carefully evaluated. More complex is the emittance increase in the main linac (and FFS) due to misalignment and the wake field. The ILC expects 10 nm increase in the vertical normalised emittance in a single pass. The major components of this emittance increase are coherent turn-by-turn effects, some of which may be cumulative. A cumulative emittance increase of as little as 0.1 nm out of a 10 nm single-pass increase can exceed the design emittance if multiplied by 400. The possible source of the cumulative components may be a combination of the above effects (misalignment and wake field) with the chromaticity, which cannot be compensated in the linacs, unlike in ring colliders.

The linac design was not specified in the proposal, so assumptions were made about the CW SRF cavities that would be used. A CBETA-like cryomodule (CM) design concept was chosen, but with dual cavities, that is, side-by-side, multi-cell, 1.3 GHz cavities with niobium cross connections so power can flow from one multi-cell cavity to its neighbor as required for energy recovery. The huge steady-state loading (1.6 GV/m) from each of the 53 mA beams makes the cavity fields very sensitive to imperfect loading cancellation (i.e. partial energy recovery). In particular, the relative timing of the e^- and e^+ bunches at the cavities may vary due to slow tunnel temperature changes that move the CMs longitudinally.

The cost of the ERLC is higher than that of the ILC as the average gradient is lower (longer tunnel) and the cavities are roughly twice as expensive. We estimated the total cost of the ERLC to be 224 % that of the ILC. The power requirements are harder to estimate as there are several different options. A major uncertainty is the fraction of the HOM power that is dissipated at 1.8 K. In the ILC, this is 7 %, which would be excessive for the high currents in the ERLC. We therefore assume that sufficient R&D has been carried out to enable 100 % of the HOM load to be dissipated at much higher temperature. With this assumption, the power was estimated by the sub-Panel to be 463 MW instead of the 130 MW estimated by the author for a luminosity of 4.8×10^{35} cm^{-2} s^{-1}. Note that recently, an optimisation of the ILC parameters resulted in a luminosity of 1.35×10^{34} cm^{-2} s^{-1}. The ERLC concept has the potential to exceed the performance projections of the ILC by over an order of magnitude, but still requires vetting of the beam dynamics to affirm that emittance preservation is possible in a recirculating linear collider with beam damping at low energy.

If shown viable, the ERLC approach might be considered as a future upgrade option for the ILC although it would require a major reconfiguration of the accelerators and cooling systems. One appealing scenario could therefore be to start the physics program with the baseline ILC configuration and to look at the ERLC as a future upgrade option of the collider. Noting that the Main Linac and SRF system amount to approximately 45 % of the total ILC budget, one can conclude further that such an upgrade of the ILC implies an additional investment of about half of the total ILC budget. While this clearly represents a significant cost item, it might still be an interesting option for the long-term exploitation of the ILC if one considers the potential increase of the collider performance by over one order of magnitude and the extension of the ILC exploitation period by perhaps another decade. This approach assumes that the ERLC cryostats are compatible with the main tunnel dimensions and that the Interaction Region design of the ERLC is designed to be compatible with the ILC Interaction Region.

The author developed an update to the published parameters with a reduced distance between bunches (23 cm instead of 1.5 m) with an equivalent reduction in the number of particles per bunch [9], which reduces the HOMs by the same factor. The luminosity is kept the same by adopting a smaller horizontal beam size at the IP (keeping the same vertical beam-beam tune shift). The new parameter set considers full CW operation, and the author estimates that the electrical power for the beams is 250 MW. This assumes that the cryogenic efficiency is equal to the Carnot efficiency (1/550). We estimate this efficiency to be 1/900 (the value obtained at LCLS-II), to which 25 % should be added for the cryomodule thermal shield cooling and utilities to dissipate the cryoplant heat loads in cooling towers. Adding the site power requirements gives a total of over 600 MW, which the sub-panel considers unacceptable. We also believe that the closer bunch spacing in the ERLC would require a crossing angle at the interaction region, adding the complexity of including a bend that returns the bunches to the decelerating linac after collision.

ERLC Recommendations: The sub-Panel supports the idea of designing a linear collider based on an ERL to reduce the energy footprint of the facility, and the ERLC is an excellent first attempt. The present proposal was developed by a single author and is therefore incomplete in many details. Therefore, the sub-panel chose to look for ways that the design could be improved as part of a more detailed study.

1. We recommend a study of the new beam dynamics problems inherent in the integration of a linac and a damping ring.
2. We recommend R&D on high Q_0 cavities operating at 4.4 K, which would reduce both the cost and the power consumption.
3. We recommend the development of twin-aperture SRF cavities in a common cryomodule.

Overall conclusions

The sub-panel was presented with two extremely interesting ideas to evaluate. While neither is ready to be adopted now, they point to the future in different ways. The CERC aims for multiple passes in a tunnel with an extremely large bending radius to minimise the synchrotron radiation loss. The ERLC proposes a single acceleration and deceleration, separating the two beams by using twin-axis cavities. Both of these ideas provide an indication of the variety of different ERL layouts that might be developed in the future. A particularly interesting prospect is to design an energy efficient, ultra-high luminosity ERL-based electron-positron collider at 500 GeV, which would enable the exploration of the Higgs vacuum potential with a measurement of the tri-linear Higgs coupling. The most important R&D activity that would make this kind of development viable at a luminosity approaching 10^{36} cm^{-2} s^{-1} is to operate at 4.4 K with high Q_0. As noted throughout this report, this is a development of general relevance to SRF technology, with other benefits.

6.5 State of the art and facility plans

6.5.1 Overview of facilities and requirements

A long road has been paved since the first SRF ERL [36] 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, the beam power 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 a luminosity of 10^{34} cm^{-2} s^{-1}, 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 has, with 1 GeV, reached the highest energy so far; and the JLab FEL, which reached the highest current of all SRF ERLs, 10 mA. Larger currents have been achieved in the normal-conducting, lower-frequency ERL facility at BINP (the Recuperator).

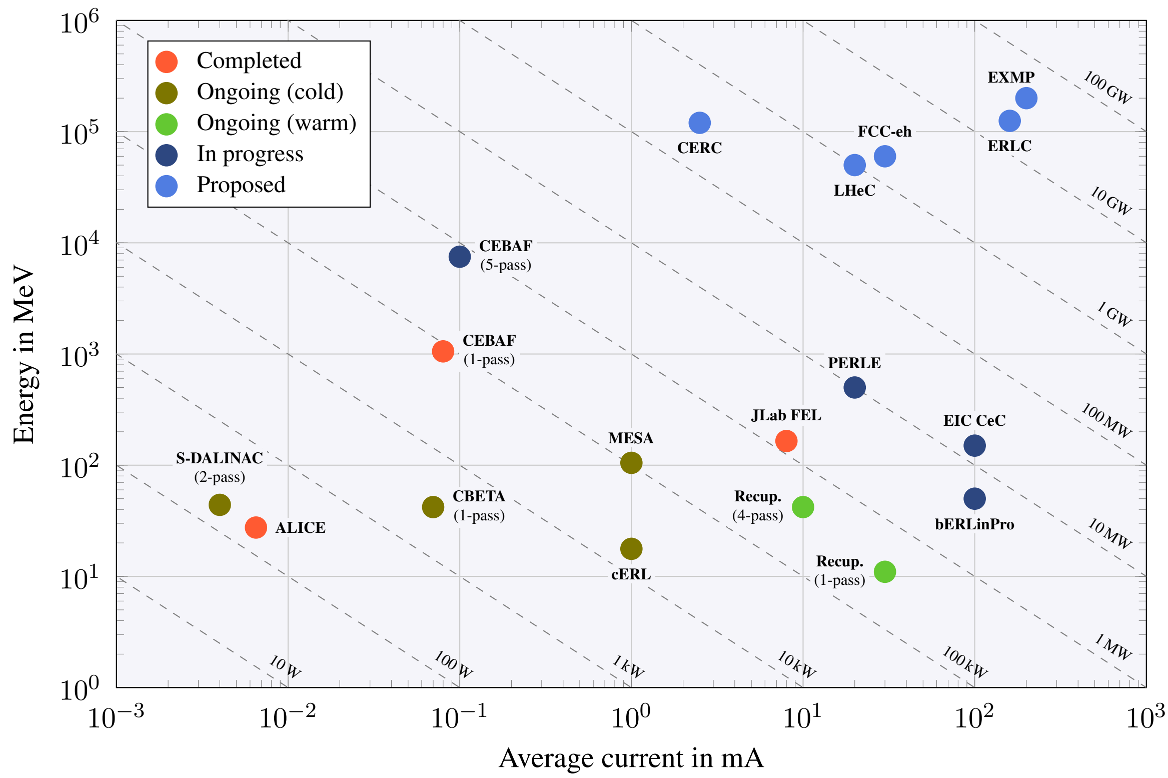

Fig. 6.1: Electron energy E vs. electron source current I for classes of past, present and possible future ERL facilities as are introduced in the text. Dashed diagonal lines represent constant power, $P[\text{kW}] = E[\text{MeV}] \cdot I[\text{mA}]$.

There are three currently operational superconducting ERL facilities (marked as 'ongoing' in dark green), S-DALINAC at Darmstadt, CBETA at Cornell and the compact ERL at KEK in Japan, to which we add MESA at Mainz as it expects to have beam in the foreseeable future. These facilities, including that at Novosibirsk, all have important development plans as presented subsequently. These developments are funded outside particle physics, and yet, the development of the field of ERLs is based to a considerable extent on their progress; for this reason, they are included as part **A** of the ERL programme.

Four facilities in progress, two of which are in Europe, marked in dark blue in Fig. 6.1, 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. PERLE is designed for medium-current (20 mA), three-turn operation leading to 500 MeV beam energy. These new facilities are described in Section 6.7. The two European projects, bERLinPro in its 100 mA incarnation and PERLE, constitute part **C** of the ERL programme.

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 GeV (LHeC) and 200 GeV (EXMP). CERC has a low current but a rather large number of beam lines. LHeC and FCC-eh are three-turn linacs with about 20 mA current delivered by the gun but 120 mA load to their cavities. ERLC and EXMP are single-pass linacs, possibly with twin-axis cavities. These plans hint at a common demand on SC cavities to tolerate about 100 mA current load, which is the goal of PERLE (in three turns) and, in a single pass, of an upgraded bERLinPro and the CeC at BNL in its most challenging configuration.

The E-I graph provides an understanding of basic ERL facility characteristics. However, it does not display the collider luminosities or cryogenic power demands. From these, as explained later, a vision arises of a 500 GeV collision energy electron-positron collider with the potential to reach 10^{36} cm^{-2} s^{-1}.

Such a variant of ERLC, when based on 4.4 K technology, would be affordable in terms of power and allow for a few-percent-accurate test of the Higgs boson self-coupling.

6.5.2 Recuperator BINP Novosibirsk

The Novosibirsk free electron laser (FEL) facility [37] includes three FELs [38] operating in the terahertz, far-, and mid- infrared spectral ranges. The first FEL of this facility has been operating for users of terahertz radiation since 2004. It remains the world's most powerful source of coherent narrow-band radiation in its wavelength range (90 to 340 μm). The second FEL was commissioned in 2009. Today, it operates in the range of 35 to 80 μm, but its undulator will soon be replaced with a new, variable-period one [39], shifting its short wavelength boundary down to 15 μm. The average radiation power of the first and the second FELs is up to 0.5 kW, and the peak power is about 1 MW. The third FEL was commissioned in 2015 to cover the wavelength range of 5 to 20 μm and provides an average power of about 100 W.

The Novosibirsk facility was the first multi-turn ERL in the world. Its notable features include the normal-conducting 180 MHz accelerating system, the electrostatic electron gun with a gridded thermionic cathode, three operating modes of the magnetic system, and a rather compact ($6 \times 40\,m^2$) design. The accelerator of the Novosibirsk FEL has a rather complex design. One can consider it to be three different ERLs that use the same injector and the same linac. The first ERL of the facility has only one orbit, while the second and the third ones are two- and four-turn ERLs, respectively. The low RF frequency allows operation with long bunches and high currents.

The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently [40]. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved. The following work is planned for the next years:

- Installation of the RF gun in the injector, while the existing electrostatic gun will be kept there. The RF gun beamline has already been manufactured and assembled in the test setup. It includes an RF chopper for the beam from the electrostatic gun.
- Continuation of routine operation with three FELs for users of the "Novosibirsk FEL" user facility.
- Optimisation of the optics for further reduction of beam loss at large energy spread induced by FEL operation.
- Optimisation of the optics for the reduction of beam loss at large emittance induced by the foil target for the bremsstrahlung radiation source. These experiments are aimed to create a hard X-ray source with few-picosecond pulse duration and a few MHz repetition rate for users.
- Demonstration of the so-called electron outcoupling technique for the FEL oscillator at the third FEL [41].

6.5.3 S-DALINAC TU Darmstadt

The S-DALINAC is a superconducting, multi-turn recirculating linear accelerator for electrons at TU Darmstadt [42]. It is used for scientific research and academic training in the fields of accelerator science, nuclear physics, nuclear astrophysics, and radiation science. The S-DALINAC employs eleven multi-cell niobium cavities for superconducting radio frequency (SRF) acceleration and operates at a frequency of 2.998 GHz. The SRF cavities have quality factors in excess of 10^9 at an operating temperature of 2 K and sustain average accelerating fields of 4 to 6 MV/m. The S-DALINAC delivers a continuous-wave (CW) beam with electron bunches every 333 ps and a bunch length of about 1 ps.

The S-DALINAC went into operation in 1991. At the time, it consisted of a thermionic electron gun, a superconducting injector linac, a main linac with two recirculations, and a suite of experimental beam lines. In 2015/16, the accelerator lattice was extended by an additional recirculation beam line capable of operating in energy-recovery mode. The maximum beam energy after four passes of the electron beam through the main linac is 130 MeV. At this energy, the maximum beam current is limited to 20 µA for radiological reasons. The emittance of the electron beam amounts to < 1 mm mrad. The main accelerator consists of four cryomodules, each housing two 20-cell niobium cavities. Any desired electron beam energy up to 130 MeV can be provided and delivered to the experimental hall by recirculating the beam up to three times through the main linac.

The ERL operating mode of the S-DALINAC was first demonstrated in 2017 [43] with an energy-recovery efficiency of 90.1(3) %. This efficiency corresponds to the decrease of RF-power consumption due to beam loading of one of the main linac's RF cavities when the recirculated beam is decelerated in the cavity. This success made S-DALINAC the first ERL operating in Germany.

In August 2021, S-DALINAC was successfully operated in a twice-recirculating ERL mode. Full energy-recovery efficiencies of up to 81.8 % had been measured for beam currents of up to 8 µA at a beam energy of 41 MeV. The beam load of the SRF cavities in the two situations – with the beam either being accelerated only once or being accelerated twice and decelerated once – resulted in the same beam load within measurement uncertainties. The measurements thus indicate complete energy recovery in the first deceleration passage through the main linac with an efficiency of 100 % within uncertainties.

Since the injection energy cannot be recovered in an ERL and a decrease of the injection energy by 1 MeV reduces the power consumption of a 200 mA ERL with 5000 hours of operation per year by 1 GW h per year, it is worthwhile to improve the technology for low-energy injection ERLs for which relativistic phase slippage is largest. Main research topics therefore include the quantification of the phase-slippage effect in extended multi-cell SRF cavities and countermeasures for its mitigation including individual off-crest working points for various SRF cavities and individual phase advance to be made possible by multi-turn SRF ERLs with individual recirculation beam lines.

6.5.4 MESA Mainz

MESA is envisioned as a facility for high-intensity electron scattering experiments in the 100 MeV energy region [30, 44, 45]. It will represent a sustained infrastructure for such experiments but also be available for further research on ERLs for a long time to come. The civil construction for the new machine will be finalised in 2022. Following the installation and commissioning of the machine, first ERL tests are expected in 2025. External-beam experiments are expected to start somewhat earlier. The ERL beam will be directed towards the so-called MAGIX experiment using a windowless gas target.

Radiation protection considerations call for a system of halo spoilers and collimators behind the MAGIX target. The unavoidable losses due to Coulomb scattering – the so-called TArget-Induced haLo, or TAIL for short – can therefore be mostly confined to a heavily shielded area which does not contain any sensitive components. The relative power losses in the ERL beam line are predicted to be below 10^{-5} of the beam power at the target when using the MAGIX hydrogen target with the nominal areal density. Therefore, a limit to the luminosity at 105 MeV under reasonable assumptions for radiation protection issues may be set to about 5×10^{35} cm^{-2} s$^{-1}Z^{-2}$ with Z the nuclear charge of the target. This value seems sufficient for the experiments that are presently being discussed.

Over the coming years, the project team will focus on the installation and commissioning of MESA. It will pursue accelerator research goals, aiming at a few topics listed below.

- **Improving electron beam polarimetry** in order to support the precision measurements of electroweak observables at MESA. This will include a chain of three polarimeters which each will reach an accuracy well below $\Delta P/P < 1$ %, in some cases even below 0.5 %. The chain will consist of two Mott polarimeters—both operating in the region of the source and the injector, respectively—and the so-called Hydro-Möller polarimeter. The latter will operate online and is based on a completely polarised electron target formed by trapped hydrogen atoms. With a target density of $\approx 3 \times 10^{16}$ cm^{-2}, it is suited for online operation but will also yield a high statistical efficiency, eliminating the slow drift of the polarisation of a few percent per week. More details can be found in [46]. The target will be incorporated into the external beam line leading to the electroweak P2 experiment. In the long run, this beam line may be extended as a third recirculation in ERL mode.

- **Installing a second photoelectron source** at the MESA injector with the potential to provide bunch charges > 10 pC with good beam quality. The present source is operated at a relatively low voltage because reliable operation parameters for the NEA photocathodes are of utmost importance. NEA cathodes are mandatory for production of spin-polarised beam but do not tolerate field emission, which is frequently associated with high voltages. Moreover, the spin-manipulation systems elongate the transfer beam line to the injector and require more complicated optics, which is also detrimental to attaining high bunch charges. However, according to simulations and experiments, an average current of 1 mA of MESA stage-1 can be produced with normalised emittance below 1 μm, which is sufficient for all presently planned experiments while limiting the available MESA beam power in ERL mode to 100 kW. To enter the MW regime, a second source will be installed which will be dedicated to experiments not requiring a spin-polarised beam. Due to the normal-conducting injector system of MESA, the input energy can be changed with moderate effort. Simulations indicate that increasing the source energy to 200 keV will allow good beam quality with bunch charges exceeding 10 pC, creating a test bed for experiments, e.g., compensation studies of transient beam loading, ion trapping, Compton backscattering, and others.
- **Improving the higher-order mode damping capabilities** of the cavities. At high average currents, HOM heating of the damping antennas will lead to a breakdown of superconductivity in the antenna and hence inhibit operation. This can be improved by coating the HOM antennas with layers of material with a high critical temperature, e.g. Nb_3Sn. The MESA research group has recently received funding to start corresponding investigations within a larger joint effort of German universities.

6.5.5 cERL KEK Tokyo

The compact ERL is a facility at KEK which is introduced in detail in the ERL long write-up [2]. Its future plans include the following aspects.

- R&D on a powerful 10 kW-class ERL-based EUV-FEL focuses on creating a high-intensity EUV light source for lithography for semiconductor microfabrication, surpassing the existing LPP-type sources (up to 250 W) by more than 40 times. Core accelerator technology development includes: high-efficiency superconducting cavity acceleration, and energy-recovery linacs (ERL).
- Realisation of energy-recovery operation with 100 % efficiency at a beam current of 10 mA at cERL and the FEL light production experiment.
- Development of an irradiation line for industrial applications (carbon nanofibers, polymers, and asphalt production) based on CW cERL operation.
- Realisation of a high-efficiency, high-gradient Nb_3Sn accelerating cavity to produce a superconducting cryomodule based on a compact freezer. We are targeting a general-purpose compact superconducting accelerator that can be operated at universities, companies, hospitals, etc.

6.5.6 CBETA Cornell

The Cornell-BNL Test Accelerator (CBETA) [47] is the first multi-pass SRF accelerator operating in energy-recovery mode [21], focusing on technologies for reduced energy consumption. The energy delivered to the beam during the first four passes through the accelerating structure is recovered during four subsequent decelerating passes. In addition to direct energy recovery, energy savings are achieved by using superconducting accelerating cavities and permanent magnets. The permanent magnets are arranged in a Fixed-Field Alternating-gradient (FFA) optical system to construct a single return loop that successfully transports electron bunches of 42, 78, 114, and 150 MeV in one common vacuum chamber. While beam loss and radiation limits only allowed commissioning at low currents, this new kind of accelerator, an eight-pass energy-recovery linac, has the potential to accelerate much higher current than existing linear accelerators. Additionally, with its DC photoinjector, CBETA is designed for high brightness while consuming much less energy per electron. CBETA has also operated as a one-turn (i.e. two-pass) ERL to measure the recovery efficiency accurately [48].

CBETA was constructed and commissioned at Cornell University as a collaborative effort with Brookhaven National Laboratory. A large number of international collaborators helped during commissioning shifts, making it a joint effort of nearly all laboratories worldwide that pursue ERL technology. Because recovering beam energy in SRF cavities was first proposed at Cornell [1], it is pleasing that its first multi-pass system is constructed at the same university.

The FFA beam ERL return loop is also the first of its kind. It is constructed of permanent magnets of the Halbach type [49] and can simultaneously transport beams within an energy window that spans nearly a factor of four, from somewhat below 40 MeV to somewhat above 150 MeV. Having only one beamline for seven different beams at four different energies saves construction and operation costs. The permanent Halbach magnets contain several innovations: they are combined-function magnets, they were fine-tuned to 0.01 % accuracy by automated field shimming, and they provide an adiabatic transition between the arc and straight sections [50].

After achieving all key performance parameters of CBETA's NYSERDA-funded construction and commissioning phase, operation was interrupted in the spring of 2020. The accelerator is now available to test single-turn and multi-turn ERL technology. Tests for the 100 mA hadron-cooling ERL of the EIC are of particular interest, as several key design parameters of CBETA's main components match that future accelerator well.

Provided funding, a test program at CBETA for the EIC hadron cooler ERL entails:

- adjusting the setup to one-turn ERL operation;
- increasing the beam current in this configuration initially to 1 mA, with increased shielding of the beam dump;
- using a low-halo cathode, installing beam-halo monitors and studying loss mechanisms, in particular halo development from ghost pulses, dark current, gas, ion, and intra-beam scattering;
- installing a halo collimation system;
- increasing shielding for larger beam currents toward 100 mA and studying beam-current limits;
- increasing bunch charge toward 1 nC and studying bunch-charge limits.

Other future options for CBETA are continued optimisation of four-turn ERL operation with increased beam transmission, the conversion of CBETA to a Compton-scattering hard X-ray source [51], and the use of the CBETA injector for ultra-fast electron diffraction [52] with extremely short MeV-scale bunches.

6.6 R&D objectives—key technologies

ERL technology has developed substantially over the past decades. A number of key technologies have been identified, which are key to the further development of the technology, and to underwrite its application to near- and further-future facilities of interest in and beyond particle physics. More information is given in the accompanying ERL overview paper [2]. The topics described below require funding and effort, typically as a combination of in-kind contributions and already-committed investments at existing or new facilities, alongside new resources to be committed in the context of the Accelerator R&D Roadmap. Resource and effort requirements are summarised in Section 6.8.

6.6.1 High-current electron sources

Injectors for particle physics ERLs, which require high average current in combination with a 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 to the performance of the photoinjector in terms of emittance and current, and a long photocathode lifetime is essential. Reproducible growth procedures have been developed, and months-long lifetimes have been achieved under operational conditions. 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 r.m.s. surface roughness) to achieve low emittance and to avoid field emission. SRF-based photoinjectors can provide excellent vacuum conditions. However, the superconducting cavities are extremely sensitive to any kind of contamination; therefore, the photocathode exchange process is 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 is the design of accelerating structures which can provide a high cathode field in combination with extremely-high-vacuum conditions. Major efforts concentrate on the development of DC guns (Cornell University), VHF NCRF (LBNL), and lower- (BNL) and high-frequency SRF guns (bERLinPro). Important insights can be gained from operating smaller facilities with high-current thermionic guns (BINP).

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

6.6.2 SRF technology and the 4.4 K perspective

6.6.2.1 Near-term 2 K developments

Superconducting RF is the key technology for energy-efficient ERLs. A vibrant global R&D program has 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 the energy sustainability of the systems further.

The focus for the linear e^+e^- collider has been 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. This different optimisation leads to a frequency lower than 1 GHz and lower gradients. Presently, operation at moderate gradients (below or close to 20 MV/m) provides the best compromise between these competing requirements.

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 $\mathcal{O}(100\,\text{mA})$ requires cavity designs and systems that minimise the excitation and trapping of higher-order modes, facilitate HOM extraction, and enable 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 measured in beam-test facilities.

6.6.2.2 Towards 4.4 K

A significant part of the power consumption of ERLs is related to the Wall-plug power required to cool the dissipated RF power in CW operation, which can be approximated by

$$P = \frac{V_{\text{acc}}^2}{(R/Q)\cdot Q_0} \cdot N_{\text{cav}} \cdot \eta_T \tag{6.1}$$

where V_{acc} is the acceleration by a cavity, R/Q the shunt impedance, Q_0 the cavity quality factor, N_{cav} the number of cavities and η_T the heat transfer, i.e. combined technical and Carnot, efficiency, which is proportional to the ratio of the cryo temperature, T, and its difference to room temperature, $300\,\text{K} - T$. This power has to be provided externally. For the LHeC it is about 15 MW for $T = 1.8$ K. A 500 GeV e^+e^- collider, however, with 10–20 times more cavities ($N_{\text{cav}} = \mathcal{O}(10^4)$) than the LHeC, requires a few hundred MW of power. This can be reduced by about a factor of three with 4.4 K technology, for similar V_{acc} and Q_0 characteristics. The overarching need to limit power consumption by building sustainable high energy accelerators in the future motivates a strong interest in 4.4 K developments.

State-of-the-art niobium has the highest critical temperature of all elements, as 9.2 K. For a reasonable resistance in the 1 GHz frequency range, it must be cooled to 2 K to attain quality factors of the order of $Q_0 = 3 \times 10^{10}$. However, given Carnot and technical efficiencies of less than 0.7 % and 20 % respectively, the overall efficiency of the cryoplant is only around 0.13 %. Furthermore, complex cold compressors must be employed for sub-atmospheric liquid helium operation. Conversely, operation at 4.4 K or above alleviates the power requirements by increasing the Carnot efficiency. This operating mode also reduces the complexity of the cryoplant design. For low-energy accelerator applications such as industrial and medical systems, 4.4 K operation even carries the potential of eliminating the cryoplant altogether in favour of cryo-coolers, thereby removing a large financial and technical hurdle for the implementation of such systems.

For niobium at $\sim$ 1 GHz, operation at 4.4 K is not an option because the efficiency gains are completely negated by an intolerable increase in resistance, with Q_0 values of below 10^9. One therefore must move to compound materials that due to their physical properties need to be coated on a substrate. Options include Nb_3Sn, NbN, NbTiN, V_3Si, Mo_3Re and MgB_2. So far, only the first three have been explored extensively. While Q_0 values $> 10^{10}$ at 4.4 K are predicted, imperfect films suffer heavily from early flux penetration, which currently limits the accelerating field values to values considerably below 20 MV/m. An approach to safeguard against this is to implement a multilayer S'-I-S structure consisting of a sub-µm-thick high-temperature superconductor (S') on a nm-thick insulator (I) on a thick Nb substrate (S), as proposed in Ref. [53].

There are two major technologies under development: a vapour-diffusion technique, mainly in the US [54] and ramping up in Japan, and sputtering with advances in Europe. A third one is atomic layer deposition with possibly good prospects for 4.4 K-based cavity systems. These basic technologies will mainly be pursued within the RF R&D programme within the overall Roadmap, and are only briefly characterised below. A goal for future ERL applications, a decade hence, is the development of a complete cavity cryomodule [8] and its test with beam, for which PERLE at 802 MHz is considered a suitable long-term option, or possibly bERLinPro depending on the frequency choice and how this field develops.

Nb_3Sn by vapour diffusion: So far, only Nb_3Sn has been successfully applied to cavities, by high-temperature Sn vapour infusion on a niobium substrate. This method has achieved Q_0 values above 10^{10} at 20 MV/m and frequencies above 650 MHz for single-cell cavities. For nine-cell, 1.3 GHz cavities, maximum fields of the order of 15 MV/m have been achieved. First attempts to produce structures for cryomodules have been limited to a few MV/m, but the effort has been very limited so far. The main challenges are (a) to develop diffusion recipes that consistently deliver the correct Nb_3Sn stoichiometry for high-field operation, (b) extend these recipes to large, complex multicell structures and (c) subsequently design cryomodules that are able maintain the performance despite the fact that Nb_3Sn systems are very sensitive to trapped flux, thermo-current generation during cooldown, and cracking due to Nb_3Sn's extreme brittleness. In parallel, an active microphonics compensation system must be included to handle the larger pressure fluctuations at 1 bar, 4.4 K operation. Nb_3Sn vapour infusion activities are ongoing in the USA and ramping up in Japan. At present, only this technique appears in line with the desirable realisation of a 4.4 K accelerating module in the next decade. Yet, vapour infusion is not compatible with other substrates, in particular copper, and it may not be adapted to other superconductors or used in multilayer systems.

Sputtering techniques: To address the limitations of vapour infusion, sputtering techniques, such as HiPIMS are being investigated. At the forefront are CERN and the European IFAST collaboration. Samples have achieved encouraging results, but first single-cell (1.3 GHz) cavities are not expected until a few years from now. Sputtering enables more precise control of material stoichiometry and is able to synthesise a wide variety of superconductors on various substrates (including copper). Being a 'line-of-sight' method, its difficulty lies in coating complex 3D structures whose orientation to the cathode varies along the structure. Film quality and thickness both are thus geometry-dependent. This may indeed complicate the production of cavities with multilayer structures.

Atomic layer deposition Atomic layer deposition (ALD) is a third technique that is very promising, but currently it is further behind than sputtering. The most advanced research activities are ongoing in France with activities ramping up in Germany. Inherently, the deposition is a self-limiting process with thickness control at the atomic level. Coating does not require a line of sight to the substrate; thus, in principle, complex structures can be coated without the difficulties encountered with sputtering, albeit the coating rates are very low. Unfortunately, ALD is not compatible with state-of-the-art Nb_3Sn. However, it can be used to coat materials such as NbN, NbTiN and MgB_2. Given its near-perfect thickness control, it is well suited for the implementation of multilayer structures. Thus, its long-term potential for high-performance 4.4 K (and above) systems may eventually be greater than that of both the vapour-infusion and sputtering techniques.

6.6.3 Fast reactive tuners

Since the accelerated and the decelerated beams are of equal magnitude but at opposite phases of the operating RF, the total beam loading current in an ERL is nominally zero. For this reason, the RF power fed into the cavity in steady state can ideally be very small. However, to cope with beam transients and microphonics, strong overcoupling is called for. This overcoupling leads to a lowered external Q and

[8] Given the very challenging basic developments required to build and test 4.4 K SRF modules, it is probably premature to cost a warm cryomodule development within the R&D programme. We have, however, included it in the vision towards an ERL based 500 GeV e^+e^- collider.

thus significantly higher power requirements. Most of the power is reflected and dumped. A side effect of the microphonics is that RF stability and hence beam stability also suffers.

A very fast tuner, fast enough to cope with microphonics and beam current transients, would allow operation with larger external Q and thus much-reduced RF power. Recent developments and tests with so-called 'Fast Reactive Tuners' (FRT) show very promising results. They use piezoelectric material referred to as BST ($BaTiO_3$-$SrTiO_3$), the ε of which can be modified with a bias voltage. The suitability and longevity of these novel FRTs with full SRF systems without and with beam must be demonstrated to capitalise on their enormous potential.

While alternative fast tuners exist, the big advantage of FRTs lies in the fact that they do not mechanically deform the cavity, thereby avoiding the excitation mechanical resonances which severely limit the ability to compensate microphonics above a few Hz. It is planned to validate the approach of using FRTs to compensate for transients and microphonics by installing suitable prototypes, in collaboration with CERN, on cavities for BERLinPro (1.3 GHz, single turn) and for PERLE (802 MHz, three turns) to thoroughly investigate the use of this technology in ERL beams.

6.6.4 Monitoring and beam instrumentation

Electron beam diagnostics and metrology systems at ERLs have unique tasks and challenges. Firstly, these arise from the combination of the very high average beam power (similar to synchrotrons) and the non-equilibrium (non-Gaussian) nature of the beams with small transverse and longitudinal emittances (similar to high-brightness linacs). Secondly, ERLs must operate with multiple beams of different beam energies transported in a beam-line. The experience of successfully operational ERLs shows that a variety of well-thought-through beam modes are indispensable. These serve for the machine setup, average-current (power) ramp-up, and high-power operation. The difference in the average beam current between the tune-up mode and the high-power mode is typically four to five orders of magnitude. This will become even more significant for higher-average-beam-power ERL systems. One more lesson of presently and previously operational ERLs and recirculating linacs is that local beam losses with an average power of about 1 W are an issue that cannot be ignored. Comparing this level of beam loss with the average beam power of 1 to 10 MW and the difference in the average beam current of the tune-up and high-power modes shows the necessity of high-dynamic-range beam measurements. A number of critical issuesare described in detail in [2]. The following advanced beam diagnostic systems must be developed for the next generation of ERLs:

1. An advanced wire-scanner system needs to be developed, tested, and then implemented at BERLinPro and PERLE for routine transverse beam profile measurements with a dynamic range of 10^6. Most of the wire scanners implemented so far provide two or three projections of the transverse beam distribution. Often, when measuring non-equilibrium linac beams, the wire scanner measurements are inferior to beam viewer images. However, wire-scanner measurements provide much easier access to the large dynamic range data. The number of measured projections could be increased relatively easily with a different mechanical implementation. Recent developments in the tomographic reconstruction techniques show that a 2D distribution can be reconstructed well based on about ten projections. The proposed advanced wire-scanner system is envisioned to take advantage of this recent development and provide tomographically reconstructed 2D beam distributions. Moreover, wire-scanner measurements can be made with the help of detectors with a bandwidth much larger than the beam repetition rate. This makes it possible to set up the system to measure beam profiles of multiple passes simultaneously. This will also be helped by the fact that the wire-scanner intercepts only a small fraction of the beam at any given time. Last but not least, if the speed of the wire can be made fast enough and the beam size is not extremely small, the wire scanners may be able to operate with a high-current CW beam.
2. Taking into account that beam imaging with the help of beam viewers frequently provides data

superior to wire scanners, we suggest that an optical system that mitigates diffraction effects to allow imaging with a dynamic range of $\sim 10^6$ be investigated and tested in a laboratory. Then, if successful, it should be tested with a beam.

3. A beam position monitoring system capable of measurements with multiple beams needs to be prepared. Here, one prototype unit needs to be developed and built first; then, it can be tested with a beam at one of the existing synchrotrons operating at a repetition rate of a few 100 MHz thus simulating conditions very similar to the next generation of ERLs.
4. A six-pass beam arrival monitor system will be indispensable for the operation of multi-turn facilities. We suggest that such a system be designed, prototyped, and tested in preparation for PERLE operation. The best candidate technology for such a system, at this point, appears to be a system based on very-high-bandwidth non-resonant pickups, an electro-optical modulator, and an ultrafast laser system with a sufficiently high repetition rate.
5. Depending on available resources, it would be prudent to start work on a non-invasive beam size monitor for beams at low (injector-like) energies in the range of 5 to 10 MeV, where SR cannot be used. Here, a physics design would be a good next step. A technique that could allow such measurements can use very low energy (50 to 100 keV), very low charge, short-pulse probe electron beam. Similar probe-beam-based systems were implemented and tested previously. However, they either did not operate with short pulses or were based on very sensitive photocathodes, which might not be very practical for a routine diagnostic system. Here additional efforts are needed to simplify such systems to make them practical.

6.6.5 Simulation and education

The design, construction, and operation of ERL facilities have to be accompanied and prepared by reliable and detailed simulations. These require much 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 using considerable CPU power. Specific beam dynamics studies related to ERLs include the following.

- Studies of coherent synchrotron radiation (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.
- Studies of the longitudinal match to compress and decompress the electron bunch in order to optimise beam transport in energy-recovery mode. Second-order corrections will 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.
- Collaborative efforts with BERLinPro on using the OPAL package as a universal tool for simulating ERL beam lines, starting from the cathode, through space-charge dominated regions of initial acceleration, and beyond into high-energy sections. Having one single tracking tool (versus many) eliminates the uncertainty of seamless transition at code junctions.

The above selection of beam dynamics studies illustrates that the ERL accelerator technology represents a challenging training ground for the next generation of accelerator scientists. Many of these topics are dealt with in PhD theses, and all of the facility centres (plus others) are engaged in training and educating accelerator physicists. The tasks to be solved, first in simulations, then in construction and operations, are far from conventional, and the rather short time scales for building smaller facilities, as compared to major particle physics accelerator or large experiments, are a plus in the attraction of young physicists.

6.6.6 Higher-Order Mode damping at high temperature

Because ERLs operate at high current, the HOM power produced can be very high. Depositing the heat load in the cold mass is highly inefficient; hence, the power must be extracted and deposited into room-temperature loads. HOM couplers come in two main types, coaxial and waveguide. Coaxial couplers are normally associated with low powers. However, the HOM couplers for the HL-LHC crabs were designed to handle up to 1 kW per coupler. Coaxial couplers are small and hence have a lower static heat load. Waveguide couplers are typically used for high powers but have a larger static heat load as they comprise a large metal link from room temperature to the cavity.

The design of HOM couplers must be multidisciplinary, balancing both RF and mechanical (thermal) requirements, as well as balancing dynamic and static heat loads. The HOM powers and thermal budgets for the cryomodule must first be understood, as well as the impedance specification that must be reached. The lower the impedance specification, the more heating appears on the coupler interface.

Fundamental power couplers can handle much higher powers than HOM couplers. The HOM couplers may need to be designed using similar methodology. Conditioning HOM couplers to operate at high power is also an area where research is required. It may be necessary to mount the HOM couplers directly onto the RF cell, so called on-cell couplers. Such concepts are common in low-beta and crab cavities, but there are only a few examples of them for elliptical cells. One option could be the split SWELL cavities proposed for FCC where the cavity is made in four quarters with waveguides between each quarter.

In addition, it is critical that the frequencies above the beam pipe cut-off are attenuated outside the cryogenic environment. Losses in superconducting materials increase with frequency squared; hence, the attenuation at high frequencies can be very high. Beam line absorbers at no less than 50 K are required to efficiently remove the radiation without helium boil-off.

Overall, the main challenges are: High-power operation of HOM couplers with acceptable static loss; multipactors absorbing RF power; strong coupling; development of on-cell coupling for elliptical cavities; and modelling of the high-frequency wakefield. Effort and timeline are provided in Section 6.8.

6.6.7 SC twin cavities and cryomodules

Twin-axis cavities are required when the accelerating and decelerating beams travel in opposite directions through long linacs. There is one example of a single-axis cavity being used for beams in opposite directions, but it accelerates the beam in both directions to attain higher beam power rather than recovering the energy. There are four examples of twin-axis cavities that have been considered.

- A purely theoretical calculation [55] was part of a proposal to build a dual-axis energy-recovery linac.
- A purely theoretical design [56] involved two Tesla-style nine-cell cavities that were partially superposed to create a twin-axis cavity. While this concept was interesting, construction of such a cavity would appear to be difficult, if not impossible.
- A design [57] comprised two three-cell cavities joined by a bridge at the power coupler end. A prototype carved out of a solid block of aluminium was built and the expected performance demonstrated. The advantage of this design is that the accelerating and decelerating cavities do not have to be identical, allowing one to design the cavities such that the higher order modes do not overlap, thereby extending the threshold for transverse beam break-up by a factor of two (which is not negligible in the context of high-current beams).

- A design [58] of a single cavity with two beam tubes for the beams being accelerated and decelerated, respectively. The advantages of this design are that the largest overall transverse dimension is smaller than that of the third design and the power is recovered in each cell, rather than being summed over all the cells and transferred via a bridge. A single-cell prototype was built from niobium and tested at cryogenic temperatures with excellent results. However, this was a single cell without the necessary power and HOM couplers, etc.

In the last two designs, the placement of the power and HOM couplers was calculated but not prototyped. In addition, a tuning mechanism would need to be developed for both designs. Given the advantages of this design in various accelerator projects, the two designs should be carried forward until it is possible to make an evaluation of the relative performance of full-scale prototypes, so that a selection can be made. An important part of the selection process would be the integration into a cryostat. Both designs are wider than single-axis cavities, so packaging in a cryostat means starting from scratch. The HOM damping is important, with the power brought out to room temperature. This requires space in the cryomodule and must be integrated into the cryostat design from the beginning. Another integration detail is how adjacent cryomodules are connected as there are two independent beam pipes. Given the close spacing of the two beam pipes (required to minimise the cryostat dimensions), the flange connections will require particular attention.

6.7 New facilities

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 for industrial applications. This is 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 vital contribution to the development of a sustainable science.

A peculiarity of the ERL roadmap and development is that it needs operational facilities with complementary parameters and tasks to be successful. The rich global landscape of ongoing ERL facilities, including S-DALINAC and soon MESA in Europe, which are under further development, has been outlined in Section 6.5.

A crucial next step towards the application of ERLs in high-energy physics and elsewhere is to conquer the $\mathcal{O}(10\,\mathrm{MW})$ beam power regime with higher energy and/or high currents. This step requires key technology challenges to be addressed, 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 in the existing and 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), 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.

6.7.1 New facilities in the US

High energy with CEBAF 5-pass at Jefferson Lab

Based on the long experience at Jefferson Lab, a novel project has been approved, with the goal of studying an ERL at an energy, chosen to be about 7.5 GeV, where the effects of synchrotron radiation on beam dynamics will be significant. The limiting factor for ER@CEBAF with 5 passes is the arc momentum acceptance, which places a bound on the maximum energy gain one can support in the linacs. Above that energy gain, the synchrotron radiation energy losses are sufficiently large that the energy separation between accelerated and decelerated beams exceeds the momentum acceptance of the arcs. Energy recovery would be made feasible in CEBAF by the addition of two modest hardware sections: a path-length delay chicane insertion at the start of the highest-energy arc; and a low-power dump line at the end of the South Linac, before the first West spreader dipole magnet. These alterations are designed to remain in place permanently; they do not interfere with any capability of routine CEBAF 12 GeV operations. For the coming years, the project has the following plans, also in collaboration with STFC Daresbury Laboratory, University of Lancaster and University of Brussels:

1. engineering design for a half-lambda delay chicane;
2. installation of dipoles for the delay chicane and the extraction dump;
3. beam dynamics studies, including:
   - Increasing momentum acceptance through adequate choice of RF phase and arc path length;
   - Optimisation of the second-order momentum compaction in recirculating arcs to eliminate curvature from the compressed bunches without compromising beam transport for the decelerating passes.
4. finalisation of the optics design, including sextupoles.

CEBAF5 is expected to begin beam operation in 2024. For the Roadmap this experiment is of special relevance as it will reach high enough energies for the beam-based study of significant effects of CSR in an ERL.

Electron cooler at Brookhaven National Lab

The Electron-Ion Collider (EIC) is laid out as a ring-ring electron-hadron collider. Its luminosity, in order to reach $\mathcal{O}(10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1})$ at its optimum collision energy of about 100 GeV, requires that the phase-space volume of the RHIC hadron beam be reduced, for which the technique of Coherent Electron Cooling (CeC), proposed a decade ago [59], has been chosen. 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 about 100 mA electron current, i.e., an average power of 15 MW or even 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. It uses a 0.4 MeV DC gun and a single-pass ERL. Alternatively, the second CeC design is based on a plasma-cascade microbunching amplifier, which uses a 1.5 MeV DC gun and a three-pass ERL. Both CeC designs therefore require an ERL operating with parameters beyond the state of the art. This development, albeit involving more challenges than those posed by the ERLs alone, is of complementary value for other ERL developments in the chosen parameter range, i.e. 100 mA current. A decision on CeC development is foreseen as part of the CD2 project phase.

6.7.2 bERLinPro

Within the scope of the Berlin Energy Recovery Linac Project, a 50 MeV ERL facility has been set up at the Helmholtz-Zentrum Berlin. The beam transport system and all necessary technical infrastructure for 100 mA operation are complete, and the single-turn racetrack is closed and under ultra-high vacuum. In a straight continuation of the gun, the ‘diagnostics line’ offers equipment for extensive gun characterisation. The machine is built in an underground bunker, and able to handle up to 30 kW continuous beam loss at 50 MeV. An overview is shown in Fig. 6.2.

In 2022, the injection line will be supplemented with the initial mid-current SRF gun, delivering up to 10 mA with an emittance better than 1 mm mrad. The in-house cathode development successfully produces CsK_2Sb-cathodes with quantum efficiencies QE >1 %, necessary to extract 77 pC bunch charge.

Fig. 6.2: Left: The layout of bERLinPro, which is essentially complete apart from the 1.3 GHz linac module and the upgraded 100 mA gun, the main hardware elements of the Roadmap for bERLinPro. *(Image credit: Helmholtz-Zentrum Berlin für Materialien und Energie.)*
Right: View from the dump position of the injector (at the back) and first racetrack part, June 2021. *(Image credit: M. Klein, University of Liverpool.)*

Three pairs of newly developed high-power couplers were successfully tested and reached record values of 60 kW CW (administrative limit), sufficient to accelerate up to 50 mA in the booster. The assembly of the existing booster parts will take place in 2022 and commissioning of the booster is planned for 2023.

Table 6.1 specifies the existing hardware and the goal parameters of bERLinPro and compares them to the PERLE project.

The table reveals that bERLinPro is eminently suited to help take the necessary next steps towards the technological developments enabling future ERLs for HEP. The bERLinPro infrastructure with gun operation will be ready by late 2022 which is also of interest for the development of PERLE. Both facilities test current loads of order 100 mA to the cavities, which in the case of PERLE result from three-pass operation. In its final phase, PERLE will operate at ten times the energy, 500 MeV, compared to the bERLinPro facility.

It is useful for future applications and the Roadmap that the two facilities chose different gun technologies, SRF and DC photoinjectors. There is no further development activity on bright guns included in the R&D Programme because this is quite an active field worldwide, which the plans of MESA (Mainz) the Recuperator (Novosibirsk), the CeC (BNL) and cERL (KEK) also underline. bERLinPro is developing the first high-current SRF gun, while PERLE is about to re-install the ALICE DC gun with optimised cathode shape. The SRF gun technology holds the promise of simultaneously high cathode fields and injection voltage in CW operation, overcoming space charge and heat load problems. Although the RF frequencies are different in the two projects, the 50 MHz laser available at bERLinPro could provide a bunch spacing of 20 ns, which is close to the 25 ns value chosen for PERLE owing to the LHC operating frequency.

The achievable bunch charge in bERLinPro strongly depends on the QE of the photocathode. The available laser power is chosen such that 1 % QE would still be sufficient to achieve close to 100 mA at 77 pC. Successful photocathodes reach QE of 10 % and above. More research is needed to learn how to reliably preserve these high values from the production over the transport and during operation. Furthermore, Na-based photocathodes, which are less sensitive to vacuum conditions, are a promising new area of research, which could well be carried out by the HZB cathode development group. Enhanced cathode research could boost the bunch charge of the bERLinPro SRF gun towards a few hundred pC. The current gun set up allows maximum currents of 10 mA, the diagnostic line beam dump up to 30 kW. Depending on the laser repetition rate and the cathode QE, different bunch scenarios can be tested. The current limit of 10 mA is set by the fundamental power coupler.

A 1.3 GHz linac module, currently not funded, with three seven-cell cavities is expected to accel-

parameters	**bERLinPro**	**PERLE**
gun-related		
gun type	SRF photocathode	DC photocathode
cathode material	CsK_2Sb	
bunch charge [pC]	77	500
norm. emittance [mm mrad]	< 1	6
gun exit energy [MeV]	2.4	0.35
laser frequency [MHz]	50/1300	40
injector-related		
injection energy [MeV]	7	7
merger	dogleg	dogleg
RF-related		
RF frequency [MHz]	1300	801.58
bunch spacing [ns]	20 / 0.77	25
bunch frequency [MHz]	50 / 1300	40
average current [mA]	4 / 100	20
linac-related		
modules	1 x SRF	2 x SRF
duty factor	CW	CW
energy gain/linac [MeV]	43	82
no. cavities	3	4
no. cells / cavity	7	5
avg. accelerating field [MV/m]	18	20
no. of turns	1	3
final beam		
electron beam energy [MeV]	50	500
bunch length [mm]	0.6	3

Table 6.1: Comparison of parameters for bERLinPro and PERLE.

erate the bunches to 50 MeV in bERLinPro. A new design for a linac with wave-guide HOM absorbers and mechanical tuners is ready for construction. However, one may alternatively consider adapting a proven, lower-risk design (such as the Cornell linac module), incorporating beam tube absorbers to integrate fast reactive tuners, contingent upon FRT development and integration taking place in collaboration with partners such as CERN. Thus, one could rapidly gain experience with this evolving technology for a sustainable solution. Once a linac is installed, all aspects of recirculation, such as phase matching or timing and beam stability issues, essential for energy efficiency, can be studied with the 10 mA beam and different bunch charges.

In order to increase the CW current above 10 mA and up to the maximal 100 mA compatible with the 600 kW beam dump, the gun module needs to be re-equipped with a new cavity body that incorporates power-coupler ports able to accommodate the recently validated high-power coupler. The module design is already compatible with these couplers. Since the gun system is very complex, it is currently preferred to assemble an independent second module with an existing cold string, which will mitigate risk and enable maximal progress through this parallel development. At present, the booster couplers are suited to minimise the reflected power at about 10 mA. To operate the booster at 100 mA, the booster module

Topic/Goal	Action required	Minimum Effort	Delta for Optimum Effort
Gun			
Commissioning of the SRF gun and the diagnostic line with 10 mA and an emittance $<$ 1 mm mrad.		Baseline activity	One FTE for commissioning
Cathode research: QE preserving transport optimisation		Baseline activity	
Cathode research: development of Na-based cathodes for reduced vacuum sensitivity		Dispenser material for Na-based cathodes	
Bunch charge: test of high bunch charges with a current limit of $\sim$ 3.85 mA, depending on cathode QE		Dispenser material for additional cathodes beyond bERLinPro program	
Commissioning of the booster and beam transport through injector and low energy path, no linac			One FTE for commissioning (see entry first row)
High current: the current limit is set by the high power coupler. With an adapted cavity, the gun module could produce 100 mA of current	Construct and build the cavity, change coupler setting in booster for high current (dismantling of booster module)	Cavity body, two additional Canon-Toshiba coupler	Second module for high current, enabling operation and module preparation in parallel, (cold string exists), one gun cavity plus backup cavities, solenoid, four additional Canon-Toshiba coupler, one construction engineer
Linac			
Linac with FRT (to dump): adapt linac design to FRT	Construct, order, assembly and commissioning	Complete linac module	Linac and operational costs plus spare cavities + one SRF engineer
50 MeV ERL operation: beyond-basic diagnostic in recirculator	Order, assembly and commissioning of diagnostics	Additional electronics for diagnostics systems	
Theoretical studies			
ERL operation with HEP parameters	Study optimal beam transport for higher charges	PhD or postdoc	

Table 6.2: Goals achievable at bERLinPro with respect to technology developments needed for HEP ERLs, along with the estimated required effort. Empty boxes correspond to topics already being worked on at HZB without external funding.

would require a reassembly without coupler spacers to increase the coupling.

Table 6.2 summarises the necessary topics and goals where bERLinPro could efficiently contribute directly to the tasks at hand for HEP-ERL development. The total effort is estimated to require about 8.4 MCHF, and 33 FTEy, see below.

6.7.3 PERLE

6.7.3.1 Introduction

PERLE, a Powerful Energy Recovery Linac for Experiments [2], emerged from the design of the Large Hadron Electron Collider as a three-turn racetrack configuration with a linac in each straight. With its three turns, 20 mA current leading to 120 mA cavity load, 802 MHz frequency, and 500 MeV energy,

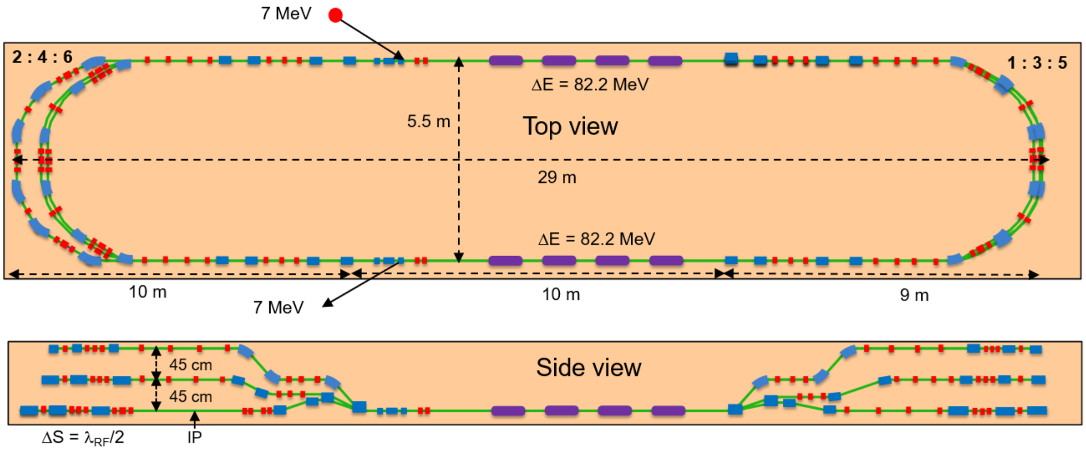

Fig. 6.3: Top and side views of the PERLE facility at IJCLab Orsay. An electron energy of 500 MeV is achieved in three turns passing through two cryomodules, each housing four 5-cell cavities of 802 MHz frequency. PERLE will be built in two stages, first with one linac cryomodule, adapted from the SPL module, and then completed with a newly designed one. The total number of magnets, including arcs, switchyards, merger and experiments, is 84 dipoles, 33 or 66 cm long, of typically 0.5 to 1.0 T bend and 118 quadrupoles, 10 to 15 cm long, with fields of 0.4 to 5.5 kG/cm.

PERLE is the ideal next-generation ERL facility with which a new generation of HEP colliders can be prepared, the 10 MW power regime be studied and novel low-energy experiments at high intensity be pursued. Its principles were published first at the IPAC conference 2014 [60] and a CDR appeared in 2017 [61]. Following several years of organisation, development, and review, a default footprint of the facility has been chosen, see Fig. 6.3, which fits into a large, free experimental hall at IJCLab Orsay.

PERLE has now been established as a Collaboration of Institutes with significant experience on ERL, SRF, and magnet technology as well as operation. The facility will be hosted by Irène Joliot Curie Laboratory at Orsay, and be built by a collaboration of BINP Novosibirsk, CERN, University of Cornell, IJClab Orsay, Jefferson Lab Newport News, University of Liverpool and STFC Daresbury including the Cockcroft Institute, with others expressing interest. Recently, an ambitious plan was endorsed aiming for first PERLE beam operation, with initially one linac, in the mid twenties. This is not impossible as the Collaboration intends to use the ALICE gun, the JLab/AES booster, and the SPL [62] cryomodules as available key components for an early start, but the bulk of funding is yet to be realised.

6.7.3.2 Description

Following detailed simulations over three years and an international review at the end of 2020, the PERLE injector has been tentatively designed. The final goal of 20 mA current corresponds to 500 pC bunch charge at 40 MHz frequency as prescribed by the LHC. Delivery of such high-charge electron bunches into the main loop of an ERL is challenging as the emittance, required to be below 6 mm mrad, has to be preserved. The beam dynamics were simulated using the code OPAL and optimised using a genetic algorithm, and a three-dipole solution was chosen for the merger. Table 6.3 shows the requirements on the beam at the exit of the main linac after the first pass. For achieving such low emittance at high average current, a DC-gun-based injector will be used, re-installing the ALICE gun delivered from Daresbury to Orsay. The complete injector will consist of a 350 kV photocathode electron gun, a pair of solenoids for transverse beam size control and emittance compensation, an 801.58 MHz buncher cavity, a booster linac consisting of four single cell 801.58 MHz SRF cavities, and the merger, Twiss-matched to the loop optics, to transport the beam into the main ERL loop.

A summary of the PERLE design parameters is presented in Table 6.4. The bunch spacing in the

Table 6.3: PERLE injector specification

Parameter	Unit	Value
Bunch charge	pC	500
Emittance	mm mrad	< 6
Total injection energy	MeV/c	7
First arc energy	MeV	89
RMS bunch length	mm	3
Maximum RMS transverse beam size	mm	6
Twiss β at 1st main linac pass exit	m	8.6
Twiss α at 1st main linac pass exit		–0.66

Table 6.4: PERLE Beam Parameters

Parameter	unit	value
Injection beam 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	24.95
RF frequency	MHz	801.58
Duty factor		CW

ERL is assumed to be 25 ns; however, empty bunches might be required in the ERL for ion clearing gaps. PERLE will study important ERL accelerator characteristics such as: CW operation; handling a high average beam current; low delivered beam-energy spread and low delivered beam emittance.

The linac optics design minimises the effect of wakefields such that the beta function is minimised at low energy. The ERL is operated on crest in order to benefit from the maximum voltage available in the cavity. The spreaders/recombiners connect the linac structures to the arcs and route the electron bunches according to their energies. The design is a two-step achromatic vertical deflection system and features a specific magnet design in order to gain in compactness.

The three arcs on either side of the linacs are vertically stacked and composed of six dipoles instead of four dipoles with respect to the previous design [61], reducing the effects of CSR. Moreover, the arc lattice is based on flexible-momentum-compaction optics such that the momentum-compaction factor can be minimised but also adjusted if needed. The low energy means that the energy spread and emittance growth due to incoherent synchrotron radiation is negligible in the arcs.

The ERL lattice design provides a pair of low-beta insertions for experimental purposes, and the multi-pass optics optimisation gives a perfect transmission with the front-to-end tracking results including CSR. Multi-bunch tracking has shown that instabilities from HOM can be damped with frequency detuning. The optimal bunch recombination pattern gives some constraints on the length of the arcs. Furthermore, the arc with the low-beta insertions will provide the necessary shift to the decelerating phase in the RF cavities. There are two chicanes in the lattice, located at the entrance of a linac and symmetrically at the exit of the other linac structure. They are needed to allow injection and extraction through a constant field. PERLE has two linacs and three passes, which leads to a six-fold increase and subsequent decrease of the beam energy.

6.7.3.3 Prospects

PERLE will serve as a hub for the validation and exploration of a broad range of accelerator phenomena in an unexplored operational power regime. A vigorous R&D program is currently being pursued to develop a Technical Design Report for PERLE at Orsay by the end of 2022. To achieve this goal, the following sequence of accelerator design studies and hardware developments has been identified:

- start-to-end simulation with synchrotron radiation, CSR micro-bunching;
- multi-pass wake-field effects, BBU studies;
- injection line/chicane design including space-charge studies at injection;
- HOM design and tests of a dressed cavity;
- bCOM Magnet Prototype;
- preparation of ALICE gun installation at Orsay;
- design of PERLE diagnostics;
- preparation of facility infrastructure.

The collaboration is aiming for the first beam at PERLE by the mid-twenties. Important milestones will be the delivery and equipment of the JLab/AES booster cryostat to Orsay and the production and test of the complete linac cavity-cryomodule, as the first linac for PERLE and the 802 MHz cryomodule demonstrator as part of the FCC-ee feasibility project. It is considered very desirable to integrate FRT microphonics control into this design. Further details on the current design of PERLE can be found in Ref. [63].

The multi-turn, high-current, small-emittance configuration and the timeline of PERLE make it a central part of the roadmap for the development of energy-recovery linacs, which has attracted experienced partners from outside Europe. PERLE includes two important goals for completion beyond the first five years of the roadmap: a) the preparation of two experiments on exotic isotope spectroscopy and possibly inverse photon scattering physics or/and ep scattering for proton radius, dark photon, or electroweak measurements (for which a polarised gun would be required), and b) the mid-term development of a first warm 802 MHz cavity-cryomodule as described above.

The total effort for the 250 MeV PERLE, based on essential in-kind deliveries (gun, booster and one linac cryomodule), is estimated to require about 14.6 MCHF for the period 2022–2025, and another 9.5 MCHF for the following phase (2026–2030). This includes IJCLab infrastructure contributions roughly valued at 10 MCHF besides considerable technical and personnel effort.

6.7.4 Long-term European ERL facility considerations

The future beyond 2030 is difficult to predict. It depends to a considerable extent on the realisation of the program of this decade. Operation of a 10 MW ERL facility has not been achieved so far, neither has the 100 mA challenge been met in a superconducting ERL machine. MESA can be expected to pursue its experimental program for a decade starting in 2024. bERLinPro will likely perform an in-depth study of 100 mA beam operation characteristics and new avenues will open up for such a unique facility. PERLE will be complete as a 500 MeV machine at the end of the twenties and enter a phase of R&D and physics exploitation. Globally the field will advance leading to a new level of cooperation which may be focussed through the demands of energy frontier colliders and sustainability. The 4.4 K program may bear fruit and change the landscape of energy recovery linacs and related SRF technology considerably. Next generation electron-hadron and electron-positron colliders may be based on ERLs and be built. Any major ERL application in industry would change the field substantially.

There are discussions and initial studies around the following generation of lower-energy European ERL facilities in Germany, France and the UK, all of which may also be important in technological support for particle physics in the longer term.

The TU Darmstadt (Germany) is currently considering to establish a Darmstadt Individually-reCirculating ERL (DICE) facility as a further investment into the international FAIR facility at Darmstadt, for enabling electron scattering on stored radioactive ion beams at FAIR with very high luminosity. DICE would represent a full-scale electron-ion collider based on ERL technology.

GANIL (Grand Accélérateur National d'Ions Lourds in Caen, France) is preparing the future with innovative projects and an electron-radioactive ions collider is one of the main options. In this scenario, PERLE is considered as a first step towards an even more powerful machine at GANIL in the mid thirties.

The UK is in the process of considering the science case for a domestic XFEL facility. In addition, a possibility of a facility comprising an ERL driving a mono-energetic photon source via inverse Compton scattering, called DIANA, is being investigated for both academic and industrial nuclear research. Depending on the UK XFEL science case requirements, options based on DIANA and other ERL developments elsewhere may open up a possibility to deliver a challenging and sustainable ERL based option for XFEL facility.

Part of the exploratory work for all these machines is in assessing how best to harmonise technical components, e.g. SRF systems & injectors with other global ERL developments. In this regard, PERLE has a central role for it shows an efficient (multi) path to the 1 GeV electron energy range, with the hope of further increased currents and lowered emittances.

6.8 Delivery plan

The ERL roadmap for this decade comprises three interlinked elements.

1. The continuation and development of the various facility programs, summarised in Section 6.5, for which no funds are needed from the particle physics field. For Europe these are S-DALINAC in Darmstadt and MESA in Mainz (both in Germany).
2. A number of key technologies to be developed as characterised in Section 6.6. Some of these, such as electron sources of high brightness (reaching the 100 mA electron current regime), FRTs and, for longer term, the development of an 802 MHz, 4.4 K cavity-cryomodule have been integrated in the plans for bERLinPro and PERLE as all require beam operation [9]. Two other, aspirational items of strategic importance deserve separate support and are included here: HOM damping at high temperature; and the development of twin cavities.
3. The timely upgrade of bERLinPro and built of PERLE at Orsay as the necessary steps to move ERLs forward to their introduction to collider developments, possibly mid-term and long-term.

This regards electron-hadron, electron-positron and maybe muon collider developments as explained above. Ahead is a new era of high power ERL operation R&D, high-intensity low-energy experiments, and industrial applications. An overview on the R&D program and its duration is given in Fig. 6.4. It includes the facilities bERLinPro and PERLE together with three key R&D items. The sections below give indicative R&D timelines for: HOM at high temperature; twin cavities; bERLinPro and PERLE; and novel beam diagnostics. Further details in each case can be found in the ERL long write-up [3].

6.8.1 Higher-order mode damping at high temperature

ERL.RD.HOM: Dynamic higher-order mode losses scale proportional to the beam intensity squared and to the number of cavities, which for ERLC reaches about 10^4. This dynamic load leads to a heat transfer related to a power 'amplification' factor $\propto T/(300\,\mathrm{K} - T)$. The power requirement for compensating dynamic HOM losses is therefore the smaller the higher the temperature T is, as has been sketched in

[9]Basic diffusion and sputtering 4.4 K technology developments are covered in the RF R&D Programme.

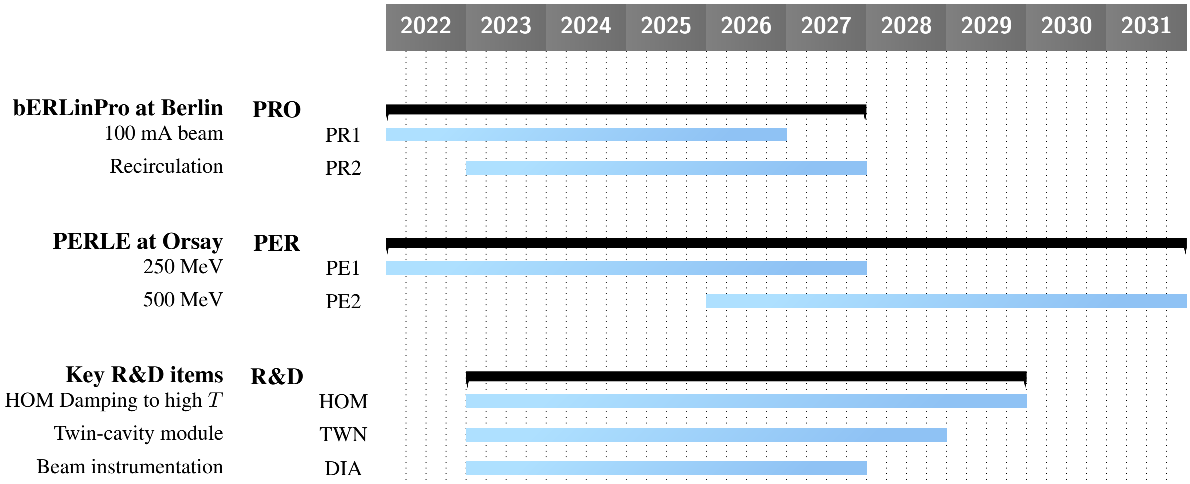

Fig. 6.4: Time lines of the key ERL roadmap themes.

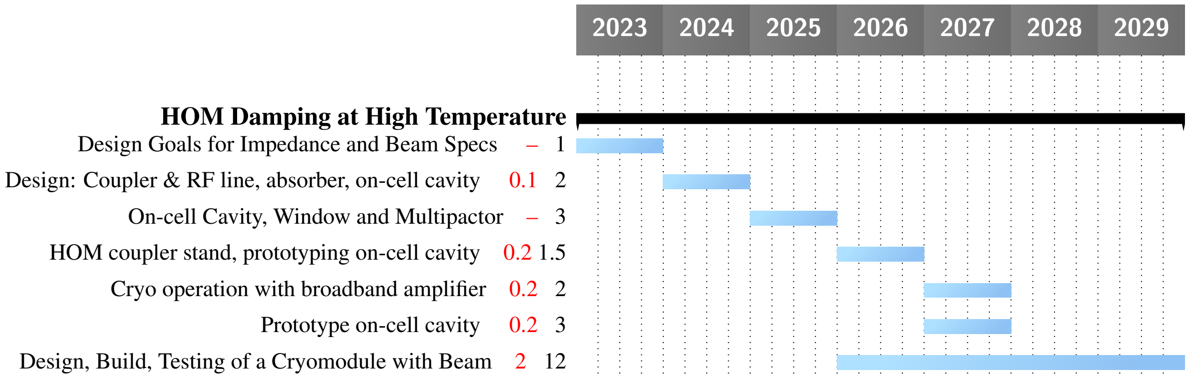

Fig. 6.5: ERL.RD.HOM: Development of HOM damping technology for high temperature. Resources required are 2.7 MCHF (red) over six years plus 24.5 FTEy years (black).

the key technology Section 6.6. Figure 6.5 summarises the sequence of steps and estimated effort for developing this area further.

6.8.2 Dual-axis cavity developments

ERL.RD.TWN: Twin-axis cavities are required when the accelerating and decelerating beams are traveling in opposite directions through long linacs. Initial developments have been made at JLab and the John Adams Institute a few years ago. For cost efficiency of a new generation e^+e^- linac, availability of high-Q_0 twin cavities is considered to be an important economy factor. The roadmap thus includes the design and production of a multi-cell twin cavity followed by a complete cryomodule. Figure 6.6 shows a possible timeline.

6.8.3 High-current operation and diagnostics

ERL.RD.DIA: ERLs have specific diagnostics needs because of the large beam power, the small emittance that is to be preserved, and the low beam loading that needs to be maintained in the main linac cavities. 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

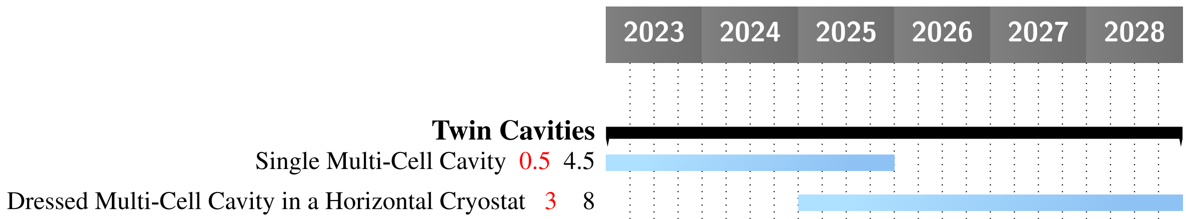

Fig. 6.6: ERL.RD.TWN: Development of dual-axis cavity and cryomodule technology. Resources required are 3.5 MCHF (red) over six years plus 12.5 FTEy (black).

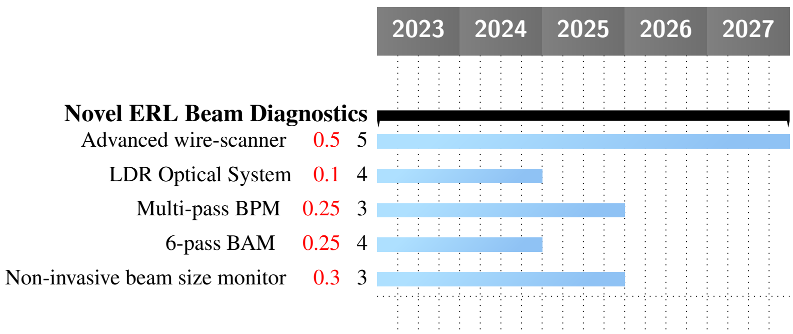

Fig. 6.7: ERL.RD.DIA: Development plan for high-current ERL beam diagnostics. Resources required are 1.4 MCHF (red) plus 19 FTEy (black).

monitors along both sides of the beam pipe in CBETA, solutions for larger beam powers still have to be developed. A work plan is shown in Fig. 6.7.

6.8.4 bERLinPro

The facility bERLinPro has been recognised as the most suitable ERL accelerator to achieve 100 mA electron beam current over the next few years. All ERL-based HEP collider concepts, past or recent, aim to reach high luminosity through such high intensity. For this goal to be achieved, bERLinPro requires two steps leading beyond their default 10 mA study.

1. **ERL.PRO.PR1**: Build and install a new 100 mA SRF gun, essentially a development based on the existing gun.
2. **ERL.PRO.PR2**: Introduce a new 1.3 GHz linac module into the completed racetrack, equipped with FRTs in order to study their effect in single-pass ERL beam operation.

This program will lead to further collaboration with other Helmholtz centers such as Rossendorf and with CERN. It will also help establishing more intimate connections to MESA or S-DALINAC in Germany and be supportive to the development of PERLE as outlined in Section 6.7. Figure 6.8 shows a timeline for the two steps.

6.8.5 PERLE

ERL.PER: The novel high-energy ERL concepts targeted at energy-frontier electron-hadron, electron-positron and electron-photon colliders, as well as further physics and other applications, require the development of high-brightness electron guns and dedicated SRF technology as prime R&D objectives. Moreover, “it needs a facility comprising all essential features simultaneously: high current, multi-pass, optimised cavities and cryomodules, and a physics-quality beam eventually for experiments” (Bob Rimmer in Ref. [3]). PERLE has been founded as a collaboration to explore the 10 MW regime with a

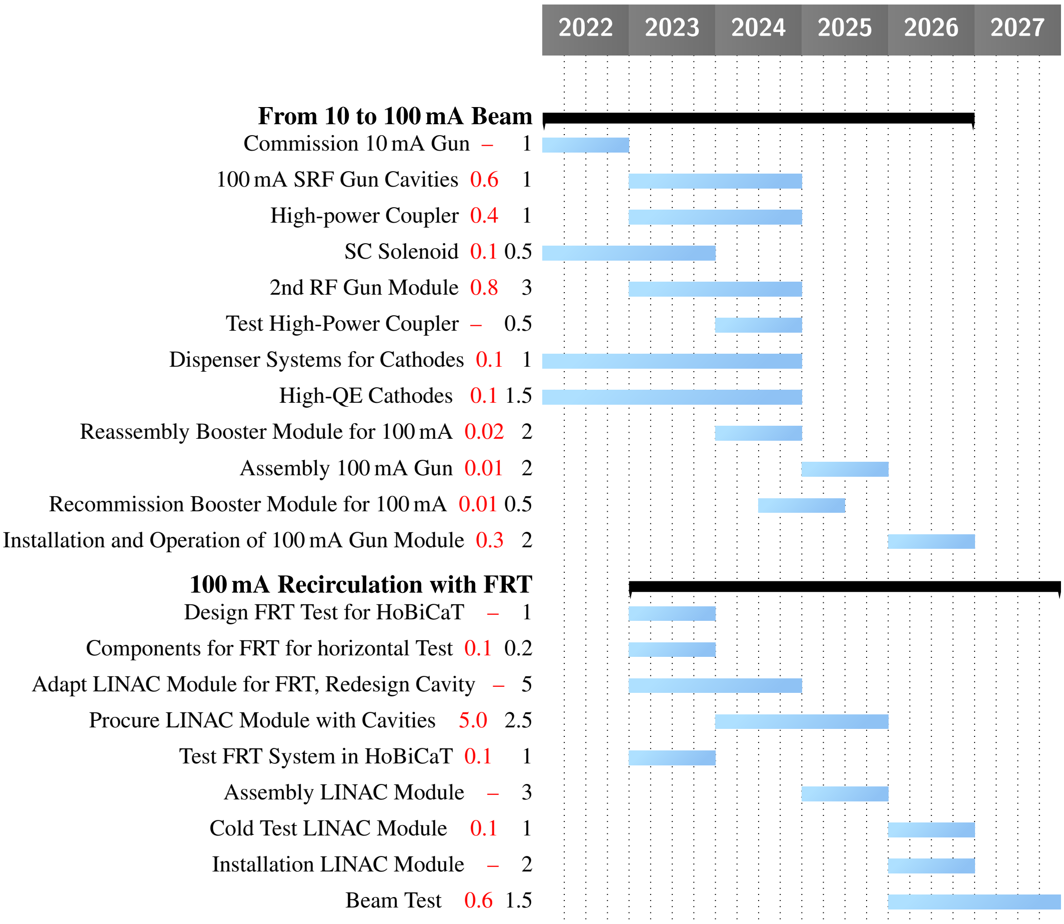

Fig. 6.8: Top: upgrade of bERLinPro to 100 mA electron current operation (**ERL.PRO.PR1**). Resources required are 2.4 MCHF (red) plus 16 FTEy (black). Bottom: completion of bERLinPro with a 1.3 GHz cavity-cryomodule in the beam **ERL.PRO.PR2**. Resources required are 5.9 MCHF (red) plus 17 FTEy (black).

three-pass ERL facility based on 802 MHz SRF technology. It will be hosted by IJCLab Orsay and be built in two stages, initially installing one linac module (250 MeV) and then a second module (500 MeV stage). Its main components are a DC photocathode gun based on ALICE to reach 20 mA, a classic booster using the JLab/AES booster cryomodule, a linac cryomodule, using the SPL module provided by CERN, housing four five-cell niobium cavities, and three return arcs, spreaders and combiners built by roughly 200 short dipoles and quadrupoles, etc. Phase B may possibly add a polarised 20 mA gun and test a 4.4 K 802 MHz cryomodule in the PERLE accelerator, subject to progress on the relevant technology developments. The main task of PERLE is to demonstrate high-current multi-turn operation, later for experiments, and to develop 802 MHz technology for future colliders, and as part of the FCC-ee feasibility study. A timeline is shown in Figs. 6.9 (**ERL.PER.PE1**) and 6.10 (**ERL.PER.PE2**).

6.8.6 Investment required

The total investment corresponding to the full scope of this roadmap is approximately 40.0 MCHF over ten years. Of this total, the cost of bERLinPro and PERLE 250 MeV are 8.3 MCHF and 14.6 MCHF respectively over the coming five years. Figure 6.11 displays the spending profile. A substantial further part of the ERL programme is covered by the existing or forthcoming facilities and their existing plans. The investments for 4.4 K basic technology developments such as sputtering and infusion are covered by the RF R&D Programme. Until and including the year 2026, a total of 29.6 MCHF is required,

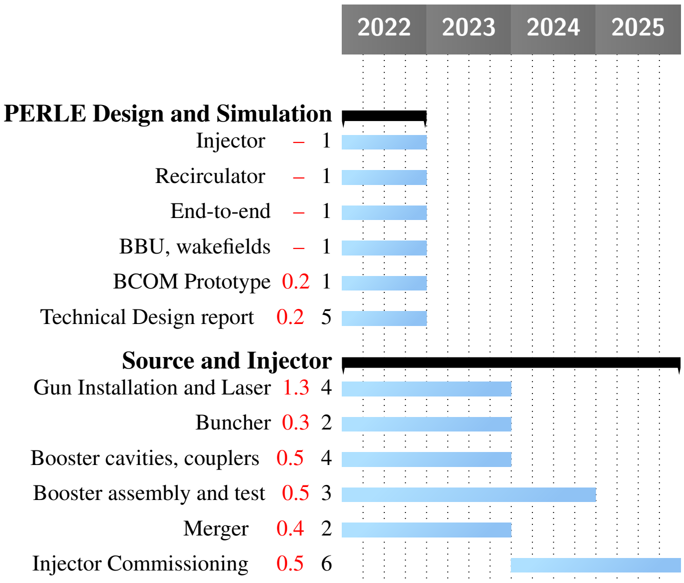

Fig. 6.9: The path to the PERLE technical design report and commissioning of the injector. Resources required are 3.9 MCHF (red), 31 FTEy (black).

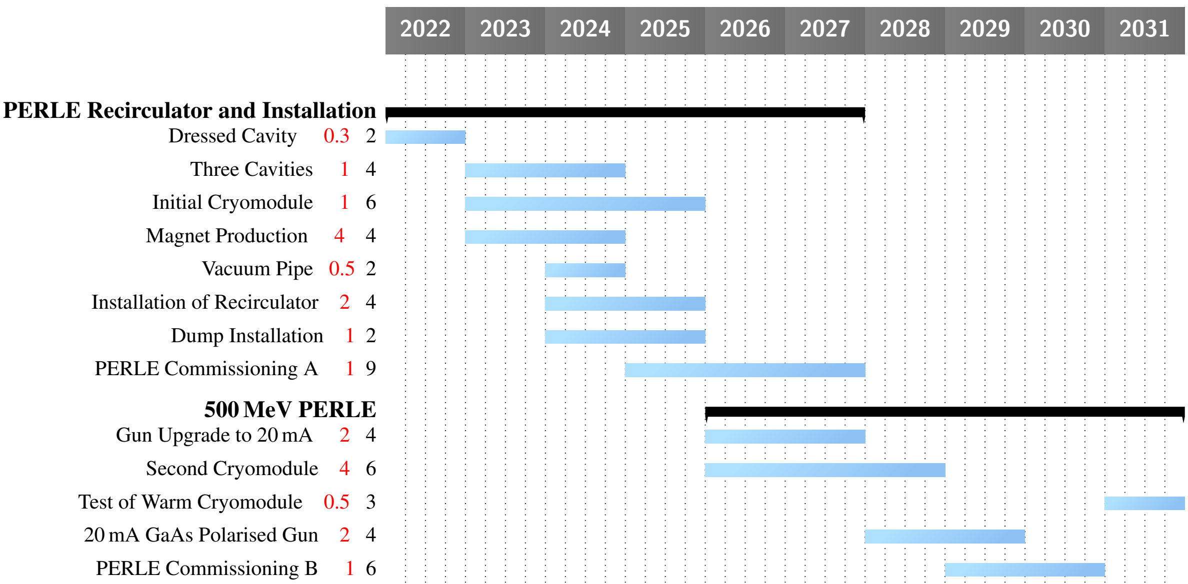

Fig. 6.10: PERLE completion in two steps: The 250 MeV phase with beam in the mid-twenties (**ERL.PER.PE1**); and the 500 MeV stage towards the end of the decade (**ERL.PER.PE2**). Resources for the first part, including funding of the TDR and injector phase: 14.6 MCHF (red), 64 FTEy (black). Resources for the 500 MeV stage: 9.5 MCHF, 23 FTEy.

comprising 13.9 MCHF for PERLE, 7.4 MCHF for bERLinPro and 7.6 MCHF for R&D. The funding profile peaks for both facilities in 2024 due to the ambitious schedule developed for providing high current ERL operation evidence in the mid twenties, around the time of the next ESPPU.

An alternative option is the pursuit of a lower-cost ‘minimal’ programme, which represents sufficient resources to maintain momentum in developments and exploit to some extent the ongoing investments in facilities. This would descope some of the key technology developments (**ERL.RD.HOM** and **ERL.RD.TWN**), resulting in a overall slower rate of progress, and a more restricted evidence base accumulated by the next ESPPU of the potential applicability of ERL techniques, not only to far-future machines, but also to near-future ones.

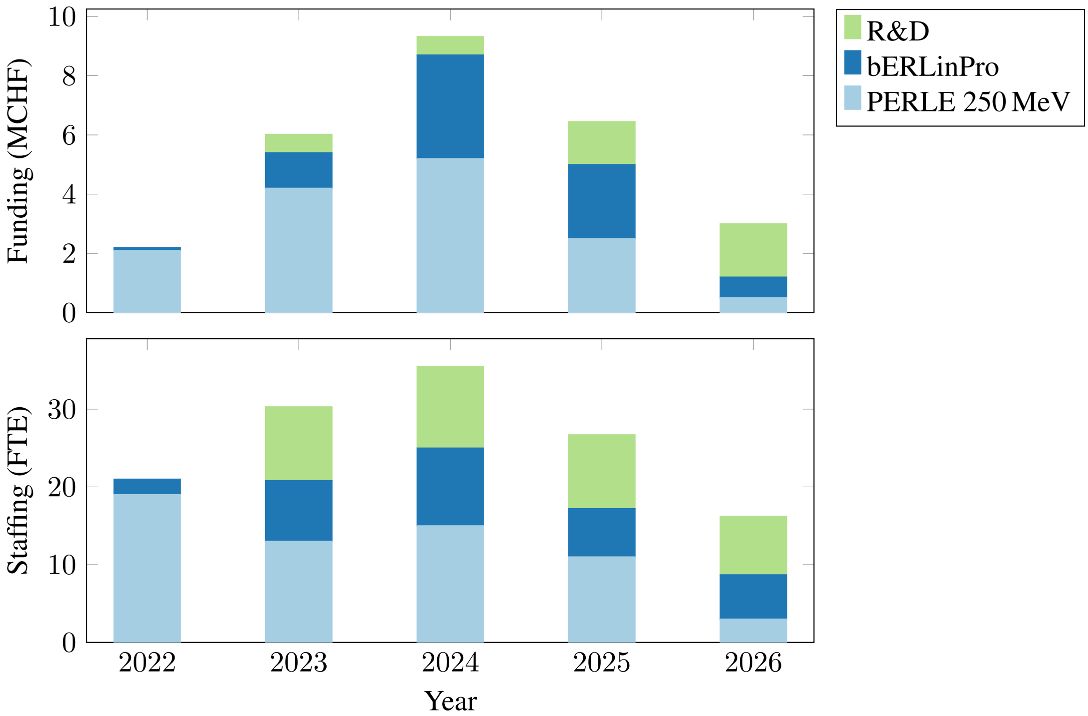

Fig. 6.11: ERL funding and effort roadmap profile for the next five years, split into its three main contributions, PERLE at 250 MeV, bERLinPro and the key R&D items (HOM, TWN and DIA): top: annual spending in MCHF; bottom: effort in FTE years, not counting provision of effort by the host laboratories and some of their partners.

6.9 Collaboration and organisation

The development and application of ERL technology has been a global international effort. A combination of generic R&D efforts in various laboratories with complete ERL facilities in the US, Russia, Japan and Europe, as described above, has advanced the field so much that one can now consider its application to energy-frontier particle physics in various types of colliders involving electron beams.

The panel is convinced that pursuing the three interlinked components of the ERL R&D Programme will allow major advances, not least since they enable a new generation of low-energy experiments, are development technologies of relevance for future HEP colliders, and promise striking applications for industry and related science developments. Implementation of such a program, in Europe and on a global scale, would much profit from a closer world-wide coordination and intensified exchange of personnel, technology and experience.

The success of this coordinated approach, and the ERL field in general, will rely both on the engagement of the community and the level of material support from major laboratories. This should include CERN participation, in concern with the efforts being made in other laboratories around existing and future facilities. As these develop, the tendency towards stronger collaboration of interested partners, around both the facilities and and underlying technology developments, is evident. PERLE is the first large institutional collaboration for building and operating an ERL facility. Its success will rely on the intellectual, technical, and financial contributions of the collaborating partner institutes, built around given the clear decision of IN2P3 and its Irène Joliot Curie Laboratory to realise this machine soon. PERLE comprises accelerator, particle and nuclear physicists, and its collaboration structure is emerging as a balance between the particle physics experiment collaboration model and a host-facility-oriented one.

Globally, ERL experts meet in accelerator conferences such as IPAC and have an annual dedicated ERL workshop, from Berlin 2019 to Cornell 2022, currently interrupted by the pandemic. They have been in close contact and jointly been working on facilities and projects, as, for example, the recent commissioning of the CBETA facility has demonstrated.

The next step of this roadmap development will be its implementation, subject to acceptance by the community at large. This will give time, in a further consultation process, to develop an appropriate organisation of ERL developments, recognising and possibly combining local, regional and continental capacities and interest with the achievement of midterm and further-future goals as we tried to described here. ERLs are one of the few routes for true innovation in future accelerators. Their potential impact on both particle physics and in other areas is substantial, and we anticipate that this will attract the interest and efforts of a continously-increasing fraction of the community.

6.10 Conclusion

ERLs have come a long way from the initial Maury Tigner sketches. Machines have been designed, constructed and exceeded their specifications. This is no longer a niche technology; rather, it is ready to be a solid basis for future e^+e^- and e-h colliders.

The European ERL roadmap that has been developed here is embedded in global efforts to develop energy-recovery linacs, and it is tightly focused on achievable deliverables, with each activity leading to the next. It shows how the diagnostics and tuner R&D feeds into bERLinPro and then PERLE, and that these advances make an LHeC a demonstrably viable opportunity for CERN, with electrons from a 50 GeV ERL colliding with the HL-LHC and/or the High-Energy LHC (HE-LHC). This could also lead to electron-hadron collisions in the FCC-eh with an even greater energy reach. These opportunities are relatively low-cost additions to the planned CERN program, each with a huge potential for physics advances.

The R&D on 4.4 K cavities developed in the RF R&D Programme feed into cryomodules which can provide energy-efficient HOM damping. Together with twin cavity development, this would provide an opportunity to develop a 500 GeV collision energy, $10^{36}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ luminosity Double Higgs Factory, of modest power consumption, as a possible upgrade to either FCC-ee or ILC, or even as a stand-alone facility. This is a prospect that was not considered in the 2020 ESPPU, but which, if the ERL development programme proceeds optimally, may be a serious consideration in the future.

The development of cryomodules operating at 4.4 K would enable universities and small research laboratories to utilise the advantages of high-power CW electron beams for a variety of research activities. This would provide a user base for cryomodules, which would enable industries producing cryomodules to thrive, benefiting particle physics and related fields.

The cost of the new investments requested is about 6 MCHF annually for the next five years, with a substantial potential return on investment made possible by exploiting existing infrastructure. An overview of the proposed R&D programme is provided in Table 6.5. A vision towards high-energy frontier colliders, which would be enabled by the R&D developments here described, is displayed in Fig. 6.12.

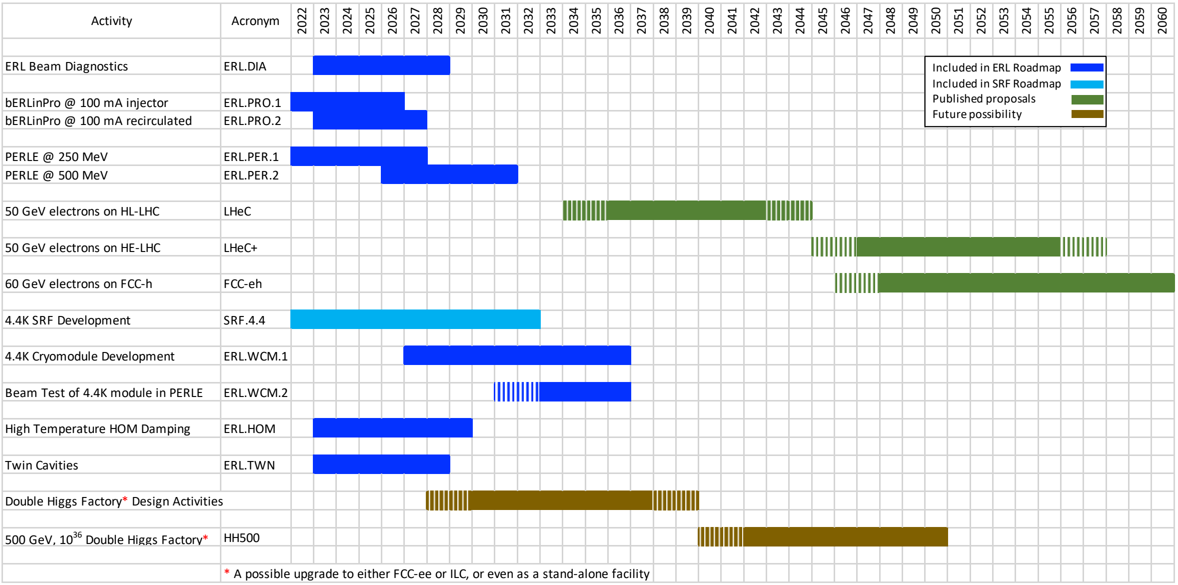

Fig. 6.12: Long-term vision for the ERL Roadmap showing how the activities in the next five to ten years lead to multiple options for future HEP Colliders.

Unprecedentedly high beam intensities open new fields of low energy physics such as nuclear photonics, elastic ep scattering, dark photon searches and exotic isotope spectroscopy. This technology also has a significant future in other fields such as FELs, EUV Lithography, Inverse Compton Scattering, etc. ERL technology is inherently energy-sustainable, which will be an important requirement for all future accelerator projects. As an innovative field, it is bound to attract new generations of accelerator physicists and engineers.

Table 6.5: Total effort for the R&D program on energy recovery linacs as presented in this roadmap, providing the total number of FTE years and MCHF for the duration as indicated. More detailed information is provided with the charts for all topics as presented above. The table does not include in-kind and infrastructure contributions nor further investments in ongoing facilities.

Label		Description	FTEy	MCHF	Start	End
ERL.RD	sum	Key R&D Items	57	7.6	2023	2029
	HOM	Damping to high T	24.5	2.7	2023	2029
	TWN	Twin cavity module	13.5	3.5	2023	2028
	DIA	Beam instrumentation	19	1.4	2023	2027
ERL.PRO	sum	bERLinPro at Berlin	33	8.3	2022	2027
	PR1	100mA beam	16	2.4	2022	2026
	PR2	Recirculation	17	5.9	2023	2027
ERL.PER	sum	PERLE at Orsay	87	24.1	2022	2031
	PE1	250 MeV	64	14.6	2022	2027
	PE2	500 MeV	23	9.5	2026	2031

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