ERL Panel Progress

News

Interim Report

For the Future (Nikolay)

e^+e^- Sub-Panel (Andrew)

aob

Max Klein, Andrew Hutton

ERL Panel Meeting, 15 July 2021

News

Andrew – thanks for the PP Symposium Panel Talk, very well received. Thank you to some of you for joining.
Surprised about muon collider operation 2038+ and buying land remark
Dave: propose ‘ambitioius but realistic objectives’, exploitation of demonstrators, sustainability, look sideways..

Subpanel continues with weekly meetings, yesterday 1h talk by Valery Telnov “progress needs phantasy”

MK with Frank Gerigk: confirms interest in FRT application for bERLinPRO (1.3GHz) and PERLE (802 MHz)

Invited to a next LDG Meeting 19.7. to report progress ..

EPS conference end of July

The Development of Energy Recovery Linacs

Interim Report for the LDG

The ERL Panel

Deepa Angal-Kalinin (STFC Daresbury), Kurt Aulenbacher (Mainz), Alex Bogacz (Jlab), Georg Hoffstatter (Cornell/BNL), Andrew Hutton (Co-Chair, Jlab), Erk Jensen (CERN), Walid Kaabi (IJCLab Orsay), Max Klein (Chair, Liverpool), Bettina Kuske (HZB Berlin), Frank Marhauser (Jlab), Dmitry Kayran (BNL), Jens Knobloch (HZB Berlin), Olga Tanaka (KEK), Norbert Pietralla (TU Darmstadt), Cristina Vaccarezza (INFN Frascati), Nikolay Vinokurov (BINP Novosibirsk), Peter Williams (STFC Daresbury), Frank Zimmermann (CERN)

1 Executive summary of findings to date

The panel has drafted a long write-up, as an introduction to "The Development of Energy Recovery Linacs" [1], held an ERL Symposium, evaluates recent electron-positron collider ERL concepts and moves towards the development of a Roadmap on ERLs to serve the future of colliders, but as well that of low energy particle and nuclear physics. The fundamental principles of ERLs have been successfully demonstrated, not just once, but across the globe. There can no longer be any doubt that an ERL can be built and achieve its goals. A next step promises a luminosity increase for physics applications by orders of magnitude, at a power consumption comparable to classic, low luminosity solutions, which is a necessary step towards the sustainability of high energy physics, as interaction cross sections fall with rising energy. ERLs are also near utilisation in several industrial and other applications.

The novel high energy ERL concepts, for energy frontier electron-hadron, electron-positron and electron-photon colliders, require the development of intense 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 cryo-modules and a physics quality beam eventually for experiments" (Bob Rimmer at the ERL Symposium).

Europe's next endeavours are MESA at Mainz, a polarised beam facility for experiments, bERLinPRO with the potential to reach 100 mA, and a dedicated high-current, multi-turn facility developed by a large international collaboration at Orsay (PERLE). Moderate investments, compared to other accelerator R&D projects, will be required to have this programme adequately supported, while ERLs globally deserve cooperation and coordination as with developments of high current ERL facilities at BNL, BINP and KEK, with the high energy experiment at CEBAF as well as of plans for next generation facilities. High current ERL operation causes major challenges, like beam breakup instabilities or RF transients, requiring collaborative efforts across the various facilities. Synergies exist with other areas such as the FCC-ee, the muon collider or possibly the plasma wakefield developments which ought to be considered.

In summary, the panel notes with much interest that the ERL technology is close to its high current and 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, at a time where caring for energy resource is a prime necessity for this planet, not least big science. ERLs are therefore primed for inclusion among the grand visions our field has been generating, and for dedication of adequate support to it for this unique potential to bear fruit.

This is what Council etc may read

2 Motivation

2.1 Sustainability

Energy Efficiency and sustainability have received a lot of attention over recent years. The concerns about climate change and global warming have to be taken especially seriously, also by the accelerator community. To quote F. Bordry (Talk at PSI 11/2019): "There will be no future large-scale science project without an energy management component, an incentive for energy efficiency and energy recovery among the major objectives." It is a prime goal for the panel to evaluate the power economy of ERLs and to emphasise techniques, such as Fast Reactive Tuners, directed to further minimise the use of power. The accelerator community drives research and development at the cutting edge of technology for a greater purpose than just making the next accelerator better: Society expects a return from the investment in this research, which includes other applications of accelerators and further spin-offs.

2.2 Accelerator Development

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

Energy Recovery is at the threshold to become a major means for the advancement of accelerators. Recycling the kinetic energy of a used beam for accelerating a newly injected beam, i.e. reducing the power consumption, utilising the high injector brightness and dumping at injection energy - these are the key elements of a novel accelerator concept, invented half a century ago [2]. The potential of this technique may indeed be compared with the finest innovations of accelerator technology such as by Wideroe, Lawrence, Veksler, Kerst, van der Meer and others during the past century. Innovations of such depth are rare and their impact only approximately predictable.

2.3 ERL based Physics Prospects

ERLs provide a maximum luminosity through a high brightness source, and high energy through high power which is recovered in the deceleration of a used beam. It is most remarkable, that following the LHeC design from 2012 [3] (updated in 2020 [4]), all these avenues have been followed: for $\gamma\gamma$ collisions [5], further for eh with the FCC-eh in 2018 [6], for e^+e^- in 2019 (an ERL concept for FCC-ee termed CERC [7]) and in 2021 (an ERL version of the ILC termed ERLC [8]) and very recently a concept for the generation of muon pairs through high energy and current $e\gamma$ collisions [9]. A common task for these colliders are precision SM Higgs boson measurements dealing with a small cross section (of 0.2/1 pb in charged currents at LHeC/FCC-eh and similarly of 0.3 pb in Z-Higgsstrahlung at e^+e^-). This makes maximising the luminosity a necessity to profit from the clean experimental conditions and to access rare decay channels while limiting power. High luminosity and energy are expected to lead beyond the Standard Model and essential for precision measurements at corners of phase space.

At low energies, the luminosity is similarly crucial for several physics applications, such as polarised ep scattering for weak interactions, elastic form-factor measurements or dark-photon searches as are planned for MESA and had been pursued at Jlab. Very high ERL intensity may permit to use internal targets which avoids external target acceptance uncertainties. In backscattered photon scattering, the luminosity available exceeds that of ELI by few orders of magnitude paving the way to nuclear photonics, comparable with the appearance of lasers in the sixties. A further fundamental interest regards the exploration of unstable nuclear matters with intense electron beams of O(500) MeV energy as is characteristic for PERLE and envisaged for GANIL in France. This follows 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".

2.4 Industrial and other Applications

The range of further applications, beyond particle and nuclear physics, is enormous, and briefly presented in the ERL paper [1] too, using high power lasers, photo-lithography and the use of inverse Compton scattering (ICS) as examples. 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 by orders of magnitude exceeding that of the XFEL. That could be a contribution for a decade of physics programme at CERN between the HL-LHC and possibly the FCC-hh or HE-LHC when time may be required for high field super conducting dipoles to be routinely available.

The industrial process of producing semiconductor chips comprises the placing of electronic components of nanometre scale onto a substrate or wafer via photolithography. For advancing this technology to a few nm dimension, i.e. in order to produce the necessary EUV power to make deployment of FELs feasible for industrial photolithography with acceptable operating costs, the FEL must be driven by a superconducting ERL. An ERL with electron beam energy of about 1 GeV would enable multi-kW production of EUV. This would benefit the global semiconductor industry by allowing study of FEL capabilities at an industrial output level, and developing and proving kW-capable EUV optical elements/beamlines for photon transport to chip scanners. If the economic viability may be underpinned by large scale high reliability, following initial surveys and design studies undertaken by industry some years ago, ERLs might well reach into the market, which in 2020 was 400 B Euro.

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

3 Panel activities

The ERL Roadmap Panel was recruited and its membership endorsed by the LDG in early 2021. It has 18 members, listed above, representing major ERL facilities (past, operational or in progress) and assembles key expertise such as on injectors, superconducting RF, operation and management. Supported by the LDG, the panel decided early on to write a baseline paper on ERLs for publication [1], from which a Roadmap would naturally emerge in a second phase of activity. Today, a draft of 220 pages exists comprising 350 references, which is being completed in the coming weeks. The write-up, besides the panel, currently has about thirty further authors for covering the field with the necessary expertise.

On Friday 4^{th} of June, an extended Symposium on the Development of Energy Recovery Linacs was held, https://indico.cern.ch/event/1040671/, introduced by Dave Newbold for the LDG. With up to 100 participants, and including an hour long discussion, this was an important consultation with a community of interested accelerator, particle and nuclear physicists. MK was invited to present to a TIARA meeting (29.6.), while AH talked at the subsequent Particle Physics Symposium (9.7.) https://indico.cern.ch/event/1053889/.

While the panel started to work, the ERLC concept was put forward to build the ILC as an energy recovery twin collider, with the prospect of a major increase of the e^+e^- luminosity as compared to the ILC default. Similarly, the CERC concept had been published to configure the FCC-ee as a circular energy recovery collider, with very high luminosity extending to large cms energy, maximally 600 GeV. This caused the formation, in agreement with the LDG, of a sub-panel [1]. to evaluate the luminosity prospects, the involved R&D, schedule and cost consequences for both ERL based e^+e^- collider options. It is intended to document the findings of the sub-panel in an Appendix to the ERL baseline paper, which will be published in early autumn 21.

Following this Interim Report, the panel will move towards the genuine ERL Roadmap document, based on its insight from the long ERL write-up [1] and corresponding to its mandate.

4 State of the art

4.1 Current Status

A long way has been gone since the first SRF ERL [10] at Stanford, as is described in the panel's write-up [1]. The key parameters of an ERL (application in particle physics) are the electron beam current I_e ($\propto$ luminosity) and energy E_e. The power is simply $P = I_e E_e$, and through recovery of the energy it is related to a real value power P_0 which is augmented by a factor $1/(1-\eta)$ where η is the efficiency of energy recovery. This way, for example, the LHeC can be designed to reach $10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ luminosity for which nominally a GW of power would be required. The current state of the art may thus be characterised by a facility overview, presented in Fig. 1, as an E_e vs I_e diagram with constant 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 reached the highest energy so far, of 1 GeV, and the Jlab FEL, which reached the highest current, of 10 mA. Larger currents have been achieved in the normal conducting, lower frequency ERL facility at BINP (the Recuperator). There are three facilities (dark green) currently operational, S-DALINAC at Darmstadt, CBETA at Cornell and the compact ERL at KEK in Japan.

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

Fig. 1 also displays the parameters of the by now five design concepts for ERL applications at the energy frontier with electron beam energies between 50 (LHeC) and 200 GeV (EXMP). CERC has a low current but a rather large number of beam lines. LHeC and FCC-eh are 3-turn linacs with about 20 mA current delivered by the gun. ERLC and EXMP are single pass linacs, with possibly twin-axis cavities. There follows a common requirement, with the exception of CERC, of about 100 mA current load to the cavities, which is the goal of PERLE (in 3-turns) and, in a single pass, of bERLinPRO, should it go ahead, and the EIC electron Cooler in its most challenging configuration.

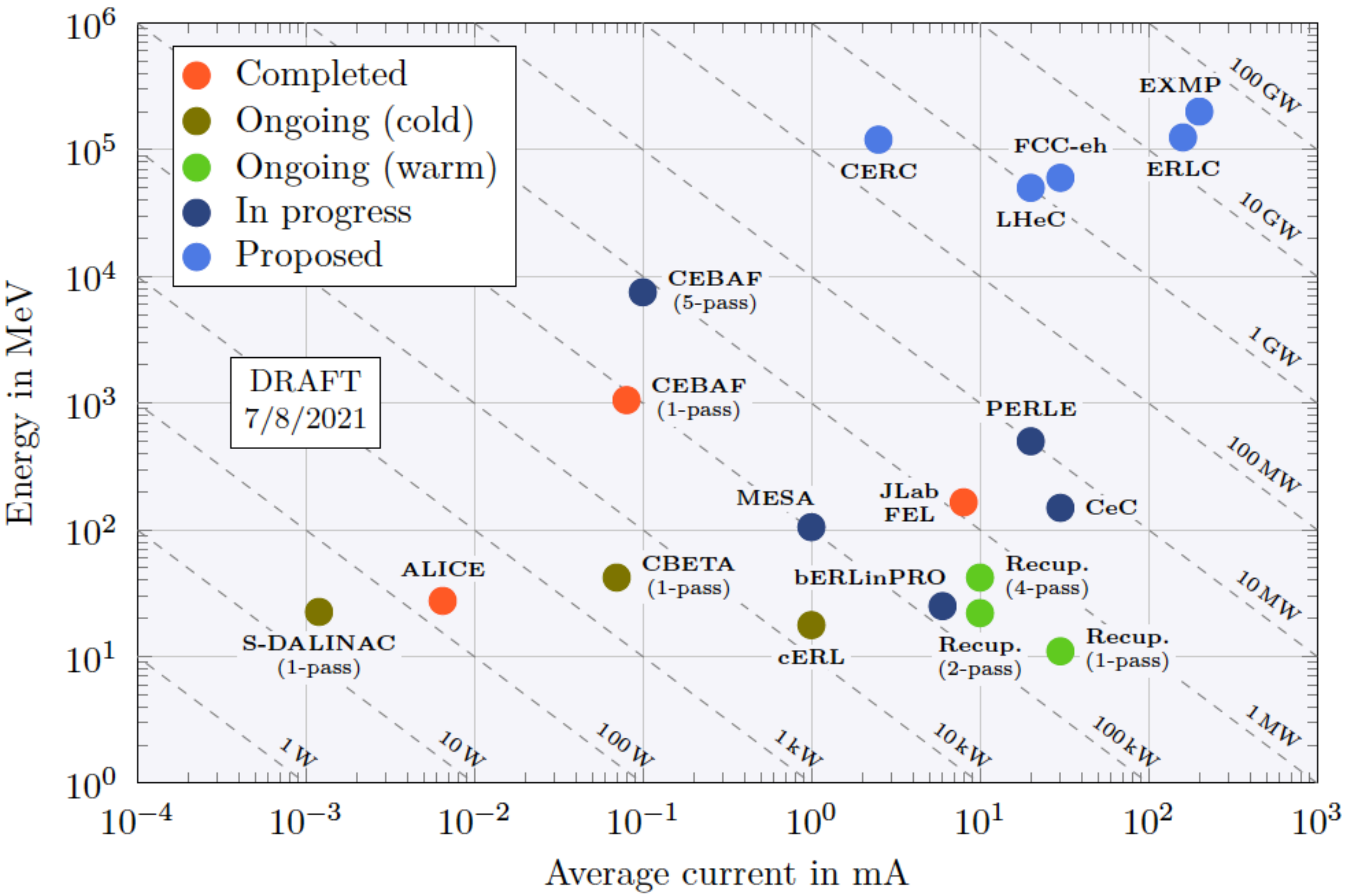

Figure 1: Electron energy vs current for ERL facilities, draft plot from [1], see text.

4.2 Plans for the Next Years - Operational Facilities

The existing and forthcoming facilities have specific development plans which are listed here and detailed in the long write-up [1]. These activities and plans underpin to quite some extent the common,

[1]**Sub-Panel on e^+e^- ERLs**: Chris Adolphsen (SLAC), Reinhard Brinkmann (DESY), Oliver Brüning (CERN), Andrew Hutton (Jefferson Lab, Chair), Sergei Nagaitsev (Fermilab), Max Klein (U Liverpool), Peter Williams (STFC Daresbury), Kaoru Yokoya (KEK), Akira Yamamoto (KEK), Frank Zimmermann (CERN).

main R&D objectives which are detailed in Section 5.

- S-DALINAC (TU Darmstadt)
  - establishment of a multi-turn SRF-ERL with high transmission (up to 70 MeV and 20 μA);
  - quantification of phase-slippage effects in multi-cell-cavitiy-ERLs and counter-measures;
  - characterisation of potential working points of individually-recirculating ERLs.

- Recuperator (BINP Novosibirsk)
  - The current of the Novosibirsk ERL is now limited by the electron gun. A new RF gun was built and tested recently. It operates at a frequency of 90 MHz. An average beam current of more than 100 mA was achieved;
  - Plans are to install this gun in the injector, while the existing electrostatic gun will be kept there. The RF gun beamline has already been manufactured and assembled on the test setup. The beam parameters were measured after the first bending magnet and at the beamline exit.

- CBETA (Cornell)
  - improve transmission, which includes investigating better optics solutions;
  - developing improved diagnostics for the decelerating passes;
  - reducing halo by using a low halo cathode possibly in conjunction with beam collimation.

- bERLinPRO (HBZ Berlin)
  - Present activities are focused on the high-current SRF photoinjector. A dedicated diagnostic line capable of handling 10 mA is installed to characterise the beam;
  - Following the booster installation, the beam can be transported through the merger to the high-power beam dump following the splitter section, allowing studies of emittance preservation, beam loss, and bunch length manipulation.

- cERL (KEK)
  - Development of 10kW class powerful ERL -based EUV-FEL;
  - Realisation of a 100% energy recovery operation with the beam current of 10mA at cERL and FEL light production experiment;
  - Development of the irradiation line for industrial application (CNF, polymers and asphalt production) based on the CW cERL operation;
  - In addition we are planning to develop a high efficiency high gradient Nb_3Sn acceleration cavity to realise a superconducting cryomodule based on the compact freezer. This cavity will serve to accelerate a high current beam at cERL.

- MESA
  - Improve electron beam polarimetry to an accuracy $dP/P \leq 0.5\%$ in order to support the first physics measurements of electroweak observables, possibly including Hydro-Moeller polarimeter;
  - Installing a second photo-source at the MESA injector with the potential to provide bunch charges > 10 pC with good beam quality;
  - Improving the cavity HOM damping capabilities, for instance by coating of the HOM antennas by layers of high TC-material.

5 R&D objectives

As the state of the art section above indicates, the development of ERLs has been a complex challenge regarding several interrelated technology issues. The panel identified three key research and development objectives of particular importance: i) the provision of electron beams of high brightness, ii) the development of high quality SRF technology designed for ERL use and iii) the exploitation and built of new ERL facilities of complementary characteristics. These are briefly characterised next.

5.1 High Current Guns

Injectors for High Energy Physics ERLs, which require high overage current in combination with complicated beam temporal 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 extra high vacuum accelerating structure.

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

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

Especially in SRF photo-injectors the superconducting cavity is extremely sensitive to any kind of contamination; therefore, the photocathodes exchange process is very critical. For weak interaction physics experiments, polarised electron beams are needed. These can be based on GaAs photocathodes, but their lifetime has still to be improved, e.g. by using newly developed activation processes.

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

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

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

5.2 Superconducting RF Developments

ERLs, being somewhere between linacs and storage rings, have unique requirements for their RF systems and therefore need optimised designs to achieve the full potential of the concept. Proposed new machines operating with about 100 mA of current, either in single or multi-pass mode, need cavities with cell shapes optimised to avoid strong beam excitation of longitudinal higher order modes (HOMs), to minimise the power extracted from the beam, and strong HOM damping of all monopole and dipole HOMs to avoid beam break up instabilities.

This also depends on the actual filling pattern proposed, the need for beam gaps, etc. Sparse filling patterns are spectrally denser and it is harder to avoid resonances. Typically cavities with frequency less than 1 GHz are favoured, having fewer cells and larger apertures. Several ERL cavity shapes have been developed and prototyped and in a few cases operated with beam. A few HOM damping options have been used, including beam line absorbers (BLAs), waveguide dampers, and coaxial antennas. Each has pro-s and cons concerning cavity size, HOM damping ability and power handling capability.

The cavities need moderate fundamental power couplers (FPCs) because of energy recovery, but in many cases the power recovery will not be 100%, so there will be some overhead required for beam loading, The coupling factor and external Q should be optimised for this and the RF system must be designed to handle start up transients, microphonic excursions etc. The exception to this is the booster modules in ERL injectors, which see full beam loading and need high power FPCs like storage rings. FPCs should be symmetrised to avoid dipole coupler kicks that can cause emittance growth.

For each new machine going forward a detailed optimised cavity design is needed taking into account these factors. Testing and demonstration facilities should be such that each of these challenges can be appropriately addressed, and fully functioning integrated RF systems can be validated, and operating over long periods of time to show reliability.

5.3 Supportive Technology

Here we intend to provide examples of supportive technology developments such as FRTs, power supplies, cryogenics innovations etc, to illustrate how the ERL field is linked to technical progress. For time reasons this is deferred to the full Roadmap report.

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\subsection{Superconducting RF Technology}
Superconducting RF  has been identified as one of the key technologies for High Energy
Physics, Photonics and Nuclear Physics. This has led to a diverse and
vibrant global R\&D program. While the main goal for a linear collider definitely
is the high accelerating gradient, which can be sustained in pulsed
operation, circular colliders and ERLs require high cryogenic efficiency at moderate
gradients in CW, along with the need to operate at very high beam
currents. Additionally, high availability is of paramount importance.
Steady performance improvements of SRF cavities and cryomodules have been
made in recent years, both in gradient reach and cryogenic effiency. Several SRF
cavities already achieved $E_\text{acc}$ $\approx$ \SI{50}{MV/m}.
For operation in CW, dynamic losses ($\propto E_\text{acc}^2$) dominate the
requirements to cryogenics and ultimately limit the gradient. Maximizing the
cavity $Q_0$ is therefore highly desired. In recent years, both Fermilab and Jlab
 have been very successful with novel techniques introducing non-magnetic
impurities to the Nb surface as part of the SRF cavity post-processing. This controlled
``doping'' with nitrogen or titanium allowed a significant increase
of $Q_0$ at low $T$ (\SI{2}{K}).
An complementary approach looks at the possible use of so-called A15 materials
(like \ce{Nb3Sn} or \ce{V3Si}) with higher $T_c$. First relevant tests  with
\ce{Nb3Sn}-coated cavities, which can be operated at higher temperature (\SI{4.2}{K})
and thus with significantly less power consumption for cryogenics,
have reached encouraging results.
To insure the beam stability and prevent beam break-up at high beam currents,
strong damping of both longitudinal and transverse higher order modes is
necessary. Possible solutions utilize waveguide-coupled dampers (for which the
 waveguide cut-off serves as high-pass filter) or beam line absorbers (where
absorbing material is placed inside the beam tube). Also the cavity geometry is
 reconsidered to possibly better separate accelerating from unwanted modes.
One area of R\&D very specific to ERLs, which---in steady state---are free of
fundamental beam loading and thus in theory require only little RF power, is
the investigation of very fast tuners. A tuner fast enough to cope with microphonics
and beam current transients would allow to increase $Q_\text{ext}$ by
possibly an order of magnitude and decrease the required RF power accordingly.
Recent experiments with ferro-electric (``BST'', \ce{BaTiO3}-\ce{SrTiO3})
based fast reactive tuners have demonstrated the feasibility and applicability of
these tuners.
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This morning from Erk

5.4 Plans for the Next Years - Facilities in Progress

The ERL development is reaching higher energies and currents in complete facilities which allow the in depth study of associated technology and operation phenomena as are described in [1]. Several facilities are in progress with programs as here sketched and design parameters as indicated in Fig. 1:

- CEBAF 5-pass (ER@CEBAF Jefferson Lab)
  Based on the large experience at Jefferson Lab, a novel project has been approved which has the target to study an ERL at highest energy, chosen to be 8 GeV, where effects such as coherent synchrotron radiation will notably occur. For the coming 4 years, the project has the following plans, also in Collaboration with the University of Brussesl and STFC Daresbury:
  - Engineering design for a half-lambda delay chicane;
  - install dipoles for the delay chicane and the extraction dump;
  - Continue ongoing beam dynamics studies;
  - Finalising the Optics design, including sextupoles;
  - Develop a step-by-step experiment run schedule (2024).
- bERLinPRO Upgrade (HZB Berlin)
  The technical infrastructure and beam transport for a dedicated 100 mA, 50 MeV ERL facility has been set up at the Helmholtz-Zentrum Berlin.It is basically complete, including power and cryogenics infrastructure, albeit still lacking the 1.3 GHz frequency linac for which a design exists. A first high current SRF gun, delivering up to10 mA of current with an emittance < 1 mm mrad, will be commissioned in 2022 and could later be upgraded to 100 mA. Further there is apartial design fora wave-guide damped high-current SRF linac,based on the VSR scheme currently under construction, and an experimental setup that allows for extensive beam studies, in an underground building with massive shielding laid out to handle up 30 kW continuous beam loss at 50 MeV. SRF systems with Fast Reactive Tuners and high-current SRF guns are examples for equipment tests that could be conducted.
- EIC electron Cooler CeC (BNL)
  Coherent Electron Cooling (CeC) is a novel but untested technique which uses an electron beam to perform all functions of a stochastic cooler: the pick-up, the amplifier, and the kicker. Electron cooling of hadron beams at the EIC top energy requires a 150 MeV electron beam with an average power of 15 MW or higher. This task is a natural fit for an ERL driver, while being out of reach for DC accelerators. Currently, BNL is developing two CEC designs. The first one is based on a conventional multi-chicane microbunching amplifier which requires a modification of the RHIC accelerator to separate the electron and hadron beams. Alternatively, the second CeC design is based on a plasma-cascade microbunching amplifier. Both CeC designs require an ERL operating with parameters beyond the state of the art.
- PERLE (IJCLab Orsay)
  PERLE is a compact three-pass ERL project using SRF technology, pushing as a new generation machine the operational regime for multi-turn ERLs to around 10 MW beam power level. PERLE will serve as a hub for the validation and exploration of a broad range of ERL accelerator phenomena in a so far unexplored operational power regime serving for the development of ERL technology for future energy and intensity frontier machines. Particularly, the PERLE facility targets the LHeC configuration by featuring a 3-turn acceleration and 3-turn deceleration racetrack configuration, 802 MHz SRF system and beam currents of up to 20 mA (corresponding to 120 mA in the SRF cavities). A first Niobium cavity realised at Jlab in collaboration with CERN had a high Q_0 of 3 10^{10} up to a gradient of nearly 30 MV/m. The facility initially uses in kind deliveries of the gun, from ALICE, the booster cryostat (from Jlab, reusing the JLEIC design) and the main linac cryostat (from CERN using the SPL module). The Collaboration (BINP, CERN, IJClab Orsay, Jlab, Liverpool, STFC Daresbury and others expressing interest), has recently established an ambitious plan for first beam operation, at 250 MeV, in the mid twenties. A second linac module and several experiments are in the early phase of planning.

6 Key points of roadmap

The roadmap on ERLs will be based on the activities at the facilities, the prospects for higher power facilities and the key requirements for enduring high current sources and high quality, dedicated SRF technology as described above. The panel needs more time to come forward with a more detailed plan. It is straightforward to estimate that a funding amount of O(10) MEuro annually for five years should be planned for in order to support the European developments as described. This will be complemented by investments into the EIC Cooler and CEBAF 5 pass (US), the Recuperator (Russia) and the compact ERL (Japan). Simultaneously, the operational facilities will accumulate further experience. With appropriate financial support and enhanced attention to the European plans, the road to powerful ERLs for application in energy frontier colliders, for new generations of intense particle and nuclear physics experiments can be timely followed with considerable confidence. ERLs are a prime example for power and resource economy, sustainability in science with potentially major impacts on industry and further applied fields.

References

(only few?)

- **Picosecond x-ray source with high (15 T) field magnet(s) on 1-GeV ERL.** This option could intensify ERL activity, transforming, for example, test facility PERLE or ERL projects for x-ray lithography FEL, to unique user facility (storage rings can not provide so short x-ray pulses, and linacs can not provide average intensity).
- **Few-GeV collider (e. g., charm-tau factory) with beam-beam compensation using positron storage ring(s) and electron ERL(s)** (N. A. Vinokurov, "Four-Beam Compensation with Two Beams", 26th Russian Particle Accelerator Conference, http://accelconf.web.cern.ch/rupac2018/papers/tuymh02.pdf, S. B. Lachynov and N. A. Vinokurov, "Beam-Beam Compensation in a Collider Based on Energy Recovery Linac and Storage Ring" AIP Conference Proceedings 2299, 020011 (2020); https://doi.org/10.1063/5.0030416).
- **Electron cooling of relativistic hadrons** (A. Skrinsky, "Continuous Electron Cooling for High Luminosity Colliders", Nucl. Instr. and Meth. A, vol. 441, 1-2, p. 286-293, Febr. 2000, N. A. Vinokurov, V. V. Parkhomchuk, A. N. Skrinsky, "RF Accelerator for Electron Cooling of Ultrarelativistic Hadrons", 12th Workshop on Beam Cooling and Related Topics, http://accelconf.web.cern.ch/cool2019/papers/tuy01.pdf).

Mail from Nikolay Vinokurov, 13.7.21