Topical Review

Superconducting energy recovery linacs

Ilan Ben-Zvi

Collider-Accelerator Department, Brookhaven National Laboratory, USA

E-mail: benzvi@bnl.gov

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Abstract

High-average-power and high-brightness electron beams from a combination of laser photocathode electron guns and a superconducting energy recovery linac (ERL) is an emerging accelerator science with applications in ERL light sources, high repetition rate free electron lasers, electron cooling, electron ion colliders and more. This paper reviews the accelerator physics issues of superconducting ERLs, discusses major subsystems and provides a few examples of superconducting ERLs.

Keywords: energy recovery linac, superconducting RF accelerators, high brightness electron beams

(Some figures may appear in colour only in the online journal)

Introduction

The short dwell time of beam in linear accelerators allows for the generation of non-equilibrium, high-peak-brightness electron beams from laser photocathode electron guns. High-average-power is enabled by the superconducting CW energy recovery linac (ERL). This is a powerful combination, which opens up new applications, such as ERL light sources and high repetition rate free electron lasers, electron cooling, electron ion colliders and more. This paper reviews the accelerator physics issues of superconducting ERLs, discusses major subsystems and provides a few examples of superconducting ERLs.

The ERL in a SRF linac was demonstrated for the first time at Stanford University. The high-energy electron beam was returned to the linac at a decelerating phase [4]. This is also the first instance of the ‘same-cell’ energy recovery technique. Another experimental demonstration of an ERL in a very different configuration took place at Los Alamos. In that case, the accelerator was a normal-conducting linac, and the beam energy recovery was done in a dedicated separate-cell [5]. The RF power recovered from the decelerating structure was coupled to the accelerating structure through resonant bridge couplers, however, the efficiency of this operation was only about 70%. The examples given above show another divergence of approach, that of SRF linacs and copper (normal-conducting) linacs, however this work is aimed exclusively at superconducting ERLs.

The next major step towards the modern SRF ERL was taken at Jefferson Lab’s (JLab) IR and UV FEL [6, 7]. This is a SRF ERL operation in a CW mode, with recovery in the same cell, and a current record of up to 10 mA was achieved at energy of up to 100 MeV. This ERL will be described in greater detail later on.

The brightness of an electron beam is directly related to the density of the beam as measured in 6D phase space. High brightness means a high charge packed into a small six-dimensional phase-space volume. In certain applications, a lower dimension (projection) of phase space is used.
Normalized brightness is related to the presentation of the beam in canonically conjugate variables. For a single bunch one can thus define the peak brightness as the ratio of the charge to the volume in 6D phase-space. However, most applications also seek a high repetition-rate, thus, the combination of high peak brightness and high average power electron beams become highly desirable. The superconducting ERL makes it possible to attain both qualities with high efficiently and CW operation.

ERLs can support the production of very intense and bright electron beams using laser-driven photocathode electron gun and CW high-current superconducting linacs. It is possible to use a polarized electron gun, and thus endow the ERL beam with a high degree of polarization. The advantage of the ERL is that the electron beam dwells a short time in the accelerator. The very short time from the instant of the generation of the beam to dumping it after the energy has been recovered means that we avoid many processes leading to emittance growth or depolarization. Expressed differently, the electron beams in an ERL, unlike in a storage ring, do not reach equilibrium with emittance dilution mechanisms. With proper care in the beam dynamics, the electron beam brightness is then determined by the electron source and thus can be high. Such high brightness electron beams present opportunities for future user facilities for discovery science in High-Energy, Nuclear Physics and Basic Energy Sciences. Applications of a high-intensity ERL range from the production of coherent radiation to electron-ion colliders. For many applications, the ERL can be quite compact. For example we can cite an x-ray source through Compton back-scattering of a laser from the electron beam. Such machines are suitable for industrial, medical and university-based applications.

In this paper I will start with some physics issues and principles of ERLs, then follow up with a description of major subsystems of an ERL. The paper will conclude with a very brief description of a few SRF ERLs, followed by a summary. The interested reader can find many references going into further detail.

**ERL physics**

High-peak-brightness electron beams are the attribute of linear accelerators, and that is why hard x-ray FELs are based solely on linacs. Storage rings reuse and do not dump the beam, and thus are capable of very high average beam power, but limited to much lower peak brightness. ERLs inherit the high peak-brightness of linac, and through energy recovery assume the high efficiency of rings, and therefore are also capable of a high average beam power at high brightness.

Decelerating the beam and extracting its energy for use in the acceleration process accomplishes the recovery of the beam energy. As mentioned in the introduction, the deceleration can be done in a dedicated structure [5], but that is less energy-efficient than same-cell energy recovery [3, 4]. The energy recovery can be done with the two beams moving in opposite direction [3] or in the same direction along the linac [4, 6, 7]. Motion in the opposite direction in a long linac may lead to parasitic collisions of the two beams, thus, ERLs currently under consideration prefer the same-direction, same-cell approach, and mostly use SRF techniques. In the following we will consider just this more prevalent SRF case.

The benefits of energy recovery are twofold:

1. The overall system efficiency is increased by orders of magnitude, leading to savings in size and cost (both capital investment and operations) and making CW operation feasible and efficient thanks to SRF technology.
2. The electron beam power to be disposed of at the beam dumps is reduced by the ratio of the final to injected energy. The lower energy at the dump leads to much reduced radiation and activation, particularly if the beam is dumped at below the neutron production threshold energy.

The main complications added (in comparison with linacs) in ERLs are:

1. Merging the beams at the linac entrance while avoiding emittance growth.
2. Separating and dumping the beam after energy recovery with a potentially excessive fractional energy spread and large emittance.
3. The multi-pass, multi-bunch beam instability, which is particularly difficult in the SRF linac, on account of the high quality factor of the higher-order modes (HOMs).

In addition to the issues associated with energy recovery, the operation of a CW machine with a high-current and high-brightness beam leads to additional considerations, such as halo, ion accumulation instabilities, spurious emissions; issues associated with the interaction of the electron beam and safety considerations.

**Energy recovery**

The ERL, like a storage ring, can be used in applications requiring the electron beam at a high-energy, but do not increase the energy spread or emittance too much, leaving most of the beam energy amenable for energy recovery. Thus, the typical ERL has the following layout: The beam is generated in a source, which is outside the energy recovery loop (injector), and transported to the entrance of the linac for acceleration. Note that the injected beam has to be merged onto the linac’s axis coinciding with the high-energy beam returning for deceleration. The injected beam is then accelerated in the linac and then transported to the location where the beam is used (interaction region). The beam transport section, comprising of the usually evacuated focusing and bending magnet systems, beam instrumentation etc is usually designed to manipulate the beam in phase space, such as bunch length compression. The used beam is then transported back to the entrance of the linac, with a path length that leads to deceleration in the linac. Following deceleration the beam is again at low energy, similar (but not necessarily the same)
to the injection energy, and can be magnetically separated from the high-energy beam and directed to a beam dump.

One important consideration in any accelerator is its cost, including both construction and operating costs. Linac sections are more expensive to build and operate than magnetic beam transport. Thus, the idea of multi-pass linacs has been proposed long ago [8, 9]. In an $N$-pass ERL the beam is accelerated in the linac $N$ times, then decelerated $N$ times. This arrangement typically increases the cost of the transport system by a factor of $N$, and reduces the cost of the linac by a factor of $1/N$. This functional dependence of the linac and transport system costs leads to a broad cost optimum, depending on the particular details, in several passes ($N$ between 3 and 6). The multi-pass ERL has been implemented in one facility operating with a multi-pass ERL [10].

The idea of the fixed field alternating gradient (FFAG) accelerator [11], and the non-scaling FFAG (NS-FFAG) [12] are quite old, but the idea of using a NS-FFAG lattice in an ERL is new [13]. The important feature of this approach is the ability to contain multiple passes, extending over a wide energy range, in a compact magnet transport system, thus leading to cost reduction of the accelerator.

Beam splitting and combining systems

The most basic ERL already incorporates more than a single pass in the linac, with one accelerating pass and one decelerating pass. For an $N$-pass ERL (meaning $N$ accelerating passes) the electron beam passes $2N$ times through the linac. These passes, which have distinct energies and trajectories in the transport system, must coincide with the linac axis. The splitting, transport and combining systems are inherent to multi-pass accelerators, linacs or ERLs. They may be simple in a small accelerator, as in a microtron, but get more difficult for higher energy machines, such as CEBAF [14]. Besides the splitting and combining functions, these systems also deal with matching the optical functions, path length, momentum compaction and other requirements, so they can become complex and occupy a lot of space. In an NS-FFAG ERL, the fraction of beam transport elements (magnets, beam-pipes, instrumentation) that is used by the splitters and combiners is larger due to the smaller number of separate transport channels.

It is desirable to keep the injection energy of an ERL small, particularly if the average beam current is high, to lower the energy in the beam dump to reduce radiation and, if possible, below 10 MeV to reduce activation of the beam dump. Thus, the injection combiner system has to introduce magnetic bending of a high-charged and low emittance beam. It should not couple transverse and longitudinal motions and avoid nonlinear terms, in particular allow for a laminar motion of the electrons, which is necessary for emittance compensation. The space-charge forces, which become significant at the low energy of the injector, introduce another complication, such as changing the energy along a bunch of electrons during its transport through the combiner, potentially leading to emittance growth.

A combiner that maintains well the beam brightness for a low-energy injection is the ‘zigzag’ system. A detailed discussion of various low-energy combiners including the zigzag system can be found in [15].

The splitter of an ERL, particularly a high-energy ERL, has to contend with a large fractional energy spread at the stage where the low energy beam directed to the beam dump has to be separated from the high-energy beam(s). Various mechanisms lead to energy spread in the beam, as will be discussed later on. As the beam energy is lowered in the energy recovery passes, the absolute energy spread mostly is preserved, thus leading to a growing fractional energy spread. A large fractional energy spread (of the order of a few 10s of a percent) is difficult to handle, and even that much requires specialized magnets and transport elements. Various techniques can be applied to reduce the large fractional energy spread. In the Jefferson Laboratory ‘IR Demo’ ERL, a large energy spread was introduced by the FEL action. Then the electron bunches were stretched by a linear energy—path length correlation produced by the transport system, then decelerated off-crest in the energy recovery pass through the linac, to significantly reduce the energy spread [16].

Impedance-related energy spread

The following impedance related effects are common to many accelerators and are not unique to ERLs. However, a brief mention is worthwhile when a high-brightness beam is concerned.

Energy spread and emittance growth can be generated by the electron beam interaction with the accelerator environment. Long electron bunches suffer from increased energy spread due to the temporal curvature of the RF fields in the linac. Short electron bunches increase the magnitude of longitudinal wakefields, in the linac as well as the beam transport system, leading to a larger energy spread.

The dominant wakes for short bunches are diffraction wakes, coherent synchrotron radiation (CSR), resistive wall and wall roughness. Diffraction wakes are produced when a short bunch passes an abrupt change in the beam-pipe, such as a step-change in the beam-pipe diameter or in the variable distance from the beam axis to the walls of a cavity. There are analytic formalisms for typical structures, and these can be used for estimating the magnitude of these effects [17]. Using good construction practices in the beam transport lines, such as avoidance of abrupt diameter changes or unshielded bellows, can reduce the diffraction impedance of that part of the ERL. The linac, with unavoidable and repetitive change of diameter in the cavities is a significant source of diffusive wake-field. This wake is proportional to the length of the linac, counting multiple passes through the linac. A lower linac frequency leads to a lower diffusive wake-field and also permits an increase in the bunch length, for a further reduction of the energy spread.

The theory of resistive-wall wakes is well developed, and the analytic expressions provide good accuracy in the
estimate of the wake [17]. In particular, one should avoid small diameter beam-pipes.

The effect of CSR can also be described in terms of wake fields [18]. It takes place in a magnetic bend when the radiation from the tail of the bunch catches up with its head. For a beam of high-current and short bunch length, this effect may become important. Electromagnetic shielding near the beam axis, in particular if the bunch length is long enough may mitigate CSR. The suppression factor involves the bunch length, the beam pipe diameter, and the bending radius of the curvature of the beam in the magnet. Dedicated measurements of shielding of the CSR were performed at the BNL Accelerator Test Facility, where both CSR-induced energy loss and energy spread were suppressed [19].

The contribution of wall roughness driven wakes can become important especially when the size of the vacuum chamber is small and the length of the electron bunch is very short. Several theoretical models were developed in the past, with some variability of results concerning its magnitude.

Experimental results of wall-roughness wake-field and a review of some models is available in [18]. One may suppress the wall-roughness wake-field using a smoothly extruded surface.

**Beam breakup**

Multi-bunch, multi-pass transverse beam break up (BBU) is one of the challenging problems of beam dynamics in multipass linacs and thus also in ERLs. This effect has been studied extensively [20] including through computer simulations and theoretically [21]. The intuitive explanation of BBU is quite simple: When a beam bunch passes through an RF cavity with a transverse offset, it deposits energy to some dipole HOM. At the same time, the HOM introduces a transverse momentum kick, which can be converted to a transverse offset by the beam transport system. Given that the beam bunches return to the same cavity and mode because of the multi-pass nature of the accelerator, we have a positive feedback loop. When the beam current exceeds a certain threshold, $I_{th}$, this process leads to instability in the beam’s motion and the HOM stored energy in the cavity. The effect is enhanced by the multiplicity of the passes [21]. The beam current threshold may be increased by several methods. The most common are effective damping of the HOMs to reduce their shunt impedance, and the introduction of a large spread of the HOM frequency, by the regular manufacturing process and possibly even by design. Other methods include decreasing the frequency of the cavities and careful choice of the optics functions of the beam transport system.

**Ion effects**

Continuous electron beams can ionize the residual gas, and then trap the ions through the electric potential well of the electron beam. This effect is well known in electron storage rings. The trapped ions can interact resonantly with the electron bunches, leading to growing coherent oscillations of both the electrons and the ions [22].

The ions can be cleared from the electron beam by various means, such as clearing electrodes or destabilizing the ions by introducing gaps in the electron beam stream.

The phenomenon called ‘fast beam-ion instability’ (FBII) involves ions that can be ionized and trapped in any continuous electron current transport line and does not require an equilibrium state of residue gas ions. The FBII was predicted in 1995 [23] and experimentally observed and mitigated in an ERL injector [24]. Simulation tools based on the weak-strong algorithm have been developed [25].

A preliminary result for the FFAG rings of the eRHIC ERL suggests that ~950 ns gaps introduced in the bunch pattern adequately suppress the FBII.

**Generation and preservation of high-brightness beams**

Linear accelerators can achieve high peak brightness because the electron beam stays for a very short time even in the longest linac. Thus, unlike the situation in a storage ring, the beam emittance is not established by equilibrium between radiation cooling and quantum excitation of emittance. Thus, the peak brightness (the brightness of a single bunch) can be high if the electron source can produce a high charge at a low 6D phase space volume and the accelerator and beam transport system do not degrade the emittance. The high peak brightness of the linac can lead to a high average brightness by providing a high bunch repetition frequency, which can be done well in an ERL.

The peak normalized six-dimensional brightness $B_n$ of a bunch of charge $q$ and normalized emittances $\epsilon_{nx}$, $\epsilon_{ny}$, $\epsilon_z$ is then given by

$$B_n \sim \frac{q}{\epsilon_{nx} \epsilon_{ny} \epsilon_z}.$$

The conservation of charge and normalized emittance means that the brightness of the beam cannot be improved in the acceleration and transport system, at best it may preserve the brightness generated in the electron source (electron gun).

The thermal energy is irreducible, but the emittance may grow within a very short distance from the cathode due to surface roughness, non-uniform charge density [26] or the effect of image charges.

Roughness affects emittance through several effects such as local surface bending causing the electron distribution to be emitted into a wider angle (non-field dependent) and through field curvature that translates longitudinal fields into the transverse direction. The former is a relatively small effect, but the latter at high electric field gradients can become catastrophic [27].

While the beam is still at a relatively low energy, emittance dilution and bunch shortening take place in the gun and beam transport by the action of space-charge forces. Space charge is reduced fast as the beam is accelerated. Therefore extreme care must be taken with space charge at the appropriate energy regime to preserve the transverse and longitudinal beam brightness in the face of space charge effects. This is best done by initially keeping the electron...
bunch as long as practically possible, and accelerating the beam rapidly to reduce the time the beam is affected by space-charge forces, which affect the beam most at low electron energies.

**Bunch compression/decompression**

High peak currents are needed in some applications of the electron beam, for example in extreme-ultraviolet and x-ray FELs. High peak currents cannot be produced directly in the electron gun, since at a low energy space-charge forces lead to a rapid emittance growth, even taking into account emittance compensation. A better strategy is to generate moderately long bunches with a peak current of about 50 A at the source, quickly accelerate the beam to a higher energy and then compress the beam as necessary for the application. Longitudinal bunch compression is typically done by introducing energy–time correlation in the bunch (so-called ‘energy chirp’), then redistributing the bunch particles with a magnet system (usually a ‘chicane’, which is essentially half a wiggler period). For a high degree of compression, two (or more) compression steps are taken.

To realize the energy slope, the RF phase in an appropriate accelerator section is adjusted in such a way that the particles are accelerated on the slope of the RF wave. The cosine RF waveform as well as other effects (such as wake impedance in the accelerating sections, or CSR in the magnetic chicanes) add nonlinear terms to the position–energy relationship inside the bunch. This nonlinearity distorts the compressed bunch distribution, adding a short leading spike and a longer tail to the ideally narrow bunch shape. For many applications, such as high-fan FEL operation, the leading and trailing current have no significantly bad effect other than the reduction of the peak current in the central bunch. One can improve the compression by using RF harmonics, such as a third-harmonic cavities in the accelerator chain [28]. In an ERL, it may be necessary to decompress very high peak currents after the beam has been used and before significant magnetic bends are introduced to reduce the generation of spurious emissions.

Bunch compression to a high peak current can lead to emittance growth due to the CSR impedance. The CSR wake potential induces emittance growth because the energy change by the CSR leads to dispersive motion of the electrons. This energy change is a function of the longitudinal position of electrons in the bunch and the emittance growth can be expressed as displacement of bunch slices in transverse phase space. Also, CSR-induced microbunching instability [29] can take place in a series of bending magnets such as bunch compressors. Solutions to CSR-induced emittance growth have been implemented in the LCLS [30].

**Beam halo**

A precise definition of how the beam is distributed between its useful part (sometimes described as the core) and the non-useful or possibly harmful part (described as the halo) is mostly intuitive, but may be defined by moments of the particle distribution [31]. As the names suggest, the core is the high-density part of the beam, and the halo is a diffuse distribution of particles over a large area surrounding the core. The subject of halo in high-intensity beams has been discussed extensively [32–35]. However, simulation of the halo is computationally very intensive. Beam halo may be generated through a variety of mechanisms, such as emission from unintended area of the photocathode, dark current from the gun and from accelerator cavities, off-energy beam tails, misalignment of beam line elements, space-charge tune depression following the beam generation in the electron gun, interaction with gas or ions, and intrabeam scattering [36]. Since ERLs are typically high current machines, even a low-intensity halo can lead to beam loss in the accelerator, causing ionizing radiation, heating, quenching of superconducting cavities and possibly damage to machine elements. Avoiding the formation of halo and collimating it as early as possible are highly desirable.

**Major subsystems**

**The electron source**

The electron source of an ERL comprises of the cathode and an initial accelerating element, such as a DC potential drop or RF accelerating field (or some combination of the two) providing some initial electron energy. In the ERL the beam brightness cannot be improved (and may indeed be degraded), therefore the brightness delivered by the photocathode is critically important for high-brightness ERLs. In the electron gun one starts with electrons emitted from the cathode. The ‘thermal emittance’, which is just the uncorrelated emittance of the electrons as they are extracted from the cathode surface, is fundamental and uncorrectable. The normalized thermal transverse emittance at the cathode is given by [37]

$$e = \frac{r}{2} \frac{kT}{mc^2}.$$  

The cathode radius is $r$ and $mc^2$ is the electron’s rest mass. The thermal energy term $kT$ (where $T$ is the temperature in degrees K and $k$ is Boltzmann’s constant) can be replaced by a representative energy spread term resulting from photoelectric emission. Clearly a small emitting area leads to a small thermal emittance, however, one must consider other effects, such as space charge, time-dependent fields and many other factors that affect the final emittance from the injector.

The emission mechanism may generate electrons with a random energy larger than the thermal emittance. In photocathodes, the momentum spread of the electrons contains a contribution from the difference between the photon energy and the work function.

If we examine the 6D normalized brightness, the thermal brightness is inversely proportional to the square of the transverse thermal emittance as given above, and it is proportional to the beam current from the cathode. Thus, for a
given cathode temperature, the thermal normalized brightness is simply proportional to the current density from the cathode. Child’s law limits the current density in a low-emittance DC gun [37]. Increasing the accelerating field gradient and the use of laser-driven photocathodes allows a large increase of the brightness even if the thermal emittance may be compromised.

The trade-off between the bunch-length, energy spread, charge and emittance depends on the application. For example, bunch compression can increase the transverse brightness at the expense of an increased energy spread. This is a common technique in FELs. Careful acceleration of the beam, for example reducing the local curvature of the accelerating field by harmonic terms [38] allows for the acceleration of longer bunches, thus reducing the emittance growth due to space charge.

At this point one must investigate other emittance growth mechanisms, since the emittance will exceed the thermal emittance limit. This leads to rather complex numerical optimization of many parameters. Sometimes scaling laws provide rapid assessment of such parameters [39]. Scaling must be treated with care, since extending a particular parameter too far can trigger new emittance dilution mechanisms. Thus, a favorite scaling aims at reducing the emittance by going to a higher frequency RF guns, with higher accelerating gradients. If the scaling is done properly, the emittance should scale as the RF wavelength, leading to very high-brightness sources. However, when the field on the cathode is increased, a new emittance growth mechanism appears at the cathode. This is the rough surface emittance growth [27, 40], which may become significant at fields as low as 3–10 MV m\(^{-1}\), depending on the level of cathode roughness. This emittance is also uncorrectable.

**The electron gun**

Following the emission from the cathode, the electrons must be accelerated. Given that the subject of this paper is linear acceleration, the electrons have to be bunched. The length of the bunch can vary from one part of the accelerator to the next by employing bunching techniques. Accelerating long bunches in a linac requires a low accelerating frequency which may lead to expensive, large accelerating cavities. However, it is possible to start with long bunches from the electron source and compress the bunch length at some intermediate energy.

In the acceleration region of the electron gun, space charge applies defocussing forces, which vary along the bunch, leading to growth in the projected emittance (integrated emittance of the whole bunch). This is a distortion of phase-space, not affecting the emittance of a very short longitudinal section of the bunch, also known as ‘slice emittance’. Similarly, in an RF gun, the RF field, in particular at the exit of the gun, also applies a distortion of phase-space that is manifested as growth of the projected emittance. These effects have been calculated analytically [41]. A technique to correct the space-charge component of the projected emittance has been discovered [42], explained [43] and demonstrated [44] and it is now in routine use [45, 46]. As an alternative, a three-dimensional ellipsoidal bunch charge distribution can reduce the emittance growth due to space charge [47].

As of this time, the only electron guns that have been used in ERLs are high-voltage DC guns, with either a thermionic emission cathodes [48, 49] or laser driven photocathodes [50].

DC guns operate at voltages less than 500 kV, with cathode surface electric fields under 10 MV m\(^{-1}\). A detailed description of measurements of a high-performance ERL injector based on a laser-phocathode DC gun is available from the Cornell team [51]. This gun also produced a record average current of 60 mA for an extended period.

Higher acceleration voltages are desirable for emittance preservation, and SRF guns have been developed to provide the desired high total voltage, also with a high acceleration gradient. These include a 704 MHz elliptical cavity SRF gun, which got up to a CW voltage of over 2 MV and produced 0.55 nC electron bunches [52], and a 112 MHz quarter-Wave Resonator SRF gun, which demonstrated 3 nC at a repetition rate of 5 kHz and a voltage of 1.56 MeV [53]. However, this is a challenging emerging technology, which has not been demonstrated yet in an operating ERL.

**The cathode**

The cathode is a critical and difficult element of the high-brightness ERL, where CW operation, low emittance and high current are essential.

The peak current of thermionic cathodes is limited by the physics of the emission process to below 20 amperes per square cm for dispenser cathodes [54]. The thermal emittance limits the radius of the cathode to a couple of millimeters, leading to a current of just a few amperes. This low peak current can lead to a charge of 100 pC–1 nC by starting with long beam bunches followed by bunch compression as necessary, but this approach adds some technical challenges to preserve the emittance, particularly when a high repetition rate is needed for a high average brightness.

Laser photocathodes are the technology of choice for high-power, high-brightness electron beam sources for ERLs. This is typically achieved by use of a photoinjector (also called photo-gun), in which a photocathode is immersed in a high gradient longitudinal electric field and emission of short high charge pulses is initiated by laser interaction with the cathode. The design of the cathode for these systems is a key challenge for next generation accelerator—based light sources [55]. The large average current requires the use of high quantum efficiency (QE) materials that also retain the high peak brightness.

Metal photocathodes have proven to be highly stable and robust [56] for low repetition rate, high peak brightness injectors with current <1 μA. With sufficient laser research this limit can be possibly pushed to the 100 μA regime. However, for higher average currents, high QE at longer wavelengths is required.
GaAs:Cs has been used with DC guns at JLab to deliver over 900 h and 7000 Coulombs at 2–9 mA CW from a single GaAs wafer between 2004 and 2007 with a lifetime of 550 Coulombs or 30 h at an average current of 5 mA CW [57]. The major limitations of this cathode are the reduction in lifetime due to ion back bombardment in the DC environment and the long response time for 530 nm radiation. To reduce the ion bombardment, the operating vacuum for these cathodes needs to be in the $10^{-12}$ Torr range. These cathodes have been tested primarily in DC guns, and their performance in an RF injector has not yet been tested.

Cs$_2$Te has been used in normal conducting guns at FLASH, PITZ and in an SRF gun at Rossendorf. At PITZ, this cathode has delivered $\sim$1 mA in a macropulse of 700 $\mu$s duration [58]. At Flash, these cathodes routinely deliver a QE of 3%–4% at a wavelength of 254 nm (in the ultra-violet). This material is therefore undoubtedly a good candidate material for the milliampere range, but is not proven at high rep rate and average current. In addition, precise transverse and temporal shaping in the ultraviolet is significantly more difficult than in the visible region.

The need for high pulse charge for FELs and high average current currant for ERLs has driven the search for cathodes with high QE at visible wavelengths. The visible wavelength allows much better laser power efficiency and efficient transverse and longitudinal pulse shaping [59]. Modern fiber laser technology is compact, stable and efficient. Photocathodes based on cesium potassium antimonide are highly efficient, green sensitive and are mid-range in terms of robustness.

The development of alkali antimonides has a long history, related in particular to photo-multiplier applications [60]. The compound CsK$_2$Sb was discovered by Sommer [61] and subsequently discussed by a number of authors [62]. A material based on these systems has also previously been used in a normal-conducting RF photoinjector [63]. This work showed that high density could be obtained, albeit with relatively long pulses and large emittance. An important aspect of this work was the quantification of the lifetime of the cathode on exposure to low partial pressures of water. Subsequent work has also investigated the sensitivity of these materials to other contaminants [64].

The significance of the Boeing- Los Alamos RF injector [63] is that a CsK$_2$Sb cathode has been used in an FEL for the first time, delivering 47 mA in a macropulse of 10 ms duration with a duty factor of 25%. The lifetime of the cathode in this measurement was dependent on the partial pressure of water vapor in the vacuum and was extrapolated to be longer than $10^8$ h for a partial pressure of $10^{-12}$ Torr. Poor vacuum in the gun limited the cathode lifetime to only 10 h in this work.

The highest average current, for long operating times, has been achieved by the Cornell DC photoinjector for a variety
of photocathode materials [65, 66]. Using a GaAs cathode, currents up to 52 mA were obtained, and up to 65 mA using a CsK₂Sb cathode. A NaKSB photocathode operated with 65 mA of average current that has been delivered for about 9 h. The QE degradation of this material had a $1/e$ decay time of about 66 h. These results demonstrate that alkali-type cathodes can provide very high average currents and long operational lifetimes.

**Beam instrumentation**

Measuring the beam parameters in ERLs is challenging, due to the requirement for non-intercepting beam instrumentation for operation in high-current mode.

A variety of beam instrumentation systems should be provided for the purpose of commissioning, tuning, and protecting the ERL. Measurements can include beam position, profiles, current, emittance, and losses were designed for the BNL ERL for the various modes of operation [67].

**Beam position monitors (BPMs).** Dual plane button style BPMs can be installed in many positions in the ERL. At the BNL ERL the buttons are 10 mm diameter Times Microwave Systems model SK-59044, mounted on stainless cubes and can be baked to 150 C. The signals are processed by Libera Brilliance Single Pass electronics from Instrumentation Technologies. These modules can be customized with a band pass filter to the frequency of choice. The configurable beam position range interlock feature offered by the Libera electronics can be employed as the first line of defense for the machine protection system (MPS).

**Beam profile monitors.** Transverse beam profiles can be measured, depending on the amount of beam current, by YAG:Ce (yttrium aluminum garnet doped with cerium) screens for low current, optical transition radiation (OTR) screens for high current. It is important that, when withdrawn, the monitor screen leave a continuous conduction path in the beam pipe.

**Synchrotron light monitors.** Transverse beam profiles can be measured continuously while running with high power beams using synchrotron light imaging for ERL with a sufficiently high beam energy, say 40 MeV and above.

**Halo scrapers.** Halo can be problematic in high-current ERLs. Measuring and disposing halo can be done by movable horizontal and vertical pairs halo scrapers, preferably installed early in the injection transport line.

**Beam emittance.** At low energy (injection), the beam emittance may be measured using a pepper pot station. At high energy the quad scan technique is effective, with data obtained from YAG & OTR beam profile monitors for set-up.
Figure 3. The energy recovering linac accelerator that is operating as a light source at Jefferson Lab, offering sub-picosecond narrow band free electron laser beams and broadband THz beams at repetition rates up to 75 MHz.

Figure 4. Close-up of IR wiggler in foreground and linac cryomodule in the background.
mode (low current) or by monitoring the image by synchrotron radiation at a known beta function location in a high-current mode.

**Beam current transformers.** DC current transformers (DCCT) can be used for high precision DC current measurements, such as Bergoz NPCT-S-115 and standard NPCT electronics. A matched set installed in the injection and extraction transport beam lines can be used to measure small beam losses between these two points. To get a high sensitivity, a null measurement is used to detect beam loss. The signal of the dump DCCT is subtracted from the signal of the gun DCCT using a differential current measurement. This may permit using this diagnostic as a second layer of the MPS [68].

Bunch-by-bunch & bunch train charge can be measured by an integrating current transformer (ICT), such as Bergoz in-flange ICT.

**Beam loss monitors.** Beam loss monitors are an important element of the MPS. A few types of detectors can be used, such as photomultiplier tube based loss detectors, or ion chamber (IC) loss detectors, which may be employed at select locations in the ERL. An extended length IC type loss...
monitors based on gas filled heliax cable provides efficient wide coverage.

PIN Diode loss detector modules built around two PIN photodiodes mounted face-to-face and counting coincidence events, to suppress the synchrotron radiation signal. These devices can have extremely low spurious count rate of <1 in 10^8 s, and up to 10 MHz counting rate for a dynamic range of 10^8, and 100 nS recovery time. Thus, these detectors are of the lowest costs and highest dynamic ranges available.

**Thermal imagers.** The beam pipe temperature can be monitored with a large area coverage by thermal imagers, to monitor beam loss in the vacuum system.

**SRF cavities for the ERL**

A comprehensive review of SRF cavities can be found elsewhere [69] as well as by other contributions to be found in this volume, including HOM damping, a subject of critical importance for ERLs. It is still useful to point out some specific aspects of SRF cavities relevant mostly for ERLs.

**SRF ERL frequency choice.** As was discussed elsewhere [70], improving the residual resistance shifts the optimal cryogenic performance of SRF linacs to lower frequencies, and this is particularly important for ERLs that operate in CW mode. An analysis [71] based on a large sample of state-of-the-art SRF cavities tested recently at JLab indicates that an optimal frequency for a CW SRF linac is about 900 MHz. With the recent, rapid advances in obtaining very low residual resistance approaching 10^{-9} Ohm described elsewhere in this issue, the optimum is expected to shift to even lower frequencies. However, even more significant are issues of beam dynamics discussed earlier, such as the multi-bunch, multi-pass BBU and the generation of HOM power, which point toward choosing the lowest possible RF frequencies in the ERL. This can be seen for example in electron-ion colliders, with 802 MHz for the LHeC, and 647 MHz for eRHIC.

**Highly damped, low frequency SRF ERL cavities.** Several HOM damping schemes have been developed over the years [72]. It is worth noting two design of extremely well damped cavities designed specifically for ampere-class ERL service, using two different approaches for the HOM coupler ports, a 704 MHz cavity designed at BNL and built by industry [73] and a 750 MHz cavity designed and built at Jefferson Lab [74]. Both of these cavities feature six ports on the large-diameter beam pipes, the main differences being the nature of the filtering used to isolate the fundamental mode from the HOM damper termination and the RF connection, which is coaxial in the BNL cavity and conventional waveguide in the Jefferson laboratory cavity. R&D is being carried out towards improved HOM damping schemes, including the novel photonic band gap approach [75].

ERLs are typically long structures and must use the available space efficiently. Hence, it is important to maintain high real-estate gradient by keeping the distance between cavities and the cavity’s end groups as short as possible. The number of cells in a cavity is a compromise between the requirements for a real estate gradient (which improve with the number of cells) and good HOM damping, which improves with fewer cells.

**A few examples of ERL facilities**

Given that some ERL facilities will be described in detail in this volume, this manuscript includes just a concise description of three superconducting ERLs that are (or were) in operation or commissioning. The BNL R&D ERL, which has been in commissioning, has a unique capability for high current—it has been designed for as much as 500 mA. The Jefferson Lab Low Energy Recirculation Facility is the first SRF ERL and operated record-breaking average power FELs in the IR and UV. Finally, the Japan Atomic Energy Agency (JAEA) ERL has been the second SRF ERL to operate successfully.

**R&D ERL (BNL)**

A high current, high-brightness ERL was constructed as part of the R&D towards electron cooling of RHIC and the eRHIC electron accelerator [76]. The common feature of both applications is that a very high current in the ERL (possibly in multiple turns) is required, in the range of hundreds of milliamperes.

The main goal of this ERL was to demonstrate CW operation of ERL with average beam current in the range of 0.1–1 amper, combined with very high efficiency of energy recovery. The major SRF components of the machine are a 703.75 MHz elliptical SRF electron gun [77] and a 5-cell 703.75 MHz SRF accelerator cavity [78].

The gun is a half-cell designed for up to 2 MeV at 500 mA. It is equipped with a photocathode insertion mechanism capable of supporting high QE multi-alkaline photocathodes and two 500 kW RF input couplers.

The ERL accelerating cavity is equipped with two beam-pipe HOM dampers. The flexible lattice of the ERL provides a test-bed for beam dynamics issues and beam instrumentation for intense CW e-beam.

The ERL’s construction has been completed and commissioning started [79], however, the commissioning is halted due to project priorities, to be continued at some future time.

The layout of the BNL ERL is shown in figure 1, and a photograph of the ERL in figure 2.

**The Jefferson Lab Low Energy Recirculation Facility**

The Jefferson Lab Low Energy Recirculation Facility is based on an ERL [6, 80], and is shown schematically in figure 3. The electron beam is produced in a DC photocathode electron gun, accelerated to 9 MeV, injected into the ERL and then recirculated once through one of the two laser beamlines. After deceleration, the beam is dumped at the injector energy. Several ERLs have been demonstrated at Jefferson Lab and
the two beam lines in this facility have operated as high power FELs with 14.3 kW the infrared and 150 W in the UV. Close-up photograph of the IR FEL wiggle in foreground and linac cryomodule in the background is shown in figure 4. The facility can also deliver hundreds of watts of TeraHertz radiation to users. The ERL is capable of recirculating up to 9 mA of electron beam current at up to 170 MeV. The beam power is much higher than the installed RF power.

Though applications of the ERL to date have concentrated on coherent laser light production, the machine can also be used for internal target experiments in nuclear and high-energy physics. This machine has also been useful in characterizing the effects of CSR and longitudinal space charge in an energy recovering geometry.

JAEEA ERL

The JAEEA ERL has been developed for a high-power FEL. The ERL was originally constructed as non-ERL configuration in 1994 and converted into the ERL in 2002 by modifying an injector chicane and adding a return loop [49]. Figure 5 shows the layout of the JAEEA-ERL, and figure 6 shows a photograph of the return loop. The injector consists of a 230 kV electron gun with a thermionic cathode, 83.3 MHz sub-harmonic buncher and two cryomodules to produce an electron beam with an energy of 2.5 MeV and an average current of 10 mA at a repetition of 20 MHz. The electron beam is accelerated by the main linac, two 5-cell cavities, and transported to the ERL undulator. All the accelerating cavities are driven at 499.8 MHz with a 1% duty cycle, macro-pulses of 1 μs at 10 Hz. For reliable and easy operation of the superconducting accelerator, they employ a stand-alone and zero-boil-off cryostat, in which no regulation of domestic pressure vessel code is required. The FEL is operated at a wavelength of 22 μm with a high-efficiency of over 2%. The return arc has an energy acceptance of 15%, which is large enough to recover the electron beam used for high-efficiency FEL oscillation [81].

Summary

Many applications of electron beams induce just a small perturbation of the electron beam emittance and energy spread and do not consume the power of the beam. Prime examples of such applications are FELs, electron coolers and electron-ion colliders. Additionally, these applications require high-brightness of the electron beam and continuous operation. In high-current, CW applications this beam power is very high, and it is usually impractical to dump this beam power considering the cost of the power in operating and capital construction costs as well as the ionizing radiation produced at the beam dump. Superconducting ERLs are emerging as a natural solution to this situation by recovering the electron beam energy, and doing so quite efficiently, thanks to the low power dissipation of the SRF accelerator components. The interesting physics and technology issues of ERLs, in particular SRF ERLs have been presented rather briefly, but with extensive references to allow the interested reader to go deeper into the issues presented in this manuscript.

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