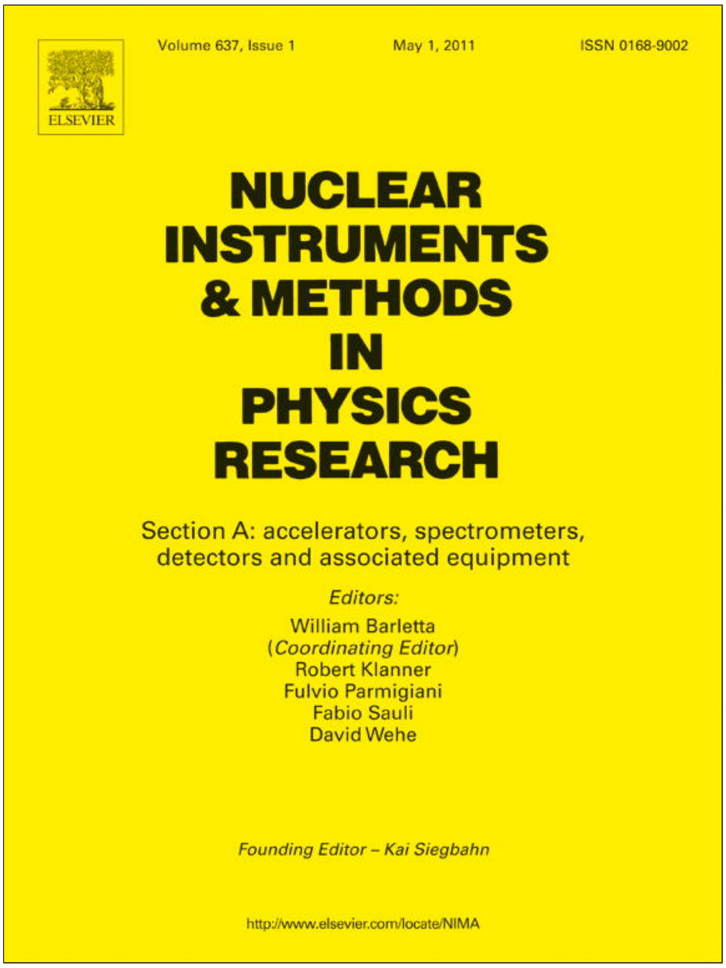
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X-ray sources by energy recovered linacs and their needed R&D

S. Benson [a], M. Borland [b], D.R. Douglas [a], D. Dowell [c], C. Hernandez-Garcia [a], D. Kayran [d], G.A. Krafft [a,e,*], R. Legg [f], E. Moog [b], T. Obina [g], R. Rimmer [a], V. Yakimenko [d]

[a] Thomas Jefferson National Accelerator Facility, 12000 Jefferson Avenue, Newport News, VA 23606, USA
[b] Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA
[c] SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025, USA
[d] Brookhaven National Laboratory, Upton, NY 11973, USA
[e] Center for Accelerator Science, Old Dominion University, 4600 Elkhorn Avenue, Norfolk, VA 23529, USA
[f] Synchrotron Radiation Center, University of Wisconsin-Madison, 3731 Schneider Drive, Stoughton, WI 53589, USA
[g] High Energy Accelerator Research Organization: KEK, Tsukuba, Ibaraki 305-0801, Japan

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ABSTRACT

In this paper we review the current state of research on energy recovered linacs as drivers for future X-ray sources. For many types of user experiments, such sources may have substantial advantages compared to the workhorse sources of the present: high energy storage rings. Energy recovered linacs need to be improved beyond present experience in both energy and average current to support this application. To build an energy recovered linac based X-ray user facility presents many interesting challenges. We present summaries on the Research and Development (R&D) topics needed for full development of such a source, including the discussion at the Future Light Sources Workshop held in Gaithersburg, Maryland on September 15–17, 2009. A first iteration of an R&D plan is presented that is founded on the notion of building a set of succeedingly larger test accelerators exploring cathode physics, high average current injector physics, and beam recirculation and beam energy recovery at high average current. Our basic conclusion is that a reviewable design of such a source can be developed after an R&D period of five to ten years.

1. Introduction

Synchrotron radiation sources may be divided broadly into two classes. Sources of "spontaneous" radiation, including most storage ring light sources, involve independent emission of radiation by each electron. The other class, which includes free electron lasers, involves coherent emission of radiation by an appropriately bunched beam. Energy recovery linacs [1] (ERLs) can drive sources of both types. In the X-ray regime of photon frequencies the primary emphasis at present is on spontaneous radiation sources that promise to provide spectral brightness several orders of magnitude greater than that available from storage rings.

To understand the potential advantage of ERLs, it is necessary to understand how the electron beam properties influence the X-ray brightness [2]. The brightness may be expressed as

$$B \sim \frac{I_e}{E_x E_y \sqrt{4\sigma_\delta^2 + \left(\frac{0.4}{hN_u}\right)^2}}, \tag{1}$$

where I_e is the electron beam average or peak current, N_u is the number of undulator periods, h is the undulator harmonic, σ_δ is the rms fractional momentum spread of the electron beam. In addition, E_x and E_y are the photon beam emittances in the horizontal and vertical plane, found by convolving the electron distribution with the single-electron photon distribution, yielding

$$E_q = \sqrt{\left(\varepsilon_q \beta_q + \frac{\lambda L}{8\pi^2}\right)\left(\frac{\varepsilon_q}{\beta_q} + \frac{\lambda}{2L}\right)} \tag{2}$$

where q is x or y, ε_q is the electron beam emittance, β_q is the electron beam beta function, λ is the radiation wavelength, and L is the undulator length. From this equation we observe that the single-electron photon distribution has an emittance of $\lambda/4\pi$ and a beta function of $L/2\pi$. If the electron beam is given the same beta function, then

$$E_q = \varepsilon_q + \frac{\lambda}{4\pi} \tag{3}$$

which is the smallest possible value for the photon beam emittance and yields the highest brightness for a given electron beam emittance. For a typical storage ring, L is 2–5 m, so that the optimum beta function is 0.3–0.8 m. Achieving such small values in a ring is difficult as it forces large beta functions elsewhere in the system, creating difficulties for dynamic aperture. This argument

* Corresponding author at: Thomas Jefferson National Accelerator Facility, 12050 Jefferson Avenue, Newport News, VA 23606, USA.
E-mail address: krafft@jlab.org (G.A. Krafft).

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Table 1
Present advanced photon source beam parameters compared to ERL X-ray source parameters in high coherence and high flux modes [4].

Quantity	APS	ERL high coherence	ERL high flux
Beam energy (GeV)	7	7	7
Average current (mA)	100	25	100
Repetition rate (MHz)	6.5–352	1300	1300
Bunch charge (nC)	<59	0.019	0.077
Horizontal emittance (geometric pm), [normalized (μm)]	3100 [42]	6 [0.08]	20 [0.27]
Vertical emittance (geometric pm), [normalized (μm)]	25–50 [0.35–0.70]	6 [0.08]	20 [0.27]
rms bunch length (ps)	>20	2	1.7
rms energy spread (%)	0.1	0.015	0.014
Photon brightness (10^{20}p/(s mm^2 mrad^2 0.1%BW))	0.3	200	60

Photon brightness at 10 keV reported.

highlights the first possible advantage for ERLs as light sources: freedom to use the optimum beta function.

Assuming that $\beta_q = L/(2\pi)$, if we additionally have $\varepsilon_q < \lambda/(4\pi)$, the source is said to be diffraction limited. In this case, we obtain the highest possible brightness and full transverse coherence. One important goal of any spontaneous X-ray source is to provide diffraction limited radiation at, say, 1 Å. This requires $\varepsilon_q < 7$ pm, a value that is achieved in the vertical plane in many modern storage rings. However, present storage ring designs cannot approach this performance in both planes (see, however, Ref. [3]). These considerations highlight the second potential advantage of ERLs as light sources: the ability to supply ultra-low electron beam emittances and hence reach the diffraction limit in both transverse dimensions.

Returning to Eq. (1), we note that if $\sigma_\delta \to 0$, then $B \propto N_u$. If, however, σ_δ is large, the benefit of a longer device is diminished. In storage rings, typically $\sigma_\delta = 0.1\%$, whereas in a linac, σ_δ can be considerably lower, being determined by the bunch length and the rf frequency. This highlights the third potential advantage of ERLs as light sources, namely, the ability to better capitalize on long undulators to achieve higher brightness. Fourthly, the electron beam longitudinal distribution is easily manipulated in the ERL because of the absence of significant radiation damping in the time it takes the electrons to traverse the accelerator. This circumstance allows the possibilities of, by longitudinal compression of the electron bunches, high repetition rate short X-ray pulse fluxes beyond those possible in storage rings.

Finally, note that Eq. (1) contains the electron beam current. In storage rings, the average beam current can easily exceed 100 mA. In the past, high average current has been a decisive advantage in favor of storage ring light sources. The energy recovery concept directly addresses this issue by reducing the power requirements for running continuous beam from a linac. ERL beam conditions supporting two possible X-ray production modes are listed in Table 1, scaled to the same beam energy, and compared to those in the forefront storage ring source [4].

2. Accelerator physics and challenges of ERLs

While essential, the concept of energy recovery does not address all of the challenges facing linac-based spontaneous light sources, which are discussed in detail in this section of this paper. Much information on the challenges and their present status may be found in the proceedings of the biennial conferences on ERLs that have been held at Jefferson Laboratory [5], Daresbury Laboratory [6], and Cornell University [7], and in recent review papers at accelerator conferences [8–10]. Here, we briefly highlight some of the most difficult challenges, which begin at the cathode where the electrons originate, and continue throughout the system until the electron beam is decelerated and finally dumped.

In the injector, challenges include the production of ultra-low emittance beams with high average current that is sustained for long periods (e.g., days), as expected at a user facility. Significant improvements in cathode technology will be essential to success on this topic. The choice of gun type is not settled, particularly given some of the difficulties that have been encountered for very high-voltage DC guns.

Given the high average current and high beam energy, controlling beam loss is a critical issue, requiring dramatically better understanding of the mechanisms of halo generation and loss. Effective collimation systems that do not adversely impact beam brightness must be developed. As for any high-brightness beam, collective effects have significant potential for impacting performance. Among these are space charge, coherent synchrotron radiation (CSR), short- and long-range wakefields, ion trapping, and intrabeam scattering. An important issue related to collective effects is management of the energy spread after deceleration, which impacts beam loss and the ability to recover to a low beam energy.

Design of the overall system presents challenges of a different type, related to optimization of cost and performance. Issues such as the choice of maximum beam energy, choice of undulator length and the number of undulators, choice of the number of passes to use through the linac, and best design for preserving the emittance must be considered. Related issues are determining tolerances and development of adequate correction and feedback systems.

Experience with free-electron lasers has demonstrated convincingly the utility of accurate, start-to-end modeling. Most of these challenges will require a significant improvement in computational capabilities and sophistication. Not only are improved codes required, but benchmarking is essential to give the confidence required to build a full-scale facility.

2.1. *Significant research and development topics needed for an advanced ERL-based X-ray source*

2.1.1. *Photocathode studies*

The three basic types of cathode that have been used to generate electron beams for accelerator-based applications are semiconductor photocathodes, metalic photocathodes, and thermionic cathodes. At Jefferson Laboratory, Daresbury Laboratory, and Cornell University, a Cs:GaAs photocathode is used in a DC gun [11], while the Budker Institute FEL/ERL [12] utilizes a thermionic cathode. To date, no other type of cathode has delivered continuous beam for an ERL-based machine. The JLab FEL DC gun delivered over 900 h and 7000 Coulombs at 2–9 mA CW from a single GaAs wafer between 2004 and 2007. Cornell University has recently demonstrated 20 mA average DC current after the gun and 8 mA from their 6 MeV injector [13]. In 1991, the Boeing normal conducting RF gun demonstrated 32 mA with a K_2CsSb photocathode and still holds the record for the highest average current from a photo cathode gun [14]. Cs_2Te cathodes have been in operation for 120 continuous days in a normal conducting RF gun at PITZ with minimal QE degradation. Thermionic cathodes have very good lifetime but gating the current in ps-long pulses is very difficult. The JAERI FEL used a thermionic cathode in a quasicontinuous, but low duty factor mode [15]. As a low repetition rate injector the CeB_6 gun works well, has successfully delivered stable 500-keV beams to the SCSS test accelerator for three years [16], and is now operating for various EUV-FEL user experiments. Such results indicate that 100 mA sustained sources are within reach. However, in order to more completely understand and quantify cathode lifetime limits, dedicated studies to understand the origin of the limits, occurring presently at Jefferson Lab, BNL, and Cornell University, will need to continue.

A primary issue regarding photocathode gun performance particularly important for ERL applications is whether it is possible to achieve required beam quality specifications. Requirements in transverse emittance are more than an order of magnitude better than has been achieved in CW electron sources to date. This issue is discussed in a companion paper to this one [17], and detailed simulations suggest that the emittances required for hard X-ray ERLs can be achieved [18,19]. Recent measurements of beam quality at Cornell University [20], in a DC photocathode gun designed to drive an ERL [21], are promising. Incomplete answers on both of these issues support the notion of measurements at photocathode test stands to perform dedicated R&D studies on long lifetime high beam quality photocathode arrangements. This idea is incorporated in the ERL R&D plan discussed below.

2.1.2. *Drive laser*

The photocathode drive laser for an ERL is integrally tied to the photocathode design. The challenges of the two complement each other. For example, a UV capable photocathode is more robust and has a longer lifetime but a UV photocathode drive laser is very challenging. If the cathode quantum efficiency is high, the drive laser gets easier but the cathode is now very hard to produce. The product of the laser power and quantum efficiency is a constant for a given laser wavelength and beam current. With very high quantum efficiency the laser power absorbed by the cathode can be reasonably low (though still requiring active cooling). For quantum efficiencies much less than about 1% for 100 mA beams, the power absorbed becomes a major engineering challenge [22]. The total power that can be absorbed by the photocathode is no more than 1 kW/cm^2 and with typical spot sizes this means that the drive laser cannot deliver more than 100 W to the cathode. The laser itself must put out more than this to provide for transport losses. This level of power is available today with custom laser systems but not in conjunction with the rest of the specifications detailed below. With the technology choices available today the mainstays of photocathode drive lasers are neodymium or ytterbium doped crystals. These lase at approximately 1060 nm in the near infrared and can be efficiently doubled to the green at 530 nm. With more difficulty they can be tripled or quadrupled to produce light near 350 or 265 nm. At high power levels the harmonic generation crystals suffer from rapid degradation. Laser systems operating in the visible are therefore greatly preferred. The drive laser must produce not just average power but a pulse train of highly stable shaped pulses with excellent contrast ratio [23]. The ideal pulse shape is that of a uniformly filled ellipsoid [24] but current technology can only produce uniformly filled cylinders with moderately sharp edges [25]. The power outside of these pulses must be as low as possible in both time and space. The pulses must also be nearly identical in shape, size, arrival time, and amplitude both on a fast time scale and over hours or days. Diode pumped systems with feedback controls can provide reasonably stable laser systems but not yet at the levels required for an ERL machine (for example 0.1% amplitude at the harmonic wavelength and 100 fs timing stability). Finally the laser time structure must be variable so that a low-duty-factor, low average current, mode can be provided for accelerating tuning. There must then be some way to smoothly transition from the tune-up mode to full current operation in a reasonable time. Ideally this time structure control and the pulse shaping should be done at low power. The pulses would then be amplified and frequency converted into the final pulses. Due to the tendency of amplifiers to have much higher amplification at the beginning of a pulse, it is not possible to select out pulse trains at the input to the amplifier. This must be done at full power but can be accomplished using low loss Pockels cells and mechanical shutters. The longitudinal pulse shapes will probably change in the amplifiers as well so the ideal pulses are not necessarily at top hat at low power. Clearly there are many severe engineering design challenges that must be met to produce a reliable, stable, photocathode laser with the desired spatial and temporal specifications and the controls necessary to power a high current photocathode gun. Fortunately, the field of lasers is progressing rapidly so such a system is not out of the question for a high power ERL.

2.1.3. *Emittance preservation*

Preservation of beam quality in a large-scale ERL poses numerous interesting challenges [26,27]. An obvious issue is the management of the various transport lattice aberrations experienced by the beam during the acceleration, recirculation, and recovery cycle. By simulation calculation it has been shown [28,29] that one can preserve emittances at 1 μm (normalized) levels by using second order achromats [30,31] of sufficiently large bending radius. In these proofs-of-principle, the transport was also used to perform compression and decompression of the bunch length. Longitudinal effects during this process can have significant impact. There is a need to compensate for the effect of the RF curvature on the longitudinal phase space; such correction has been demonstrated using arc sextupoles and octupoles [32]. This correction must be completed with some care and caution, as it has been observed to drive intolerable phase space degradation in the aforementioned studies [33] with a devastating effect on the emittance. Though harmonic RF can be used for this compensation [34], it is a very costly option, inasmuch as the cost of the linac increases by more than 20% because the linearization process uses deceleration at the harmonic frequency and phase. In addition, it presents considerable opportunity for instability (via the impedances and wakes introduced by the harmonic RF) and operational difficulty (due to the aperture constraints imposed by the higher frequency cavities). The use of very high order achromats [35,36] or integrable lattices [37–40] has the potential to accommodate all functions in the arcs with preservation of the emittance: returning beam for deceleration, compensating the effect of RF curvature, compressing/decompressing the bunch length.

Incoherent synchrotron radiation (ISR) has been recognized as a performance limitation even in the earliest electron storage rings [41]. Recent existence proofs [42] demonstrate that the required performance can be achieved even in multiply recirculated systems, but considerable care must be taken and the resulting systems can be large and complex. In contrast, bunch self-interactions such as longitudinal space charge, microbunching instabilities, and coherent synchrotron radiation represent significant and ongoing challenges to contemporary linear-accelerator-driven light sources, particularly in high charge, short duration pulses. Success with the management of these effects in the Linac Coherent Light Source (LCLS) [43] provide promise that appropriate accelerator design and use of as-yet novel techniques to mitigate CSR-induced energy spread – by use, for example, of shielding – would allow a more complete optimization of the parameter space and admit a move toward operating with shorter bunches [44]. This could make systems less susceptible to RF curvature effects. There are a number of theoretical studies on the subject, but only two experimental results [45,46] with limited relevance that do not allow us to draw a conclusion one way or another about the viability of the method.

Emittance degradation is also driven by other interactions of the beam with itself and its environment. Scattering effects such as the Touschek effect and intrabeam scattering as well as beam-gas scattering—can degrade ultra-low emittance beams [47,48]. In addition, the interaction of the beam with environmental impedances has been demonstrated as a performance limit not only in storage rings, but also in existing ERL-based light sources [49]. Care in limiting wake effects and managing the impedances of beamline components must therefore be taken [50].

Despite the numerous challenges and the incomplete maturity of ERL technology when writ large, there exists a considerable basis both theoretical and empirical indicating that beam quality preservation is a tractable problem at levels required for ERL-based 4th generation light sources. Preservation of emittance at the level of 1 μm has been achieved in simulations, albeit using expensive solutions with large radius bends and third harmonic cavities. Large reductions in cost can be achieved if solutions are found for mitigation of CSR induced energy spread (such as by shielding and/or lattice designs alleviating CSR effects) and compensation of RF curvature effect in arcs using sophisticated nonlinear optics. Extrapolation of these methods may allow even more dramatic cost reductions through the use of multi-pass architectures.

2.1.4. Beam halo

With the advent of high average beam power, it becomes increasingly important to measure and control beam halo, and guarantee that excessive beam losses do not occur in the ERL. Measurements at the CEBAF accelerator at Jefferson Lab at relatively low average power and low beam charge show that halo generation at high energy can be controlled to the 10^{-4}–10^{-5} level compared to the Gaussian core current [51], even after most of the beam energy has been recovered [52]. Localized continuous losses less than 1 μA at several GeV energy scales are needed to assure vacuum containment in the accelerator beam lines, and are continuously monitored by differential current measurements in CEBAF [53]. A similar requirement on continuous loss has been placed on the Jefferson Lab free electron laser, operating at up to 160 MeV, and been achieved at 10 mA average current, including the fact that the FEL itself generates substantial energy tail. So present experience is within two orders of magnitude compared to potential ERL requirements, which are at the 10^{-5}–10^{-6} relative loss level.

Because the requirements for beam loss, particularly within small gap undulators posited for ERLs, are somewhat more stringent than present experience, it is reasonable to suggest that thorough measurements of beam halo are appropriate in order to understand beam halo mechanisms in ERLs. The measurements should be able to distinguish 10^{-6} level currents, and their spatial distribution, in the presence of the primary beam. Halo sources are expected in the gun region (laser halo and space charge), linacs (wake and other collective effects), and recirculation arcs (CSR). Therefore, repeated measurements quantifying each expected source term at each stage of acceleration are desirable. Particularly important is to ensure the beam quality after deceleration back to low energy will be adequate. Existing high average current storage ring experience, where small halo is generated by quantized synchrotron radiation emission, a mechanism which should lead to similar time-averaged losses in ERLs, leads to optimism that adequate solutions will be found.

2.1.5. Ion effects

Ion effects in particle accelerators are not a new phenomenon [54–56], and the theory of their cause and effects is well documented [57–59], particularly in circular machines. Unfortunately, a completely effective solution for clearing ions has not been established [58], and ions which are not cleared may have serious consequences for the performance of an X-Ray ERL light source. Ion effects have only been observed in circular machines, never in any operating ERL device. This may be due to the limited size, low current, or low pulse repetition frequency which existing ERLs operate at and the difficulty in definitively measuring the effect. The effects which have been observed from ion trapping in rings include: tune shift [60], emittance dilution [61], halo production [62], head–tail effects [63], and the fast ion instability [64]. For an ERL device, the equivalent effect to ring tune shift is a focusing mismatch between the lattice and some of the particles. This in turn can cause emittance growth [65] and halo formation of the beam [66,67]. Emittance dilution due to direct ion interaction with the beam [68] has been documented in damping rings. Because of the stringent requirements on beam emittance and halo production in an X-ray ERL, these problems must be addressed in the design phase of the device or risk meeting ultimate performance goals.

The mechanism for ion production in an X-ray ERL is collisions between the electron beam and residual gas in the beam pipe [57]. The ions produced are trapped in the electric field of the electron beam. DC clearing works by producing a large electric field which overcomes the trapping field, allowing the ions to escape. There are two problems with this scheme; DC clearing cannot be deployed everywhere and the electrodes themselves need to be designed to avoid impacting the beam through reflected waves or wakefields [69]. Another technique used is to insert gaps in the bunch train which allow the ions to drift out of the beam path. For ERLs this has the problem that gaps in the bunch train induce transients in the injector RF systems, HOMs, and power supplies [59], and these transients may push the beam parameters out of specification. Another technique used in storage rings to eliminate ions is beam shaking or RF clearing, using an AC field to resonantly drive the ions out of the field of the electron beam [58]. In circular machines this is accomplished by driving the electron beam close to a resonant tune and letting that resonance drive the ions. It is unclear if such a scheme could be made to work in an ERL or if direct drive at the ion resonance would be required. Work has been done on developing numerical models for ion production and mobility and integrating them into a simulation tool [65]. The simulation tool allows rapid analysis and design of an ion clearing system for ERLs.

Still needed is to develop a set of experiments and instrumentation which allow the production and effects of ions in ERLs to be quantitatively measured. For example, one could use existing pickup structures (BPMs, striplines, cavities, etc.) on ERLs to measure the change in impedance of the pipe due to the presence of ions as a possibility. The results of such experiments would be used to verify/modify the numerical models which could in turn be used to design an X-ray ERL light source with an integrated ion clearing system.

2.1.6. Beam stability

Presently, there are very few published measurements of beam stability and quality of ERL beams. Given the high demands placed on beam stability by a light source application, more information on this subject needs to be obtained as light source proposals are developed. Demanding experiments at CEBAF with relative rms energy spreads at $2–3 \times 10^{-5}$ have been operated for periods of a month, with centroid shifts under this spread held for periods of days [70]. The beam path on recirculation in CEBAF changes at the 250 μm level (1°) due to daily temperature excursions [71]; these drifts are only periodically corrected. Measurements of micro-bunch phase stability have been performed at CEBAF and the Jefferson Lab FEL [72]. These measurements indicate tight control of the centroid fluctuation to the sub-100 fs level, on time scales up to 1 kHz. Fast position feedback systems, with update rates of several hundred Hz, are deployed at CEBAF. Position fluctuations at the 10 μm level, after correction, and angular fluctuations at the μ radian level are obtained with a system operating at 10−100 μA beam current [73]. As position signal levels with a typical ERL beam will be around three orders of magnitude larger, one anticipates position and angular stability, with feedback, at a level comparable to the storage ring source standard [74].

Perhaps the most difficult parameter to stabilize will be the average beam current because new beam is continuously injected into the ERL. Present experience with the Jefferson Lab FEL indicates current stability at the several per cent level. Advanced fast current locking systems have not been needed on existing recirculated linacs, and have not been developed. More information on this important topic should be forthcoming from ongoing work at Cornell.

2.1.7. High power beam diagnostics for ERLs

ERLs require exceptional beam quality in order to enable the science envisioned. To maintain the exceptional quality during user operational periods will require a suite of diagnostics capable of non-invasively monitoring the beam. Most of the bunch diagnostics available today were developed to operate in a single bunch or low power mode; see Refs. [75,76] for an overview. These diagnostics will need to be adapted to analyzing the electron beam in a non-destructive manner during production runs [77]. Non-invasive diagnostics which can monitor the beam quality during high power operation have been used on synchrotron storage rings for years [78], but depend on the fact that the lattice in a storage ring sets most of the beam properties, and that time averaging the result is desirable since that mirrors the user experience. In the ERL, by contrast, each pulse is produced separately and is only a function of the cathode and the intervening beam structures. Advanced synchrotron radiation monitors have been used in linear electron accelerators to monitor the transverse and longitudinal bunch dimensions [79,80], the energy spread [81], and get insight on the longitudinal phase space distribution [82]. Electro-optical diagnostics which utilize the electric field surrounding the beam to cause a Pockel's effect in adjacent crystals, have been implemented by various groups [83–85] with sub 100 fs resolution.

One of the resolution limits in these diagnostics comes from the $1/\gamma$ (γ being the Lorentz factor) opening angle of the bunch's electric field distribution. Such an energy-dependent resolution makes the electro-optical imaging technique not suitable to diagnose the bunch length at low energies (i.e. in the injector or beam dump region after deceleration). The resolution in these diagnostics is limited by the degree to which the bunch's electric field is perpendicular to the crystal, defined by the beam's energy, so this technique may not be applicable to the injector or beam dump region. The optical replica synthesizer method proposed and demonstrated at FLASH [86,87] shows great promise to allow single bunch analysis of the beam with minimal disruption. The technique can be extended to yield transverse slice emittance directly by placement of optical synchrotron radiation detectors with the proper phase advance along the beam path from the initial modulation. The resulting transverse profiles can be used to reconstruct the phase space of the beam. Many of these diagnostics depend on the ability to synchronize the diagnostic to the electron beam with a resolution and stability much smaller than the bunch length. Synchronization systems with these specifications have been demonstrated [88] but will need further work to be integrated into the controls and diagnostic suites described. Further R&D will also be needed in order to take the research instruments cited above and re-engineer them for use on a user X-Ray ERL light source.

2.1.8. Undulators for ERLs

Undulators that are intended for use on an ERL can be similar to those presently in use at storage rings, or can take advantage of characteristics specific to an ERL to enhance the photon output. An ERL electron beam is smaller than a storage ring electron beam. The smaller beam allows the possibility of a smaller gap and higher field from a given undulator. That higher field translates into a tuning range that extends to lower photon energy, or can be used to make shorter period lengths possible without loss of tuning range. The shorter period undulator produces higher brilliance than a longer period (on the same harmonic), for all photon energies that it can reach. The ERL electron beam is also nearly round in cross-section, so magnetic components can be placed closer to the beam horizontally. This would allow the undulator to be turned so its field is horizontal and the resulting photons are vertically polarized. Users' mirrors would then deflect horizontally, keeping the entire beamline at the same height above the floor. The round beam will also increase the possibilities for polarizing undulators, because horizontally closer magnets and the resulting stronger horizontal field make stronger-field circular undulators possible. (See, for instance, the Delta [89] and APPLE-III [90] undulators.) Helical undulators with wire wound directly around the beam tube [91,92] also become possible. If one uses a design that puts permanent magnets closer to the beam and the source of stray radiation, consideration should be given to enhancing the radiation resistance of the permanent magnets, though today's high-coercivity magnet grades are much more radiation resistant than the magnet grades of the past.

The smaller electron beam energy spread of an ERL also offers possibilities. As the length of the undulator increases, the energy width of a harmonic peak decreases and the peak brilliance goes up, until the contribution from the energy spread of the electron beam becomes the dominant contributor [93]. Beyond that, there are no further gains in brilliance from increasing the undulator length. The smaller energy spread of an ERL electron beam extends the brilliance gains to longer undulators, so that the longest reasonable undulator might be 10 × longer for an ERL than for a typical storage ring. There are challenges involved in building such a long undulator, however. R&D would be needed to devise and produce a means of keeping undulator segments in phase as the gap is changed. Also, the energy loss in the electron beam from such an undulator may be larger than the beam energy spread. This could lead to a long-undulator beamline affecting beam characteristics of a downstream beamline. RF cavities located downstream of the long undulator have been suggested as a correction [94], but this would require R&D. Also, there could be timing changes downstream as the gap of a long undulator is varied that would interfere with timing-sensitive applications. The smaller beam from an ERL also can present challenges to undulator tuning. With a very small spot size, users, especially microscopists, will become more sensitive to photon beam motion. Some variation in the kick at the end of an undulator is inevitable as the undulator gap is changed, and electron beam position monitoring is not sufficient to determine the photon beam position. Instead, the photon beam position itself must be monitored and used for feedback. Another possibility offered by an ERL is an increased coherent fraction in the photon beam as compared to a storage ring. This is most pronounced in the bending direction because of the much smaller horizontal beam size in an ERL as compared to a storage ring. The various types of undulators presently being developed for storage rings would also find application on ERLs. In-vacuum, cryogenic permanent magnet, and superconducting undulators would offer enhanced capabilities, in similar ways to their possibilities on storage rings. The advantages of schemes to remove higher harmonic contamination from the spectrum, such as quasiperiodic [95,96] designs or the use of circular polarization would also apply to ERLs.

2.1.9. SRF guns for ERLs

Superconducting radio frequency (SRF) electron guns hold promise to produce beams of exceptional brightness as part of an ERL system. They do this by generating very large CW electric fields at the cathode, resulting in brighter beams at a given bunch charge [19]. Several implementations of SRF guns are in development world wide [97–101]. The devices currently under development [102] can be broadly divided by their operating frequency and shape. High frequency guns tend to be elliptical in design, while low frequency guns tend to be quarter wave resonator cavities, with the elliptical technology being more mature. Several mechanisms for mating a high temperature photocathode to the cavity have been employed. The difficulty is providing a thermal gap between the cathode and the cavity while making it appear to be a short circuit to the rf fields. This problem has been overcome using tuned structures between the cathode and the cavity. Many other areas of R&D remain, however. Some of those areas are cathode compatibility with the cavity, high power couplers and HOMs, particularly in cases where the device will be called on to produce relativistic beams at high average currents.

2.2. Significant computational requirements

Next, we briefly assess the status of existing computer codes relative to the physics challenges faced by ERLs. We attempt to identify where our modeling ability is weakest, and in particular to point out those phenomena which pose a significant risk to the success of an ERL light source but that are inadequately modeled presently.

Gun issues include modeling with space charge, cathode physics, and design-specific challenges such as insulator breakdown. Recent results [103] from the LCLS show that when sufficient care is taken in the modeling and engineering, results can be obtained that meet expectations. The development of improved cathode materials could have a significant payoff in terms of ERL brightness and feasibility as a user facility. One promising approach [104] is to use computation to model the electronic structure of candidate materials. This can be used to pre-select materials with the desired properties for experimental characterization. The state of code development for this effort appears to be adequate, but could benefit from streamlining and automation. Another significant challenge with DC guns is obtaining the required high voltage necessary to get ultra-low emittance [18]. Modeling tools could speed the development process and would have a high impact on the success of an ERL light source [105].

Loss of beam halo particles is a significant concern due to the high average current. There are many mechanisms for halo generation, most of which are poorly understood and modeled. In this latter group are phenomena such as field emission from the gun and linac, drive laser reflections and halo, cathode non-uniformity, and residual gas scattering. A few phenomena, such as Touschek scattering [106–109], external field nonlinearity, and space charge, are adequately covered, though application to ERLs has not necessarily been made. A related issue is design of effective collimation systems, which is adequately covered by combinations of existing tracking codes and Monte Carlo codes.

Computation of wakefields for picosecond bunches in long structures (e.g., a long insertion device chamber) is a challenge. The adequacy of existing higher-order electromagnetic codes, such as SLAC's T3P code [110], needs to be evaluated. Roughness wakes [111] and resistive wall effects [112] are also important and in need of more detailed computational study. Coherent synchrotron radiation effects are treated by several codes [113–115], using variants of a 1-dimensional model that has yielded good results for LCLS [103]. The parallel version of `elegant` [116] is capable of determining microbunching gain curves for a large ERL [117]. With the recent addition of shielding in BMAD [118], this subject is believed to be adequately modeled.

Start-to-end (S2E) modeling has proved very valuable in development and understanding of X-ray FELs [119,120]. The first application of S2E to an X-ray ERL [121] yielded some surprising results. A significant missing piece is fully integrated modeling of the laser system, including errors.

3. From R&D to facilities and evaluation of readiness

3.1. Key photon beam performance objectives

Up to present, discussions of ERLs as light sources have been specific to relatively hard photons, exceeding 1 keV, with photon fluxes exceeding only by small factors those present in existing storage ring sources, but with average and peak brilliances considerably above storage rings. Presently, serious proposals posit from 5 to 7 GeV in the ERL electron beam; to achieve high brilliance it is essential that exceptionally high average brilliance electrons be produced in the electron gun, and that the brilliance be increased during acceleration by the usual transverse betatron damping by acceleration. Thus ERLs are not so attractive at lower photon energies, both because competing storage rings have smaller damped normalized emittances there, and the advantage from betatron damping is not so great [122].

In order to fully utilize the higher electron beam brilliance, it will be necessary that the beam stability in transverse position at the insertion devices be a small fraction of the beam size there. Such small fluctuations are achieved at present day storage rings in the vertical direction, and lead to optimism that suitable feedback system designs can be developed starting with those deployed at rings [74].

3.2. Which topics could be addressed today?

Significant parts of the development process leading to the possibility of a high energy ERL-driven X-ray source can be, and are being addressed at present. For example, experiments can be performed in existing facilities at Cornell University, the Jefferson Lab energy recovering FEL, the Brookhaven National Lab ERL, and even at the CEBAF accelerator at Jefferson Lab, to elucidate ERL accelerator physics. Topics that could be investigated quantitatively with R&D support include: beam merging, emittance preservation in arc transport systems, CSR characterization and mitigation, quantitative ion trapping studies both through direct detection of accumulated ions and through detection of their effect on the electron beam dynamics, longitudinal space charge, beam stability in recirculated and energy recovered linacs, instability mitigation using transverse feedback systems, characterizing resistive wall effects, particularly in insertion devices, and benchmarking of codes with experiment.

A recurring theme in this workshop was the need to become more systematic in cathode studies. There are specific issues, particularly regarding cathode lifetimes in high average current applications and space charge generated emittance limits [123], that can be addressed at the cathode surface physics laboratories being developed around the country [124,20]. Provisions for measurements of extracted beam quality at these laboratories is essential for future ERL development.

As shown in Fig. 1, Cornell University is completing an injector test facility whose overall goal is to demonstrate high average current electron beams of beam properties suitable for ERL light source applications [125,13]. The results from this test stand will be highly important in demonstrating suitable initial beam quality and control of the beam dynamics in the first parts of the accelerator. It will also allow, not as conveniently at the cathode physics laboratories, cathode studies with the photoemitter integrated into a real operating environment.

3.3. Which topics could be addressed with a short term [few years], focused R&D program?

In the near term three high level goals could be achieved through a focused R&D program: (1) demonstrate production of high average brightness beams, (2) demonstrate suitable transport and phase space manipulation of high average brightness beams including quantifying injector halo, and (3) demonstrate requisite injector beam stability. Topic (1) includes demonstrating suitable beam current, and demonstrating a usable cathode lifetime for the ERL application in close-to-final injector configuration. Topic (2) includes direct checks of emittance growth during acceleration, demonstration of suitable emittance compensation schemes [25], and measurement and mitigation of any beam halos generated in the injector regions of the accelerator. In topic (3) one needs to demonstrate that the fluctuations in the beam bunch centroids in transverse position, angle, and longitudinal phase are small compared to the final injector bunch dimensions. Such measurements have been done in a cursory manner, and not necessarily with the precision required in a light source application, at existing facilities [70,73]. Presently, all of these issues are being addressed experimentally at the Cornell injector test facility, in a DC electron gun arrangement. The results of their studies will form a linchpin of all future ERL light source studies. In this paper it will be assumed that the Cornell injector will be supported to conclusion of these studies, and that the existing injector test stand can be made available for driving a small beam recirculation experiment afterwards.

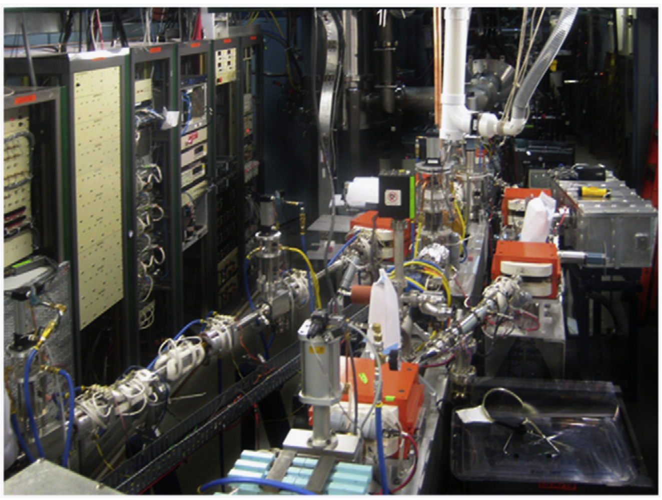

Fig. 1. Beam analysis lines of Cornell University's high average current ERL Injector.

On the 3–6 year time horizon, two high level goals could similarly be accomplished: (1) develop an RF-gun-based alternative to the present DC guns used in ERL applications and (2) recirculate high average current beam through more that two accelerating and decelerating passes in an ERL configuration. It is well known that DC guns have technological limitations and difficulties that it would be nice to avoid [126]. There are reasons to think that RF guns, if they could be developed to operate in a CW mode, may produce beams with superior quality. As DC gun development is already proceeding at Cornell with National Science Foundation support, it may be wise that CW RF guns with high repetition rate be developed under Department of Energy stewardship.

In the future, when a final proposal for a light source is assembled, it will be necessary to know whether multiple accelerating and decelerating passes in the ERL configuration will be possible, because of possibilities of cost reduction. Because a highest energy recirculation must be done in any case, the question reduces to whether lower-energy recirculations contribute significantly to beam quality reduction, and whether average beam current limitations in the accelerator structures will be exceeded by multiple beam recirculations. These issues will be directly addressed by deploying an ERL test facility, which would take beam from the injector test facility and recirculate it multiple times around a few beam acceleration modules.

3.4. Which topics could be addressed in the longer term?

In the longer term several high level goals need to be achieved through the R&D program: (1) design of a full energy source using information obtained through prior R&D efforts, (2) establish the beam halo performance of the full design through simulations and experiments, (3) SRF cavity optimization regarding Q_0, high order modes (HOMs), and frequency choices, (4) RF system optimization, and (5) cryogenics plant optimization. The final three topics are significantly related to the final operating costs for the full energy facility. Successful R&D on these topics could substantially reduce future facility operating costs.

The overall goal of any proposed development plan has to be to complete the studies needed to put forward a credible design for an ERL-based X-ray source. Up to now, existing source designs have utilized extant storage ring infrastructure, usually by having one of the turn-around arcs of the ERL consist largely of an existing storage ring. For comparison purposes, and to fully evaluate performance limitations imposed by such a selection, determining the performance of green field designs deploying the best available ideas could be highly useful in answering the question whether such choices are worthwhile. The answer to this question may evolve as designs are adjusted as more information becomes known.

The halo in the final machine, so important for machine protection, must be repeatedly addressed at each new level of device size. It is anticipated that studies on this particular topic will continue throughout the development process, and indeed, not receive rigorous resolution before the final source is built.

For next generation ERL-based light sources it is desirable to have the highest bunch rate possible to provide high average brightness. This requirement, combined with the need for high average accelerating gradient to keep the machines to manageable size, drives the requirement for CW superconducting RF (CW SRF) technology. Fortunately large-scale installations such as CEBAF [127] have shown that this technology is mature enough to make such facilities feasible. Existing ideas on light sources have been predicated on deploying superconducting RF cavities that were originally developed for High Energy Physics applications. Such cavities were not developed to be optimal for CW applications.

Although very much more efficient than normal-conducting RF, the operating costs of high gradient CW SRF are nevertheless significant. Capital costs of installed SRF as well as large-scale cryogenic capability are cost drivers for major projects. A typical design requires more than 1 MW of RF power and 10 s of MW of power devoted to cryogenic cooling. The RF power may be supplied by a large number of relatively small sources, giving maximum flexibility of operation, or fewer higher power sources with more sophisticated control and distribution but a possible cost advantage. The best choice for any application will depend on many detailed factors.

ERLs require high circulating current, typically of the order of 100 mA per pass, placing a premium on HOM damping for beam stability. Multi-pass acceleration, as employed in CEBAF, offers the possibility of reduced SRF costs in exchange for the cost of recirculation arcs and spreaders and combiners provided the emittance can be preserved through these extra elements. The high average currents in ERLs require strict HOM damping [128,129], favoring designs that are shorter (5–7 cells) or have strong cell-to-cell coupling and cell-to-damper coupling. Such machines will have extremely tight stability requirements for energy and phase jitter [130], and require very low trip rates for user operations.

For CW SRF the most significant factor in operating cost is the efficiency of the accelerating system. For a given cavity geometry this translates to the highest possible quality factor Q_0. The achievable Q_0 depends on many factors including material properties, processing history and surface morphology, as well as operating frequency and temperature. The well-known BCS theory [131] describes the ideal variation of superconducting cavity surface resistance with temperature and frequency and implies that the optimum operating point would be at the lowest practical temperature and frequency. However, the actual surface resistance of presently produced niobium cavities deviates from this ideal behavior and asymptotes to a residual surface resistance significantly higher than BCS theory predicts [131]. There is also a large variation in the practically achieved surface resistance in cavities that is as yet poorly understood. The typical average value is high enough above BCS that the theoretical gains from lower temperature and frequency are not realized in practice. For this and other reasons, most present or proposed CW machines remain at relatively high frequency (1.3–1.5 GHz). The origins of anomalous losses at typical operating gradients are the subject of ongoing investigation and any advancement in this area will pay large dividends in terms of usable gradient and overall facility costs. Recent excellent results with electro-polished cavities suggest that high operating Q_0 at the accelerating gradient of 20–25 MV/m may be reliably attained. If these results prove to be typical, they have the potential to shift the cost-optimal operating point to higher gradient. Field emission can seriously degrade the Q_0 and limit the usable gradient if cavities are imperfectly processed or mishandled after cleaning. Although great strides have been made in combating field emission, including recent tests to over 35 MV/m with no detectable X-rays, elaborate procedures will be necessary to ensure this can be achieved reliably for a large ensemble of cavities. Care must be taken in the design of magnetic shielding in the cryomodule [132] to achieve the full potential of the cavities. In practice the ideal shielding configuration is often compromised by the many penetrations necessary for tuners, couplers etc.

In practice the choice of frequency may be influenced by other factors besides SRF operating efficiency. Lower frequency cavities may support higher charge per bunch, but have longer RF buckets so depending on the detailed user beam requirements this may or may not be advantageous. Final choice of operating frequency, structure type and cryogenic temperature should be the result of a complex optimization and may be quite unique to a specific facility. A number of "light-source optimized" cavity designs are under development worldwide [133] and they vary considerably in frequency, cell shape, number of cells, HOM damper type and power coupler configuration. An important milestone in cavity development will be beam test of these designs. The best verification of HOM damping, microphonics, power coupler etc. is with beam in a real machine or test facility. Several such facilities exist or are planned globally [134–136].

One of the fundamental aspects of successful energy recovery is the absence of a beam load on the RF system because the load is canceled by design [137]. Typically, the coupling in SRF cavities is chosen to match the beam current load, including provisions of extra RF drive and extra cavity bandwidth to allow for precise RF control of the fields in the cavity. When a beam load is not present, the possibility of significantly increasing the cavity fundamental mode Q_L arises, leading to less RF power required to drive the cavities [130]. At present, SRF cavities on the Jefferson Lab FEL/ERL have been successfully operated with a Q_L of 1.2×10^8 [138], including an energy recovered 5 mA beam passing through the cavities. The extra drive and bandwidth is required to ensure stability of the cavity gradient when the structure undergoes small tuning excursions due to external disturbances. This "microphonic" effect can be measured and to some degree mitigated by careful design, stiffening of the structure and good isolation or active feedback, but nevertheless places a practical limit on the maximum Q_L that can be operated stably. Further work on this subject, particularly in designing SRF cavities that are insensitive to coolant pressure fluctuations and noise pickup from the physical environment, and the design of quiet cryogenic systems which have smaller source terms for cavity resonance frequency fluctuations, could allow increases of the design Q_L still further. With success, the operating RF power requirements of the light source facility are proportionately lower. This research program is easily summarized by answering a simply stated question: what is highest practicable, fundamental mode Q_L obtainable in an SRF system with specific requirements for amplitude and phase control?

Research with the largest cost leverage would be that dedicated to improving the Q_0 at the operating gradient. Research is ongoing in this area, including studies of the high-field Q drop [139] and origins of residual resistance. Improvements in field emission free cavity processing would provide more confidence in higher operating gradients and could also allow cavity shapes to be contemplated that have lower operating losses but higher surface electric fields. Improvements in HOM damping, packing factor in the cryomodule, static losses and construction costs would all be worthwhile. Reduction of microphonics could allow for even higher operating efficiency in ERLs providing that nearly ideal energy recovery can be achieved. Success in this regard might ultimately allow solid-state amplifiers to be used with attendant simplifications and reliability.

Two recent examples of parametric studies have been performed for potential large light source facilities, the Cornell full-scale ERL source [140], and the UK NLS FEL project outline design report [141]. The optimal configurations for each are quite sensitive to detailed assumptions in the models, however, they share several common features. Both find a broad cost minimum (capital + 10 years operating costs), between about 15–25 MV/m and both chose gradients in the lower half of this range to be conservative. Both also end up choosing 1.3 GHz as the preferred operating frequency. Optimum operating temperature could be as low as 1.8 K depending on the assumed residual resistance. As might be expected the ERL study favors shorter (7-cell) but strongly HOM damped cavities, while the FEL study uses ILC-like 9-cell cavities. Some variables were not included in these studies, however, such as the variation of RF power costs, residual resistance and optimum operating temperature with frequency, and the relationship between end-use optical output and electron beam properties as influenced by all of the above. A comprehensive evaluation including such variables should be undertaken for any new major facility.

As a final comment, further progress in increasing the energy efficiency of large cooling plants [142] is likely to occur over the next several decades. Dedicated basic research funding to optimize CW cryogenic plants may be appropriate, especially if it is determined that the final source is best run at elevated temperatures compared to today's standards.

4. Route to an ERL-driven X-ray source

Fig. 2 shows a schematic summary of a potential research path for an ERL X-ray source. We have left the duration of the individual steps undefined, the purpose of the diagram is to lay out parallelism and sequencing of the individual components one would expect to need for a full proposal to be developed. Arrows in the figure indicate completion dependencies between the various development projects most likely to lead to exceptional source performance. As indicated in Fig. 2, many parallel activities could start immediately: (1) measurement programs in existing facilities, (2) photocathode research devoted to high current photoinjector issues [17], (3) initiating the process of developing new SRF structures optimized for ERL light source applications, and (4) developing code focused on ERL beam dynamics.

As discussed in detail above, examples of potential measurements at existing facilities are quantitative 6-dimensional beam centroid stability measurements, ion trapping accumulation and mitigation measurements, beam halo generation, and even deploying and testing BBU mitigation hardware. Photocathode R&D work could be performed at the newly emerging cathode laboratories; for ERLs the issue of cathode lifetime needs serious attention in addition to the beam quality monitoring needed for other applications. Starting the process of deciding on the most optimal SRF accelerating cavity design for an ERL application could begin very soon.

After a short period, of order several years, we would expect, as is being presently accomplished at Cornell University as part of their National Science Foundation ERL X-ray source program, that a device called the injector test facility be completed. This device should be designed to fully support beam current and beam quality requirements needed for the eventual non-recovered portions of the final X-ray source. Demonstration of an injector capable to drive the full current in the source with good beam quality would go a long way towards resolving quantitatively whether potential large brilliance gains will be possible by adopting ERL technology for an X-ray source application.

Before adoption of final source parameters, and utilizing the newly optimized SRF cavities, we propose that a natural next step would be an ERL test facility, where a small version of the final ERL accelerator would be built. It would consist of one or two cryomodules containing SRF cavities of the final design within an energy recovery loop, and would allow qualification of RF performance of the SRF cavities and controls in conditions very close to the final conditions that would be experienced in the final source. Completing this work would place one at the completion of Phase I of the original Cornell X-ray source plan [134]. But in contrast to this plan, we recommend that the test facility adopt at least two accelerating passes and two decelerating energy recovery passes in order to fully explore whether final facility costs can be reduced by multiple-pass recirculation. At the end of experiments demonstrating beam requirements after this stage, one should be able to make final design choices to construct the best X-ray source possible. Multiple-pass recirculation is being discussed in reference to advanced Free Electron Lasers [136], making the issue of multiple pass beam recirculation of broader relevance than to just the ERL X-ray source community.

In parallel with and in support of all the experimental activity, it is our expectation that codes describing all the relevant beam phenomena would continue to improve. It will be necessary to have benchmarked codes and their predicted results available to assemble a final proposal. Undulators are, of course, also important in determining the photon characteristics of an ERL, just as they are for storage rings. The development work presently underway for storage ring light sources, such as the work on superconducting undulators and long undulators, would therefore also enhance the capabilities of ERLs.

To conclude, it was the consensus of the meeting that R&D activity establishing the viability of an ERL X-ray source could be completed in a period of five to ten years, depending on the rate at which funding was available devoted to this purpose. The program at Cornell University will provide much useful guidance, and to a certain extent our discussions have repeated and reinforced the soundness of the existing plans there for developing ERL-based X-ray sources. Any R&D plan ultimately adopted by

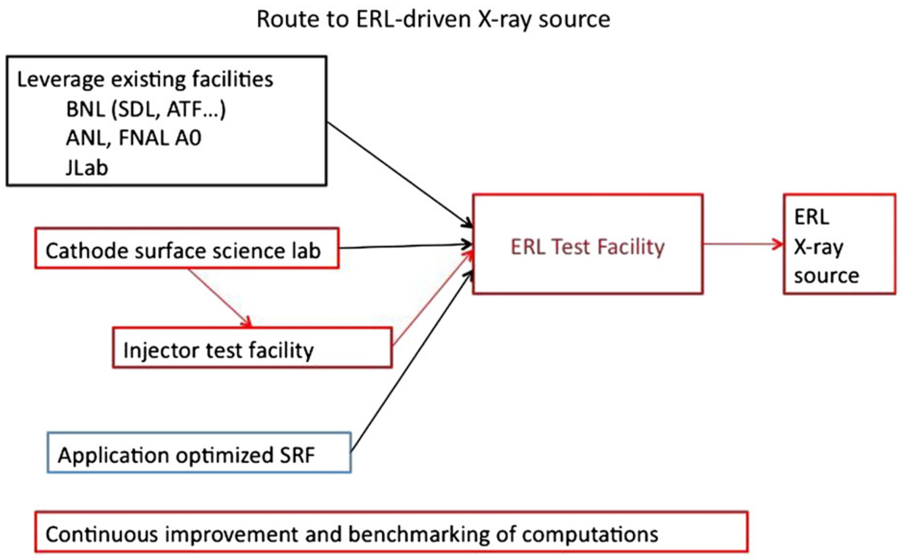

Fig. 2. Research path to an ERL X-ray source.

the Department of Energy for ERL X-ray source development should be highly integrated into the Cornell project, to avoid unnecessary duplication of effort. On the other hand, there are any number of issues, for example CW RF guns, long-term machine reliability, user operations, etc., where substantial Department of Energy support could greatly assist in ERL X-ray source development.

5. Summary

X-ray sources of a novel type, and with unique and interesting beam properties, can be built from multi-GeV scale energy recovered linacs. Energy recovered linacs are in their infancy, and high current multi-GeV devices will require a significant development effort to realize. There is a large body of interesting and substantial issues that could be addressed on existing facilities, even today, with R&D support. In addition to fully utilizing possibilities for measurements supporting ERL development at existing facilities, we foresee several phases in the development of large ERL machines including: demonstrating adequate photocathode performance for ERL applications at a cathode development facility, a high average current test injector that would demonstrate suitable beam performance characteristics for the large driver, and a high average current beam recirculation experiment with at least two accelerating and two decelerating beam passes. Concurrently with this effort, we believe that simulation software should be developed and improved to address physics in energy recovered linac accelerators and that R&D efforts be undertaken to develop SRF cavity technology better optimized to specific ERL applications. We believe that a proposal for a full energy X-ray source can be developed to level of detail suitable for such a major project, and construction of a full source begin in 5–10 years.

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