ENERGY RECOVERY LINACS*

Lia Merminga#, Jefferson Laboratory, Newport News, VA 23606, U.S.A.

Abstract

The success and continuing progress of the three operating FELs based on Energy Recovery Linacs (ERLs), the Jefferson Lab IR FEL Upgrade, the Japan Atomic Energy Agency (JAEA) FEL, and the Novosibirsk High Power THz FEL, have inspired multiple future applications of ERLs, which include higher power FELs, synchrotron radiation sources, electron cooling devices, and high luminosity electron-ion colliders. The benefits of using ERLs for these applications are presented. The key accelerator physics and technology challenges of realizing future ERL designs, and recent developments towards resolving these challenges are reviewed.

INTRODUCTION

In an ERL, in its most basic configuration, electrons are generated in a high brightness electron source, accelerated through the linac, and transported by a magnetic arc lattice to the point of their end use, which could be a photon generating device (a wiggler or an undulator) if the ERL is used as a light source, or the interaction region with protons or ions if the ERL is used either for the electron cooling of high energy ion beams, or to provide the electrons in an electron-ion collider. After they are used, the electrons are transported back to the entrance of the linac 180^0 out of phase for deceleration and energy recovery and they are dumped at an energy close to their injection energy.

In the linac, the net beam loading is nearly zero therefore ERLs can, in principle, accelerate very high average beam currents with only modest amounts of RF power. This feature makes energy recovery an attractive concept for a variety of applications. In this paper we assume that the linac is a superconducting RF (SRF) linac. As energy recovery is much more efficient in an SRF linac, most new ERL proposals are based on SRF linacs.

ERLs can be compared and contrasted with the two traditional types of accelerators, storage rings and linacs. In a storage ring, electrons are stored for hours in an equilibrium state, whereas in an ERL it is the energy of the electrons that is stored. The electrons themselves spend little time in the accelerator (from ~1 to 10's of μs) thus never reach equilibrium. As a result, in common with linacs, the 6-dimensional phase space in ERLs is largely determined by the electron source properties by design. On the other hand, in common with storage rings, ERLs have high current carrying capability enabled by the energy recovery process, thus promising high efficiencies.

* Authored by JSA, LLC under DOE Contract No. DE-AC05-06OR23177

#merminga@jlab.org

PRESENTLY OPERATING ERLS

At the present time there are three operating ERLs, all of which are used as FEL drivers: the JLab IR FEL Upgrade, the Japan Atomic Energy Agency (JAEA) FEL, and the Novosibirsk High Power THz FEL. Table 1 summarizes the parameters of the operating ERLs (emittance is rms). The most advanced of these ERL-based FELs is the Jefferson Lab IR FEL Upgrade [1], shown schematically in Fig. 1.

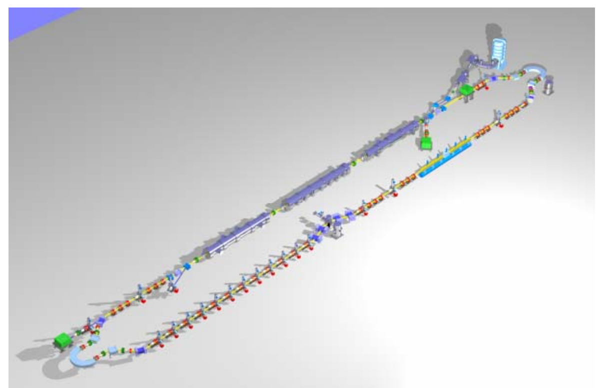

Figure 1: Layout of the JLab IR FEL Upgrade

Table 1. Parameters of Operating ERLs

	JLAB Design/ Achieved*	**JAEA**	**Novosibirsk** Operating/ Upgrade
E [MeV]	145/160	17	12/14
I_{ave} [mA]	10/9.1	8.3**	20/150
q [pC]	135/270	400	1700
ε_n [μm]	30/7	30	30/15
Bunch Length	200/120 fs (rms)	12 ps (fwhm)	0.07/0.1 ns
Bunch rep. rate [MHz]	75	20.8	11.2/90
Duty Factor [%]	100	0.23	100

*Not simultaneously ** In the macropulse

The JLab FEL has energy recovered the highest beam power to date, approximately 1.3 MW, by accelerating 9.1 mA of average current to 150 MeV. In October 2006 the JLab FEL reached record CW laser power of 14.2 kW at 1.6 μm wavelength. The JAEA ERL-FEL [2,3] operates at 17 MeV energy and 0.4nC charge per bunch. The linac consists of 500 MHz SRF cavities. The third operating ERL-FEL is the Novosibirsk High Power THz FEL [4] based on 180 MHz normal conducting RF. This ERL has energy recovered the highest average current to date, 20

 1-4244-0917-9/07/$25.00

mA at 1.7 nC per bunch. Upgrade plans of this ERL include multiple recirculations, and increase of the average current to 150 mA.

ENVISIONED ERL APPLICATIONS

The success and continuing progress of these pioneering ERLs have inspired multiple uses of ERLs which include FELs of higher laser power and shorter wavelengths, spontaneous emission light sources, electron cooling devices, and high luminosity electron-ion colliders.

The next generation ERL-FELs tend to aim at either high average laser power (~100 kW) or shorter wavelengths (VUV). The process of energy recovery helps accomplish these goals with high system efficiency and reduced dump activation (as the beam is dumped at a relatively low energy). Future ERL-FELs are typically of relatively small scale, in the energy range of 100-600 MeV, with charge requirement from 0.1-1 nC per bunch, transverse normalized emittance of order 1-10 μm, longitudinal emittance below 100 keV-ps, and average current from 1 to 100 mA. Several conceptual designs of ERL-FELs are under development worldwide. The most advanced designs include the upgrade of the Novosibirsk THz FEL to multiple passes [4], the 4GLS at Daresbury with a suite of FELs operating at various wavelengths [5], a multi-FEL system designed in the FIR/NIR/MIR range for the National High Magnetic Field Laboratory in Florida [6], the Arc-en Ciel in France [7], and the Peking University IR FEL [8].

ERLs are also being considered for the generation of radiation by spontaneous emission. The ERL beam properties are ideally suited to meet the synchrotron light user requirements. Specifically, high average brightness can be attained by the low electron beam emittance (~1 mm-mrad normalized), high average current (~100 mA), which is typically a combination of relatively low bunch charge and high repetition rate (equal to the RF frequency), and geometry that allows the insertion of long undulators. Full spatial coherence and high temporal coherence can be attained with diffraction-limited round electron beams and small relative energy spread ($\sim10^{-4}$ rms) respectively, high average flux results from high average beam current and sub-ps X-rays can result from sub-ps electron bunch pulses (~100 fs). Presently there are several designs of ERL-based spontaneous emission light sources under exploration worldwide. The concepts from Cornell, Japan, and the APS at Argonne are for sources of hard x-ray radiation and they require multi-GeV ERLs, whereas the 4GLS proposal uses a 550 MeV ERL.

ERLs are being considered for the electron cooling of intense, high energy ion beams. Presently ERLs offer the *only* credible concept for the electron cooling of high energy, colliding beams. Since the cooling efficiency falls sharply as a function of energy, electron cooling of an intense ion beam with $\gamma\sim100$ requires electron beam with high charge per bunch (~ nC), low emittance (ε_n ~1 mm-mrad), small energy spread ($\sim10^{-4}$), relatively short bunches (~ cm), and high average current (~100 mA). The most advanced design of an ERL-based electron cooler is the RHIC-II cooler, with the following design parameters: energy is 54 MeV, charge per bunch is 5 nC, normalized rms emittance less than 4 mm-mrad, and average current of ~ 50 mA [9].

Another potential application of ERLs is to provide polarized electron beams for collisions with protons and ions for Nuclear Physics experiments. High polarization at the 80% level is important for the Nuclear Physics program and it is expected to be delivered by a high-current polarized electron source. The use of ERLs for high luminosity Electron-Ion Colliders (EICs) is more speculative and the degree of their advantage over other schemes depends largely on the ion beam parameters. A principal advantage of an ERL-based EIC compared to a storage-ring collider is the potentially higher luminosity as a result of the higher allowed beam-beam tuneshift parameter of the electron beam ($\xi_e\sim0.5$). This is due to the fact that the electron beam can be disrupted much more since it is dumped after each collision. Another advantage is that spin issues are greatly simplified, since longitudinally polarized electrons are delivered directly from the source. A significant technological challenge of ERL-based EICs is the high current polarized electron source. A particular implementation of an ERL EIC is eRHIC which is based on RHIC. The required parameters of the ERL-based eRHIC are very challenging: energy is 10-20 GeV, charge per bunch is ~10-20 nC, normalized rms emittance is ~20 mm-mrad, and average current of the polarized electron beam is ~250 mA [10].

ACCELERATOR PHYSICS AND TECHNOLOGY CHALLENGES OF ERLS

All of the future ERL proposed applications extend significantly the achieved performance of ERLs in several parameters. The realization of these proposals necessitates resolving a number of physics and technology challenges, centered largely around three areas: achieving high electron source brightness, maintaining high beam brightness through the accelerator transport, and dealing with high peak and average current effects in superconducting RF systems.

Challenge I: Generation and Preservation of Low Emittance, High Average Current Beams

In an ERL the highest quality beam must be produced at the source and preserved at the low energy regime, where space charge forces can degrade the beam quality. The challenge for ERLs is to minimize the space charge induced emittance growth - which generally requires the use of high accelerating gradients to rapidly accelerate the electrons from the cathode - while operating at high repetition rate. There are 3 basic approaches to high brightness electron sources to date, all of which are based on photocathode guns: DC, RF and SRF photoinjectors.

DC photoinjectors have operated at the highest bunch-to-bunch repetition rates to date. The state of the art in DC

1-4244-0917-9/07/$25.00

photoinjectors is the Jefferson Lab FEL gun operating at a repetition rate of up to 75 MHz, with cathode voltage from 350 to 500 kV. To date it has produced normalized rms emittances between 7 and 10 mm-mrad (measured at the wiggler) for bunch charge between 60 to 135 pC and up to 9 mA of average current [11].

There are several DC guns under construction or testing including the Cornell 500-750 kV, 1.3 GHz, 100 mA gun [12]; the JLab gun/AES injector at 500 kV, 750 MHz, 100 mA [13]; the Daresbury ERLP gun which is a duplicate of the JLab FEL gun and is designed to operate at 6.5 mA [14]; and the JAEA 250 kV, 50 mA gun [15].

As DC guns employ relatively low gradient at the cathode, the biggest challenge of a DC gun is to minimize the emittance growth due to space charge. An optimization study done for the Cornell ERL prototype injector concluded that emittance as low as 0.2 mm-mrad at the exit of the injector is possible, for 77 pC, 3 ps bunches, dominated by the thermal emittance [16].

RF photoinjectors employ extremely high accelerating gradients (~100 MV/m) to minimize the space-charge induced emittance growth in the low energy regime, and have produced the lowest normalized emittances to date (~1 mm-mrad at bunch charge of 0.1-1 nC), although at relatively low bunch-to-bunch repetition rate (10-100 Hz). The challenge for RF photoguns is to balance the high accelerating fields with the high repetition rate, which gives rise to significant thermal effects.

An approach which promises high gradient CW RF fields is the SRF photoinjectors. Presently there are two major ongoing SRF gun developments, the Rossendorf 3½-cell Nb cavity design at 1.3 GHz and the BNL/AES ½-cell Nb cavity design at 703.75 MHz. The Rossendorf gun is expected to operate in 3 modes: 77pC at 13 MHz, 1 nC up to 1 MHz, and 2.5nC at 1 kHz [17]. The design energy of the BNL/AES gun is 2.5 MeV and the average CW beam current is 0.5 mA. An interesting enhancement of this SRF gun is the diamond window amplified photocathode which protects the cathode from contamination, while the secondary emission enhanced photoinjector allows for much higher average currents [18]. Although SRF guns appear ideally suited for ERL applications, significant R&D is required before they become operational.

Challenge II: Accelerator Transport

The next challenge is to ensure preservation of the 6-dimensional emittance and management of the phase space during acceleration and energy recovery. There are several aspects to this topic which include longitudinal phase space manipulations, effects of coherent synchrotron radiation (CSR) and longitudinal space charge (LSC), halo and beam loss, and beam stability and diagnostics development.

Longitudinal phase space manipulations are important in ERLs, especially for FEL applications. In dealing with them, one can rely on the successful operational experience at the JLab FEL, which includes correction of nonlinear distortions in phase space, required to obtain the correct phase space at the FEL and ensure proper energy recovery [19].

Emittance preservation especially in synchrotron light ERLs is very important, and one aspect of it is ensuring minimum beam quality degradation due to CSR and LSC as the beam is transported in a typical ERL configuration. The effects of CSR and LSC are seen at the JLab FEL Upgrade with 135 pC bunches and rms bunch length of ~150 fs. The minimum injected bunch length is limited by LSC to a value (~ 6 degrees) beyond which the beam quality and achievable short bunch length degrade [20]. In a series of measurements at the JLab FEL, as the bunch compression was varied at the exit of the chicane located in the back leg, from under to maximum compression, the energy spread increased by up to 30%, and when the bunch was over-compressed its distribution appeared to change and the bunch appeared to filament. During these observations, the incoming energy spread, as measured in the first arc, was kept constant. These observations have features consistent with CSR (present in the bends) and LSC effects (accumulated along the drifts), and they are most severe at full compression. The quantitative contribution of each effect is under investigation through simulations, analysis, and further experimental studies [21].

The combination of short bunch lengths and high average currents in future ERLs presents challenges of beam quality preservation and heating generation. Resistive wall wakefield effects are expected to be particularly challenging as the high current beam traverses the small gap wiggler vacuum chambers in future light sources. At the JLab FEL approximately 200W was deposited on the wiggler vacuum chamber with 3.5 mA CW beam current, and 150 fs rms bunch length [22], consistent with the power dissipation due to resistive wall wakefields.

Halo and beam loss in future ERLs will be important to control. Beam loss is a serious issue since it can directly damage equipment, it can cause unacceptable increase in the vacuum pressure, the linac cryogenic load, or it can cause radiation damage to equipment. Beam losses in the JLab FEL have been quantified in several different ways during ~10 mA operation. The Beam Loss Monitoring (BLM) system sets beam loss to a level below 1 μA, while actual losses are below 100 nA in the worst locations, and ~ 10 nA in most locations. Losses at the wiggler are limited to 10-20 nA [22]. Presently beam loss at the JLab FEL is managed by beam optical methods resulting in more than an order of magnitude improvement. In future ERLs, operating at 100 mA average current, beam loss must be controlled to better than 1 PPM. Meeting these specifications will likely include collimation, and improved machine protection systems.

For some of the future ERL applications beam stability is important and bunch to bunch variations in charge, position, angle, and energy will likely have to be controlled. Measurements at CEBAF have shown promising results in orbit stability at the 2-4 μm level, energy stability at the $1x10^{-4}$ level, and energy spread stability at the $2x10^{-5}$ level with the implementation of feedback.

Unique to ERLs is the need to diagnose and control short bunches at high average beam power. Generally, diagnostics development is needed in the areas of real-time, non-invasive techniques that will allow the continuous monitoring of transverse and longitudinal beam properties, synchronization systems, and improved protection systems [23].

Challenge III: High Current Effects in Superconducting RF Systems

Ensuring stable and efficient operation of future ERLs with currents up to 1 A creates challenges for the SRF systems and RF field control. Strong Higher Order Mode (HOM) damping of monopole and dipole modes is essential. Longitudinal wakes excited by high average current, short bunch length beams in SRF cavities, in addition to causing beam quality degradation, also give rise to HOM power, which can be of significant magnitude (~100 W up to kW) and extends over high frequencies (of order hundreds of GHz) [24]. The challenge is to ensure adequate damping of HOMs and the extraction of HOM power with good cryogenic efficiency. Several HOM extraction schemes have been proposed for broadband HOM damping with power dissipated at room or intermediate temperatures (for example, 80 K) [25, 26].

Dipole HOMs in ERLs can pose a beam stability challenge. In recirculating linacs in general, the beam and the RF cavities form a feedback loop, which closes when the beam returns to the same cavity on a subsequent pass [27]. The closure of the feedback loop between beam and cavity can give rise to a transverse Beam Breakup (BBU) instability at sufficiently high currents, driven predominantly by the high quality factor of the superconducting cavities. Energy recovery linacs, in particular, are more susceptible to BBU because they can support currents approaching or exceeding the threshold of the instability. The theoretical models for BBU is by now mature, and in excellent agreement with simulations. Furthermore, in a series of comprehensive measurements at the JLab FEL, the BBU threshold current was experimentally determined (2.5 mA) in good agreement with simulations (2.7 mA) [28]. Various methods for increasing the instability threshold have been studied experimentally with varying degrees of effectiveness, including Q-damping schemes, and beam optical methods [29].

In the long-run BBU can be significantly ameliorated by specially designed RF cavities operating at lower frequencies. Examples of such developments are the BNL cavity design at 703 MHz [30], and the JLab high-current cavity/cryomodule concept at 750 MHz [26], both of which promise BBU thresholds above 1 Ampere. A recent design optimization of a 1.3 GHz, 9-cell cavity for high current ERL operation resulted in BBU threshold current of 300 mA, adequate to support 2-pass ERL operation at 100 mA [31].

RF field control of high Q_L-cavities, desired for efficient ERL operation, is a challenge due to microphonic detuning, and random beam loading, typically reactive, resulting from path length (phase) errors. In a proof-of-principle experiment, Cornell's digital LLRF system was tested in one of JLab FEL's 7-cell cavity. After initial tests at the design $Q_L = 2 \times 10^7$, the loaded Q_L was increased to about 10^8. Field stability at the 10^{-4} for amplitude and 0.02^o for phase was achieved with 5.5 mA of average beam current in energy recovery mode. No dependence of the field stability on beam current was observed [32].

To address the most important of these science and technology challenges of future ERLs, three major test facilities are presently under construction or commissioning: The Cornell Injector prototype, presently under operation, is aimed towards the verification of the beam production [12]; the Daresbury ERLP, which achieved first beam in August 2006, and is expected to demonstrate energy recovery by the end of 2007 [14]; and the BNL R&D ERL, a 20 MeV, 0.5 Ampere test ERL accelerator expected to start commissioning in February 2009 [33].

SUMMARY

Energy recovery linacs provide a powerful and elegant paradigm for a broad range of applications, including high power FELs, high average brightness, short-pulse radiation sources, electron cooling devices, and high luminosity electron-ion colliders. The pioneering ERL-FELs, presently in operation, have established the fundamental principles of ERLs. Challenges and R&D opportunities exist for the realization of the next generation ERL designs. These challenges center around three major topics: source brightness, emittance preservation and phase space manipulation, and high peak and average current effects in an SRF environment. Tremendous progress has been made over the past years in advancing ERL physics and technology. Test facilities are under construction and commissioning, and vigorous R&D activities in many laboratories around the world promise to resolve the outstanding issues. The multitude of ERL projects and proposals worldwide promises an exciting next decade for ERL physics, as existing ERLs will reach higher performance, key R&D issues will be resolved, and new ERLs will begin construction.

ACKNOWLEDGEMENTS

The author is grateful to the following colleagues for generously sharing information and data for the preparation of this paper: I. Bazarov, G. Hoffstaetter, M. Liepe from Cornell University, I. Ben-Zvi from Brookhaven National Lab, R. Hajima from JAERI, J. Clarke and S. Smith from Daresbury Laboratory, N. Vinokurov from BINP, and S. Benson, J. Delayen, S. Derbenev, D. Douglas, P. Evtushenko, G. Krafft, C. Leemann, R. Li, G. Neil, R. Rimmer, and H. Wang from Jefferson Lab.

REFERENCES

[1] S. Benson et al., "High Power Operation of the JLab IR FEL Driver Accelerator," Proc. PAC07 (2007)
[2] R. Nagai et al., Proc. FEL06, 312 (2006)
[3] N. Nishimori et al., Proc. FEL06, 265 (2006)
[4] N. Vinokurov et al., "Status of the Novosibirsk High Power THz FEL," Proc. FEL06, 492 (2006)
[5] The "4GLS Conceptual Design Report" can be found at: http://www.4gls.ac.uk/cdr/4GLS_CDR.online.pdf
[6] P. Evtushenko et al., "National High Magnetic Field Laboratory FEL Injector Design Consideration," Proc. PAC07 (2007)
[7] M. E. Couprie et al., "The Arc-en-Ciel FEL proposal," Proc. FEL06, 146 (2006)
[8] G. Wang et al., "Energy recovery transport design for Peking University FEL," Proc. PAC07 (2007)
[9] I. Ben-Zvi et al., "Status of the R&D Towards Electron Cooling of RHIC," Proc. PAC07 (2007)
[10] V. Pritsyn, "From HERA to Future Electron-ion Colliders," Proc. PAC07 (2007)
[11] C. Hernandez-Garcia et al., "Performance and Modeling of the JLAB IR FEL Upgrade Injector", Proc. FEL04, 558 (2004)
[12] C. K. Sinclair et al., "Performance of a Very High Voltage Photoemission Electron Gun for a High Brightness, High Average Current ERL Injector," Proc. PAC07 (2007)
[13] A.M.M. Todd et al, "State-of-the-art electron guns and injector designs for energy recovery linacs (ERL)", Proc. PAC05, 2292 (2005)
[14] S. Smith et al., "The status of the Daresbury energy recovery linac prototype," Proc. PAC07 (2007)
[15] T. Nishitani et al., "JAEA photocathode DC gun for an ERL injector," Proc. FEL06, 319 (2006)
[16] I. V. Bazarov, C. K. Sinclair, *Phys. Rev. ST-AB* 8, 034202 (2005)
[17] J. Teichert et al., "Cryomodule and tuning system of the superconducting RF photoinjector," Proc. FEL06, 575 (2006)
[18] X. Chang et al., "Recent Progress on the Diamond Amplified Photo-cathode Experiment," Proc. PAC07 (2007)
[19]P. Piot, D.R. Douglas, G.A. Krafft, *Phys. Rev. ST-AB* 6, 030702 (2003)
[20] D. Douglas, Private communication
[21] D. Douglas, P. Evtushenko, R. Li, Private communication
[22] S. Benson, D. Douglas, Private communication
[23] A. P. Freyberger, G. A. Krafft, "Summary report on synchronization, diagnostics and instrumentation," NIM A 557, 370-373 (2006)
[24] L. Merminga, et al., Proc. Linac00, 860 (2000)
[25] M. Liepe, Proc. SRF Workshop (2003)
[26] R.A. Rimmer et al., "JLab high-current CW cryomodules for ERL and FEL applications," Proc. PAC07 (2007)
[27] L. Merminga, D.R. Douglas and G.A. Krafft, *Annu. Rev. Nucl. Part. Sci.* 53:387-429 (2003)
[28] D. R. Douglas et al., *Phys. Rev. ST-AB* 9, 064403 (2006)
[29] R. Rand and T. Smith, Particle Accelerators 1980, Vol. II, pp. 1-13.
[30] R. Calaga et al., "Ampere class linacs: Status report on the BNL cryomodule," NIM A 557, 243-249 (2006)
[31] R. Hajima, Proc. ERL Workshop 2007
[32] M. Liepe and J. Knobloch, "Superconducting RF for energy-recovery linacs," NIM A 557, 354-369 (2006)
[33] V. Litvinenko et al., "Status of R&D ERL at BNL," Proc. PAC07 (2007)

1-4244-0917-9/07/$25.00