# ENERGY RECOVERING LINACS *

L. Merminga[†], D. R. Douglas, G. A. Krafft,
Jefferson Laboratory,
Newport News, VA 23606, USA

*Abstract*

Energy Recovering Linacs (ERLs) are potentially powerful types of recirculating linear accelerators in that they deliver beams of linac quality (short pulses and emittance and energy spread determined by the source) with efficiency approaching that of storage rings. As a result, in addition to the two existing ERLs being used as FEL drivers, the Jefferson Lab (JLAB) IRFEL and the JAERI FEL, ERLs are being contemplated for a variety of other applications. These applications include the generation of X-ray radiation, high energy electron cooling, and linac-ring colliders for nuclear and particle physics. The required beam current for these applications is of order 100 mA, a factor of 20 higher than presently demonstrated at the JLAB IRFEL. The energy of these applications spans the range from the currently achieved 50 MeV to 5 GeV. This paper reviews the existing and planned energy recovering linac projects and their accelerator physics and technology issues. Experimental data obtained at the JLAB IRFEL energy recovering linac are used to evaluate the limitations and ultimate performance of ERLs.

## 1 INTRODUCTION

Electron storage rings have fulfilled the needs of the accelerator community for high current applications for several decades with high efficiency and increasingly improved performance. They are at present however confronted by two fundamental limitations. The first is on the minimum available 6-dimensional phase space, which is determined by the equilibrium between radiation damping and quantum excitation. The second is on the maximum available beam lifetime, which is limited by the Touschek effect. In contrast, linear accelerators can deliver beams with small emittance, energy spread, and very short bunches; they have, however been limited to relatively low average currents, of order 1 mA, by prohibitive rf power requirements.

Let us consider a linac in which the beam, after it has been used, is returned back to the rf cavities $180^0$ out of phase where it is decelerated and returns its beam power back to the cavities as microwaves that are used for the acceleration of new bunches. This is the process of energy recovery and as a result the rf power required becomes nearly independent of the beam current, the overall system efficiency is increased, the beam dump design is much simpler because the decelerated beam is being dumped at much lower energy, and under certain circumstances, the dump radioactivation may be reduced. Energy recovering linacs (ERLs) combine characteristics of both storage rings and linacs, in that they can produce beams of linac quality – with emittance and energy spread determined by the source and with very short bunches (sub-picosecond) – yet they promise efficiencies approaching those of storage rings.

The term “energy recovery” first appears in the literature by Maury Tigner in the 1965 reference [1]. Some of the early experimental demonstrations of energy recovery took place at MIT-Bates [2] and in the Stanford Superconducting Accelerator SCA/FEL [3]. Several other energy recovery experiments followed,

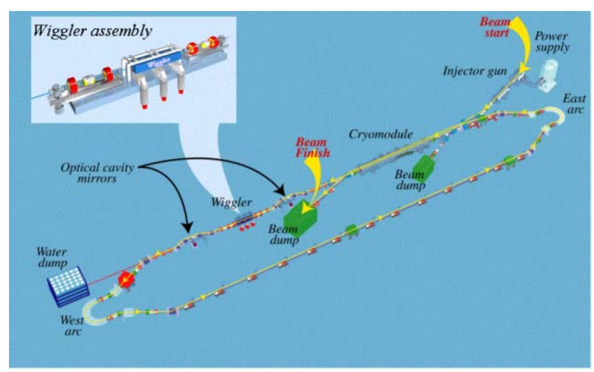


Figure 1. Schematic layout of the Jefferson Lab energy recovering linac IRFEL.

using both normal and superconducting cavities [4,5]. The highest power energy recovery experiment to date has taken place in the Jefferson Lab IR FEL, shown schematically in Figure 1, where a cw beam current of up to 5 mA has been accelerated to ~50 MeV and energy recovered [6]. Energy recovery is used routinely in this system during its operation as a user facility.

Today a number of ERL-based FEL facilities worldwide are at various stages of construction and commissioning. Recently the JAERI FEL succeeded in lasing in energy recovery mode [7], becoming the second ERL-based FEL. The KAERI FEL in Korea is in the installation and construction phase [8], and so is the Accelerator-Recuperator FEL at the Budker Institute for Nuclear Physics in Novosibirsk. Finally, the Jefferson Lab IR FEL has been dismantled and an

* Work supported by US DoE contract No. DE-AC05-84ER40150, the Office of Naval Research, Commonwealth of VA and the Laser Processing Consortium.
[†]merminga@jlab.org

upgrade to 10 kW IR FEL and 1 kW UV FEL are being installed [9]. Commissioning of the JLAB FEL Upgrade is scheduled to commence in the fall of 2002.

## 2 FUTURE ERL DIRECTIONS

The success of the JLAB IRFEL has, further, inspired a number of proposals for ERL-based synchrotron light sources. Thus Cornell, in collaboration with Jefferson Lab, is proposing the ERL, shown schematically in Figure 2, a 5-7 GeV facility for the production of X-rays [10]. Daresbury Laboratory is proposing the 4GLS, a new synchrotron radiation facility which will include three FELs and a synchrotron radiation source from undulators driven by a 600 MeV ERL [11]. The University of Erlangen in Bavaria is envisioning an ERL upgrade to their proposed synchrotron radiation facility, ERLSYN, driven by a 3.5 GeV superconducting linac [12]. The Budker Institute was an early proponent of the concept of ERL-based light sources with the project MARS, a Multiturn Accelerator-Recuperator Scheme, which is designed to reach the energy of 6 GeV and produce radiation both from undulators and from the bends in the recirculating arcs [13]. The MARS scheme, together with the Accelerator-Recuperator FEL, are the only proposed ERLs that are based on normal conducting rf cavities. Finally, the Lawrence Berkeley Lab proposal of a femtosecond light source maintains the option of an ERL-upgrade in case there is demand for increased beam power [14].

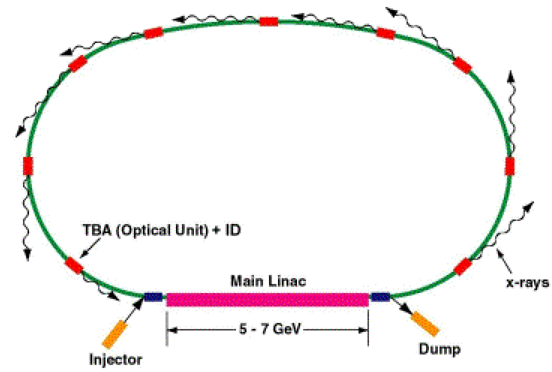


Fig. 2: Schematic layout of the Cornell/Jefferson Lab ERL, a 5-7 GeV facility for the production of X-rays.

High energy electron cooling is deemed feasible with the demonstration of the technical viability of energy recovering linacs. Brookhaven National Laboratory, in collaboration with the Budker Institute, is working on the technical design of an electron-cooling prototype aimed towards exploring the challenges of electron cooling of the heavy ions at RHIC. This cooler will be driven by a 50 MeV, 100 mA ERL [15].

Finally ERLs have been suggested for polarized electron-ion colliders for Nuclear and Particle physics. Two such schemes are being considered: eRHIC, an electron-ion collider, which collides heavy ions from RHIC with electrons from a 10 GeV ERL [16], and

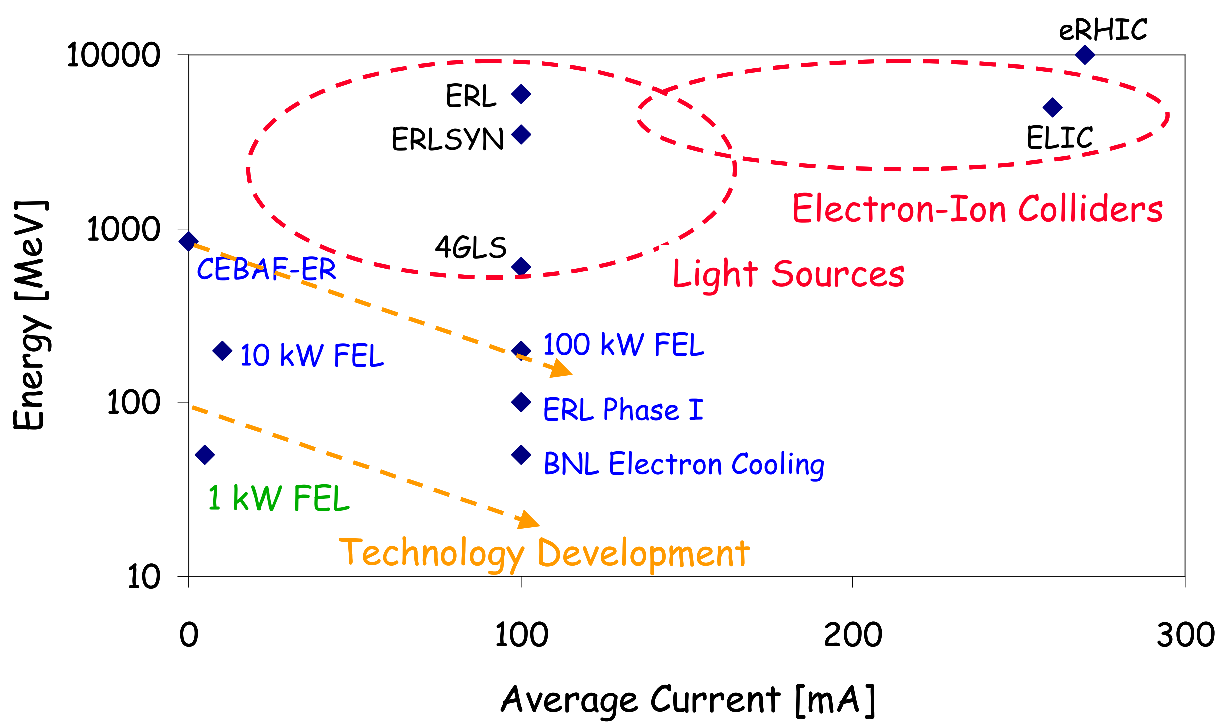


Figure 3: Energy recovering linac landscape: Existing, planned, and proposed ERL-based facilities.

ELIC, an electron-light ion collider which collides electrons from CEBAF, operating in energy recovering mode, with light ions from a storage ring [17]. Both schemes appear to have advantages compared to ring-ring scenarios with respect to spin manipulations and flexibility in operations. Preliminary design studies show that ELIC can reach luminosities at the level of $10^{35}$ $cm^{-2}sec^{-1}$.

Figure 3 is a graph of beam energy vs. average current depicting the parameter regimes occupied by the various ERL applications discussed. ERLs for light sources are designed to operate in the energy range from hundreds of MeV up to a few GeV, with average current that can be as low as 10 mA, in the *high coherence* mode, or as high as 100 mA, in the *high average flux* mode. ERLs for colliders are envisioned to operate in the 3-10 GeV energy range and they require average currents of order 100-200 mA. The parameters required by these ERL proposals are an extrapolation from today's demonstrated performance by one to two orders of magnitude both in beam energy and in average current, so that a number of technical issues need to be resolved in order for the feasibility of these designs to be demonstrated and for the ultimate limitations of ERLs to be understood. A number of prototype facilities have been proposed to address and explore the technical feasibility of future ERLs. Among the proposed prototypes are: The Cornell/Jefferson Lab ERL Phase I, a 100 MeV, 100 mA ERL, designed to demonstrate technical feasibility of the ERL Phase II machine. The BNL/BINP electron-cooling prototype designed to demonstrate technical feasibility of an ERL-based electron-cooling device. Finally, Jefferson Lab's 10 kW FEL Upgrade and its likely successor, the 100 kW IR FEL, will also be used to ascertain the limits of ERLs in general, and ERL-driven FELs in particular. We now proceed to discuss the technical challenges of the next generation ERLs, focusing on the superconducting rf linac-based schemes.

## 3 ACCELERATOR PHYSICS AND TECHNOLOGY CHALLENGES OF ENERGY RECOVERING LINACS

### *3.1 Generation and Preservation of Low Emittance, High Current Beams*

The majority of ERL applications require low emittance (normalized rms emittance ~1 mm-mrad) and short bunch length (rms bunch length from ~100 fsec to ~1 psec) beams. In order to take full advantage of the ERL technology, one should both generate and preserve a low emittance, high average current beam. Laser-driven, DC photoemission guns are considered likely source candidates [18], but technology development is required to demonstrate operation at the highest possible cathode voltage and to ensure adequate life time under high current conditions. Once the low emittance beam is generated, one needs to ensure its preservation first at the low energy regime where careful emittance compensation must take place against space-charge effects, and then in the linac and beam lines against wakefield affects, and in the recirculator against coherent synchrotron radiation-induced emittance degradation [19]. Other effects that could degrade the beam quality performance include ion effects and halo formation.

### *3.2 Longitudinal Beam Dynamics*

For proper energy recovery, longitudinal phase space manipulations are necessary [20]. In the JLAB IRFEL, for example, proper matching of the longitudinal phase space is required for high peak current (minimum bunch length) at the FEL and management of the large electron beam momentum spread, introduced by the FEL interaction, during energy recovery. Off-crest acceleration in the superconducting rf linac, together with non-zero momentum compaction in a chicane give rise to maximum compression at the wiggler. A second magnetic chicane (acting as a bunch decompressor) downstream of the wiggler is followed by a recirculation transport, which provides both a linear ($R_{56}$) and a quadratic ($T_{566}$) momentum compaction, the latter introduced by sextupoles. The sextupole-induced curvature on the longitudinal phase space of the bunch is essential to compensate the rf-induced nonlinearities, acquired during deceleration of the relatively long bunch. As a result, the bunch arrives at the energy recovery dump with relatively small momentum spread, and minimum beam loss.

### *3.3 Transverse Beam Dynamics*

In addition to the transverse matching issues common to all types of accelerators, ERLs face the challenge of preserving the quality of a high brightness beam during acceleration and the energy recovery of a potentially degraded beam phase space through common linac and transport channels. The linac optics in ERLs must ensure stability of both accelerating and decelerating beams as they traverse the same focusing channel, while they can be at very different energies, particularly at the two ends of the linac. Furthermore, the decelerating beam is adiabatically anti-damping, which leads to increase in the relative energy spread and betatron envelopes, and has the potential for scraping and beam loss. These issues are particularly accentuated in a high energy ERL with a long linac transport channel. In order to investigate transport beam dynamics aspects of energy recovery in large-scale systems, we have designed and proposed the experiment CEBAF-ER [21]. CEBAF-ER is a high energy demonstration of energy recovery and will take place at CEBAF. A 45 MeV beam will be injected into the north linac, accelerated to 445 MeV, injected to the south linac where it is accelerated to 845 MeV. A $\lambda/2$

phase delay chicane will allow the beam to re-enter the north linac 180 degrees out of phase, where it will be decelerated down to 445 MeV in the north linac and finally to 45 MeV in the south linac. The injection energy will be varied from approximately 10 MeV to 67 MeV, thereby allowing us to investigate energy recovery with energy ratios up to 80. The 6-dimensional phase space and the amount of beam loss will be measured at critical locations for different injection to final energy ratios. The experiment has been approved and is scheduled to take place in March 2003.

### *3.4 Collective Effects*

In recirculating linacs, in general, the beam and the cavities form a feedback loop, which closes upon the return of the beam to the same cavity on a subsequent pass. The closure of the feedback loop between beam and cavity can give rise to instabilities, at sufficiently high currents, driven predominantly by the high-Q superconducting cavities. Energy recovering linacs, in particular, are more susceptible to these instabilities because they can support currents to reach the threshold of the instabilities. The following types of instabilities can occur:

1) The transverse Beam Breakup (BBU) instability, which results from the interaction of the beam with the cavity's transverse Higher Order Modes (HOMs) [22].

2) The longitudinal BBU instability that can result from the interaction of the beam with longitudinal HOMs [23].

3) The beam-loading type instabilities, which can arise from fluctuations of the cavity fields in the linac and can cause beam loss on apertures and phase oscillations [24].

Theoretical models of the instabilities have been developed and initial measurements on the JLAB IR FEL are being used to benchmark codes and models [25,26,27]. At the present time, it appears that transverse BBU is the limiting stability mechanism [28]. The 5 mA ERL of the JLAB IRFEL has a BBU stability threshold of 27 mA, while the 100 mA ERL of the Cornell ERL, has a threshold of approximately 200 mA. Clearly, design currents begin to approach the limits imposed by stability considerations. So one might ask "What is the maximum average current that can be recirculated and energy recovered?" It is expected that, with better HOM damping in multi-cell cavities and bunch-by-bunch transverse feedback, similar to the one used in B-Factories, it is conceivable that the stability threshold could be raised to 0.5 - 1 A.

### *3.5 Superconducting RF Issues*

Although energy recovery works well with pulsed beam, its potential is truly realized with cw beam (high average current). As a consequence, all the ERL applications proposed to date, require cw rf fields. Superconducting rf (srf) parameter optimization for ERLs in the multi-GeV energy range, which minimizes linac length and cryogenic power consumption, points towards gradients of ~20 MV/m at $Q_0$~1x10$^{10}$. This level of srf performance has not been demonstrated in cw, high average current operating conditions. Furthermore, R&D towards increasing the quality factor $Q_0$, of the cavities would directly reduce the ERL operating costs and increase the overall ERL efficiency.

Further damping of transverse HOMs in multi-cell cavities is required to ensure stability against multibunch BBU instabilities, as discussed earlier.

Finally, efficient extraction of HOM generated by sub-picosend short bunches must be ensured. High average current and short bunch length beams in superconducting cavities can excite higher order modes which, in addition to beam stability consequences, could result in increased cryogenic load due to power dissipation in the cavity walls. The power in HOMs, primarily longitudinal, depends on the product of bunch charge, $q$, and average current, $I_{ave}$, and it is equal to $2qk_{||}I_{ave}$ where $k_{||}$ is the loss factor of the superconducting cavity and the factor of 2 accounts for the two beams in the cavity (accelerating and decelerating). The total power depends on the bunch length through the loss factor. At high currents and short bunches, the amount of dissipated power can be quite high. For example, for average current of 100 mA, bunch charge equal to 0.5 nC and $k_{||}$=10 V/pC, the HOM power is approximately equal to 1 kW per cavity. Part of this power is expected to be extracted by HOM couplers and be absorbed in room temperature loads, part of it is expected to be absorbed by cooled photon absorbers placed between cavities or cryomodules. The excitation of high frequency HOMs by the short bunches can, in principle, degrade the cavity's quality factor, according to BCS theory, and result in increased power dissipation in the cryogenic environment [29]. Detailed measurements in the proposed ERL prototypes will be needed to demonstrate adequate efficiency of the power extraction schemes.

### *3.6 RF Issues*

In superconducting cavities, in the absence of beam loading, the coupling optimization is dominated by the amplitude of microphonic noise [30]. For example, in the Cornell/Jefferson Lab ERL, the optimum $Q_{ext}$ is 2.6x10$^7$ assuming 25 Hz of microphonic noise. With this coupling, the required rf power is 8 kW per cavity! Clearly, higher $Q_{ext}$ implies higher ERL efficiency. The question is what is the highest practical value of $Q_{ext}$. With the higher $Q_{ext}$, the rf control system design becomes more challenging, in the presence of microphonic noise-induced phase and amplitude variations that must be corrected, and a net beam loading vector, that may result either from beam loss of from phase errors.

## 4 R&D ACTIVITIES

We present a list of R&D topics that need to be addressed to ensure technical feasibility of high power energy recovering linacs.

- Development of high average current, low emittance guns and injectors.
- Effects of coherent synchrotron radiation on beam quality.
- Beam halo formation and control of beam loss.
- Demonstration of required level of srf performance in cw, high average current environment.
- Adequate damping of HOMs *Q*'s.
- Increase of the quality factor $Q_0$ of the superconducting cavities.
- RF control and stability under maximum practical $Q_L$.
- Efficient extraction of HOM power.
- Development of multibunch BBU feedback.

## 5 CONCLUSIONS

Energy recovering linacs are an emerging and potentially powerful application of rf super-conductivity for a wide variety of applications, including FELs, light sources, electron cooling devices and electron-ion colliders. The success of the JLAB IRFEL energy recovering linac has demonstrated technical feasibility of the concept. Proposed ERL prototypes are expected to elucidate the ultimate limitations of energy recovering linacs.

## 6 REFERENCES

[1] M. Tigner, Nuovo Cimento 37, pp. 1228-1231 (1965)

[2] J. B. Flanz and C. P. Sargent, IEEE Trans. on Nuclear Science, Vol. NS-32, No. 5 (1985)

[3] T. I. Smith et al., "Development of the SCA/FEL for use in Biomedical and Materials Science Experiments," NIM A 259 (1987)

[4] D. Feldman, et al. "Energy Recovery in the Los Alamos Free Electron Laser," NIM A 259 (1987)

[5] N. Sereno, "Experimental Studies of Multipass Beam Breakup and Energy Recovery Using the CEBAF Injector Linac," Ph.D. Thesis, University of Illinois (1994)

[6] G. R. Neil, et al., "Sustained Kilowatt Lasing in a Free Electron Laser with Same-Cell Energy Recovery," Physical Review Letters Vol. 84, Number 4 (2000)

[7] N. Nishimori, et al., Proc. of EPAC (2002)

[8] B.C. Lee et al., Proc. of Linac Conf. (2002)

[9] D. R. Douglas, S. V. Benson, G. A. Krafft, R. Li, L. Merminga, B. C. Yunn, "Driver Accelerator Design for the 10 KW Upgrade of the Jefferson Lab IR FEL," Proceedings of Linac Conf. (2000)

[10] I. Bazarov, S. Belomestnykh, D. Bilderback, K. Finkelstein, E. Fontes, S. Gray, S. M. Gruner, G. A. Krafft, L. Merminga, H. Padamsee, R. Helmke, Q. Shen, J. Rogers, C. Sinclair, R. Talman, and M. Tigner, "Study for a Proposed Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University", CHESS Technical Memo 01-003 and JLAB-ACT-01-04 (2001)

[11] http://www.4gls.ac.uk/

[12] http://www.erlsyn.uni-erlangen.de/

[13] G. Kulipanov, A.N. Skrinsky, N. Vinokurov, J. Synchrotron Rad. 5, 176-178 (1998)

[14] J. Corlett, et al., Proc. EPAC 2002, pp.668-670

[15]http://www.rhichome.bnl.gov/RHIC/RAP/ap_notes/ap_note_47.pdf

[16] I. Ben-Zvi, J. Kewisch, J. Murphy and S. Peggs, "e-RHIC Accelerator Physics," Proceedings of the 2nd eRHIC Workshop, Yale University (2000)

[17] L. Merminga et al., Proc. EPAC 2002, pp. 203-205

[18] C.K. Sinclair, Proc. of PAC 1999, pp. 65-69

[19] R. Li, Proc. of PAC 1999, pp. 118-122

[20] Ph. Piot, D. Douglas, G. Krafft, "Study of the Energy Compression Scheme to Energy Recover an Electron Beam in Presence of an FEL Interaction," Proc. EPAC 2000, pp. 1543-1545

[21] http://casa.jlab.org/internal/research/er/er.shtml

[22] J. J. Bisognano and R. L. Gluckstern, "Multipass Beam Breakup in Recirculating Linacs," Proceedings PAC 1987, pp. 1078-1080

[23] J. J. Bisognano and M. L. Fripp, "Requirements for Longitudinal HOM Damping in Superconducting Recirculating Linacs," Proc. Linac Conference 1988, pp. 388-390

[24] L. Merminga, P. Alexeev, S. Benson, A. Bolshakov, L. Doolittle and G. Neil, "Analysis of the FEL-RF Interaction in Recirculating, Energy-Recovering Linacs with an FEL," NIM A 429 (1999) 58-64

[25] G. A. Krafft and J. J. Bisognano, "Two Dimensional Simulations of Multipass Beam Breakup," Proceedings PAC 1987, pp. 1356-1358

[26] B. C. Yunn, "Beam Breakup in Recirculating Linacs," Proc. PAC 1991, pp. 1785-1787

[27] L. Merminga, Campisi, Douglas, Krafft, Preble, Yunn, Proc. PAC 2001, pp. 173-175

[28] L. Merminga, NIM A 483 (2002) 107-112

[29] L. Merminga, G. A. Krafft, C. W. Leemann, R. M. Sundelin, B. C. Yunn and J. J. Bisognano, "Specifying HOM-Power Extraction Efficiency in a High Average Current, Short Bunch Length SRF Environment," Proc. Linac Conf. (2000)

[30] L. Merminga and J. Delayen, "On the optimization of $Q_{ext}$ under heavy beam loading and in the presence of microphonics," Jefferson Lab Technical Note TN-96-022 (1996)