ENERGY RECOVERY LINACS LIGHT SOURCES: AN OVERVIEW

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Abstract

Sparked by the highly successful operation of energy recovery linac (ERL) free electron lasers (FELs) at TJNAF [1] and JAERI [2] and also by the novel MARS light source (LS) proposal from BINP [3], numerous facilities worldwide are now considering ERL based light source projects. A survey of the various light sources and FELs based on ERL technology will be given. An overview of the critical R&D issues that must be addressed in future ERLs will also be presented.

INTRODUCTION

Motivation for an ERL Light Source

State of the art storage ring based synchrotron light sources are achieving horizontal emittances of a few nanometers & values of 10^2-10^3 less for the vertical plane yielding a brightness ~ 10^{21} ph/sec/0.1%BW/mm^2-mrad^2. Further reduction in the equilibrium emittance is becoming very challenging due to dynamic aperture limitations and short lifetimes. It is also unlikely that electron bunch lengths in rings will shrink much below 10 ps (RMS). ERL based light sources are being explored as the pathway to even higher brightness and sub picosecond pulses.

In contrast to an electron storage ring which stores the same electrons for hours in an equilibrium state, in an ERL it is only the energy of the electrons, not the electrons themselves, that is 'stored'. Individual electrons may spend as little as 1 μs in an ERL and as such never reach an equilibrium state. It is precisely the fact that the electrons are continually being refreshed, while the energy is recovered for use by succeeding electrons, that makes an ERL such an attractive concept.

Why Energy Recovery?

The power in an electron beam of current I and energy E can be written as:

$$P\,[GW] = E\,[GeV] \bullet I\,[Amp]. \quad (1)$$

For a 6 GeV light source like the ESRF the power in the electron beam is 1.2 GW. This is possible because the same electrons are circulating in the machine generating the large average current (200 ma) and the RF system only has to replace a small fraction of this power, that which is radiated in the dipoles and insertion devices, ~ 1-2 MW. To generate a 200 ma CW average current in a 6 GeV linac without energy recovery would require paying the electric bill for the full 1.2 GW.

Brief Historical Perspective

As early as 1965 Tigner [4] proposed 'energy recovery' in opposing superconducting (SC) linacs to generate colliding beams for high energy physics. Recirculating linacs & racetrack microtrons have been part of the accelerator landscape for more than twenty years [5,6]; some of the early machines already included SC cavities: the Illinois racetrack microtron [7], the Stanford SC recyclotrons [8] and the S-DALINAC at Darmstadt [9].

However it wasn't until 1986 that 'energy recovery', in the sense now being considered, was successfully demonstrated on the SCA FEL machine at the Stanford HEPL [10]. This pioneering experiment, which included 1.3 GHz SC multicell cavities, succeeding in accelerating a beam in the linac in the first pass and by adjusting the path length in the return arc the beam was properly phased and decelerated in a second pass through the linac. In addition to recognizing the possible savings in RF power and shielding, and the increases in overall efficiency, the HEPL team also suggested the installation of an FEL wiggler in the return leg. This last suggestion for an ERL FEL was never realized on the SCA machine, it would take another dozen years for this novel idea to be brought to fruition at TJNAF and JAERI.

Stimulated by these innovative machines, numerous proposals to use ERL technology to construct novel light sources have appeared recently.

ERL Light Source Basics

In its most basic form an ERL light source (LS) consists of an electron source, a linear accelerator, a magnetic arc lattice to return the electron beam through the linac with a 180° phase shift for deceleration, a device to convert electron kinetic energy into photons (an undulator or FEL) and finally a beam dump (see Fig. 1).

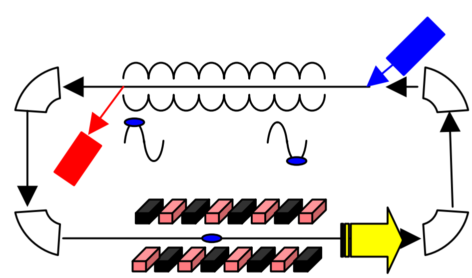

Figure 1: Generic 1.5 Turn ERL Light Source

Variations on this basic theme are also possible:

- N-passes through the same linac coupled with N-arcs can reduce the size of the linac and yield N different energy beams but this requires the linac to support N-times the current in one arc,
- linac sections can occur on opposite sides of the arc to generate two different energy beams, etc.

The objectives in an ERL LS are to:

- produce the highest quality electron beam in the injector with the "lowest possible energy as this energy is unrecoverable,

- accelerate the electron beam to the final energy with high efficiency,
- transport the electrons to the photon generator (e.g. undulator, FEL) without corruption & with optimized transverse and longitudinal profiles,
- convert as much kinetic energy of the electrons to photons as possible,
- recover as much of the remaining electron energy in the linac to maximize the overall wall plug efficiency before dumping the beam with a minimum of activation in the dump.

KEY ELEMENTS OF AN ERL

Electron Injectors

In contrast to a storage ring where an injected electron beam of poor quality can be "cleaned up" with radiation damping, in an ERL one must produce the highest quality beam "at birth" as effects such as space charge, wakefields & dilution will only degrade the beam quality. However, this fact cuts both ways, and suggests a "natural upgrade path" for an ERL whereby improvements in the injector could enhance the overall system performance.

There are several possible injectors we shall only mention two, both of them photoinjectors: DC & RF. The first class of injector has produced the highest rep rate beams (~100 MHz), while the second class has produced the best normalized emittances ($\varepsilon_N \equiv \gamma\varepsilon \approx 1$ µm) for a charge per bunch Q ~ 0.1-1 nC.

The JLAB FEL is driven by a DC photoinjector operating at 350 kV and it produces an electron beam with ε_N ~ 15-25 µm for a charge per bunch of 60-135 pC at a rep rate of 37-75 MHz [11]. The gun has recently been upgraded to operate at 500 kV and it is undergoing commissioning.

An RF photoinjector makes use of extremely high accelerating gradients (~ 100 MV/m) to rapidly accelerate the electrons from the cathode and thereby reduce the emittance growth at low energy caused by space charge [12]. To date, the RF guns have produced the highest quality electron beams but typically at a rep rate of 10-100 Hz. The exception is the 433 MHz Boeing injector which operated with a 25% duty cycle [13]. The challenge for high rep rate RF photoinjectors is to balance the high gradient, which produces the low emittance, against thermal effects.

One way to bypass thermal problems is to make use of a SC photoinjector. In fact a SC RF gun is being explored but significant R&D will be required before this is the gun of choice [14].

Superconducting Linacs (SC RF)

In the last decade, superconducting RF technology has matured to the point that virtually all new and future accelerators, be they for light sources or otherwise, incorporate SC RF. This is true for rings, FELs and recirculating machines, e.g., CEBAF, LEP, SNS, SOLEIL, TESLA, XFEL, etc,

The JAERI FEL [2] makes use of two five cell 500 MHz SC cavities, but most of the other ERLs considered in this overview chose higher frequency cavity designs such as those in Table 1. Even though the TESLA design has benefited from extensive development in the last decade, it is slated for use in a "pulsed mode" for both the collider and the XFEL. Additional work will have to be done on any of the linac structures if average currents are to exceed 100 ma, as significant HOM power will have to removed from the cryostats.

Table 1: SC Linac Properties

Parameter	**CEBAF (Original/New)**	**TESLA**
f_{RF} [GHz	1.5	1.3
Cells per Cavity	5/7	9
Grad. [MeV/m]	5-8/12	15-20
Q	$2\text{-}5\times10^9/6.5\times10^9$	1×10^{10}

Arc Optics

The magnetic arcs in an ERL serve two purposes, 1) to return the electron beam to the linac entrance with a phase shift for deceleration and 2) to optimize the transverse and longitudinal profiles of the electron beam for both photon generation and recovery in the linac and dump.

The choice of arc optics is dictated by the energy of the ERL, its particular application and the quality of the electron beam required. Quantum fluctuations due to incoherent synchrotron radiation in 2π of bending magnets of the arcs gives rise to an energy spread and emittance increase [15]:

$$\Delta\sigma_e^2 = \frac{55\pi r_e \lambda\!\!\!^-_c}{24\sqrt{3}} \frac{\gamma^5}{\rho^2}, \tag{2}$$

$$\Delta\varepsilon_x = \frac{\sigma_e^2}{2\pi\rho} \int_{BM} H\, ds, \tag{3}$$

where $H(s) \equiv \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$ is the Courant-Snyder parameter.

To prevent excessive energy spread the dipole bending radius, ρ, must be chosen sufficiently large. To combat the rapid growth in emittance with energy, $\Delta\varepsilon \sim \gamma^5$, the Courant-Snyder parameter must be kept small by segmented the dipoles into many pieces as is done in storage ring LS lattices. For example the 180° Bates bends which are suitable for the 48 MeV TJNAF FEL are not acceptable for a 5 GeV low emittance ERL LS. This latter source might require a large number of triple bend achromat (TBA) cells for the arc which minimizes emittance growth and provides tuning of the momentum compaction of the arcs for bunch compression [16].

Combining an energy chirp from the linac with either a dedicated bunch compressor or using the dispersive nature of the arcs allows for manipulation of the longitudinal phase in an ERL, in particular compression of the electron bunches to the sub picosecond level. Nonlinearities in the linac and arcs will affect the minimum bunch length achievable: the long electron bunches from the injector will sample the nonlinearities in the linac waveform and this can be compensated with a third harmonic cavity, while nonlinearities in the arcs can be compensated using sextupoles and higher order multipoles.

The focusing in the linac can present a challenge even for the simple ERL configuration of Figure 1 as the beam energy is increasing on the first pass and decreasing on the second pass so that the effective strength of the quadrupoles varies by the energy ratio $E_{final} / E_{injection}$. The limit on this ratio is not yet known. Simulation suggests that a ratio as large as 5 GeV / 10 MeV might be possible [17]. Recent experimental work has achieved ratios of 1 GeV / 20-50 MeV [18].

The overall optics of the ERL also plays a critical role in determining the threshold current for the multi turn beam breakup instability [6]. The characteristic behavior of the threshold current can be seen if one assumes a single HOM with frequency ω, initial electron momentum p_0, HOM shunt impedance & quality factor (R/Q) & Q, recirculation time τ_r, and TRANSPORT matrix element R_{12} [6,19,20],

$$I_{th} = \frac{2c^2 p_0}{e[R/Q]Q\omega \left| R_{12} \mathrm{Sin}(\omega\tau_r) \right|} . \quad (4)$$

For the more realistic case with many HOMs distributed in a long linac a numerical solution is required [19].

Wakefields

Longitudinal wakefields can modify the electron bunch phase space, increase the energy spread, lead to heating of machine components and result in emittance growth. For effects on a single bunch, such as the coherent synchrotron radiation wakefield (CSR), it is the peak current that is of concern, while in the case of component heating the average current also plays a role. The multicell linac wake and CSR are “unavoidable” as the beam must be accelerated and bent in the arcs to be returned for deceleration. The resistive wall and surface roughness wakes must be accounted for in insertion devices, particularly small gap devices.

FEL ERLS

Oscillator FELs

FELs operating in an oscillator configuration have long been the workhorses of FEL user facilities based on both linacs or storage rings. While the storage based FELs are limited by the quality of the “captive electron beam”, the linac based devices have the advantage of replenishing the electron beam on each pulse. In either case, only a few percent of the electron energy is converted to photons.

The “ERL twist” allows for:

- an overall improvement in the wall plug efficiency,
- a tremendous increase in the average electron current and hence the FEL power,
- reduced activation in the beam dump.

At present there are two operating FEL oscillator ERLs based on SC linacs, one at TJNAF [1] and the other at JAERI [2]. There is also an FEL ERL at BINP which makes uses of room temperature RF cavities and has started operation in single pass mode but has plans for an 8 turn racetrack configuration [21]. The TJNAF machine is the most developed of the three, having achieved an average power of 2 kW at λ = 3 μm operating in ERL mode in 2000. A summary of the parameters of these ERLs, and their proposed upgrades, is given in Table 2.

Table 2: Operating Oscillator FELs (I) & Upgrades (II)

Parameter	TJNAF I	TJNAF II	JAERI I/II	BINP I/II
E [MeV]	48	160	17	14/100
I_{ave} [ma]	5	10	5/40	4/50
Q/bunch [pC]	65	130	500/ 1000	700
ε_N [μm]	15	10	30	20
Rep Rate [MHz]	75	75	10	5.6-22.5
Duty Cycle	100	100	1/100	100
P_{FEL} [KW]	2	10/4	2.3/10	-/100
λ_{FEL} [μm]	3-6	3/0.5	22	150

In addition to the operating oscillator FELs, the 4GLS proposal from the Daresbury Laboratory includes both IR and VUV oscillator FELs in a 600 MeV SC linac based ERL [22]. An R&D program leading up to the 4GLS received governmental approval in April 2003.

High Gain FELs

FELs operating in the IR or UV can make use of mirrors to provide feedback in a “low gain” oscillator configuration. For soft or hard x-ray FELs mirrors are not available necessitating a high gain FEL scenario, either a Self Amplified Spontaneous Emission (SASE) or a seeded scheme such as High Gain Harmonic Generation (HGHG). There are several ERL proposals which include high gain FELs:

- LANL has proposed a SASE FEL with a tapered wiggler and a room temperature linac [23],
- 4GLS proposes a SASE XUV FEL [22],
- LUX includes soft x-ray HGHG FELs with an option for energy recovery [24],
- an HGHG FEL was studied as part of a racetrack microtron injector for MAX IV [25],
- BESSY’s soft x-ray FEL proposal mentions an option for energy recovery [26].

While the virtues of energy recovery for high average power oscillator FELs has already been proven, the need for energy recovery is less clear for high gain FELs, a notion supported by the fact that neither the LCLS nor the XFEL incorporates it. It remains to be seen what rep rate is optimal for these devices which will determine if energy recovery is worth the additional expense. If the sample is destroyed on a single shot from the extreme peak power in a pulse, there's no need for a MHz rep rate!

SYNCHROTRON LIGHT ERLS

The Holy Grail in a synchrotron light source is to produce a high brightness photon beam using a diffraction limited electron beam. The on axis average brightness for an undulator source is given approximately as,

$$B_{ave} \approx \frac{1}{8\pi}\frac{I}{e}\frac{\alpha N_u}{\left(\varepsilon_x \oplus \lambda\!\!\!^{-}/2\right)\left(\varepsilon_y \oplus \lambda\!\!\!^{-}/2\right)}\frac{\Delta\omega}{\omega}, \qquad (5)$$

where the larger of ε or $\lambda\!\!\!^{-}/2$ is chosen in each bracket of the denominator. A diffraction limited source is defined as $\varepsilon \approx \lambda\!\!\!^{-}/2$; there is little gained by reducing the electron emittance beyond the light emittance ($\lambda\!\!\!^{-}/2$).

For 12 keV x-rays (1 Å), a diffraction limited electron beam should have ε ~ 8 pico-meter! This is more than 2 orders of magnitude smaller than the typical horizontal emittance in present day storage rings (1-5 nm); the vertical emittance in a third generation ring can be pushed to the diffraction limit at the expense of beam lifetime.

The potential promises of an ERL based light source are:

- diffraction limited round electron beams ($\varepsilon_x = \varepsilon_y$) from photoinjectors or nanotips,
- very long insertion devices in the return arcs,
- energy recovery will permit large circulating currents and hence high fluxes,
- "top-off" operation,
- bunch compression will provide sub picosecond electron bunches,
- reduced electron energy spread,
- variable pulse formats for timing experiments.

Attracted by the above possibilities, several facilities are developing conceptual designs for an ERL light source. The novel MARS concept introduced by the BINP team in 1998 has been followed by at least five other ERL based light source proposals which emphasize different subsets of the aforementioned ERL promises. Table 3 lists these ERL proposals & their anticipated brightness.

Table 3: Conceptual Synchrotron Light Source ERLs

Item	Cornell [27]	ERL SYN [28]	KEK [29]	LUX [24]	PERL [30]	MARS [3]
E [GeV]	5-6	3.5	2.5-5	2.5-3	3	5.4
I_{ave} [ma]	100	100	100	-	200	1
B_{ave} [10^{22}]	1	6	3	-	0.1	30

The machines in table 3 all emphasize the production of hard x-rays using multi GeV electron beams and they can roughly be group into three categories:

- MARS emphasizes diffraction limited electron beams with very long undulators to generate high brightness photon beams with a narrow line width, but at the expense of photon flux since I = 1 ma,
- Cornell, ERL SYN, KEK and PERL consider large circulating currents I ~ 100 ma to satisfy the flux users while preserving the option to trade off current to reduce the beam emittance and boost brightness,
- LUX as presently proposed is a recirculating machine which has energy recovery as an option; it includes both HGHG FELs and a novel scheme of "photon compression" to generate tunable, sub 100 fs pulses by spontaneous emission in undulators [31].

It should be noted that none of the machines under discussion here are actually in the construction phase as each faces R&D challenges before a full fledged multi GeV ERL based light source facility can be realized. True to form for an evolving technology, several paths forward are under consideration:

- the Cornell [32] & KEK teams have proposed low energy (100-300 MeV), high current (100 ma) prototype machines before embarking on a multi GeV facility,
- PERL [33] & ERL SYN [34] have suggested a staged approach whereby a multi GeV machine is initially operated as a storage ring, and later upgraded to an ERL as the technology matures,
- to reduce the duty cycle on the injector and the linac it has been suggested that electrons could circulate for a small fraction of a damping time (~ 100 turns) in an "circulator ring" before deceleration in the linac [35, 36].

An important first step toward the realization of a high energy ERL was taken recently at TJNAF when the CEBAF machine was operated in energy recovery mode with 85 μA. The 50 MeV injected beam was accelerated up to 1 GeV and back in two complete passes [18].

OTHER ERL PROPOSALS

For completeness it should be noted that ERLs are also being considered for purposes other than light sources; there are at least two proposals related to nuclear physics:

- Electron cooling of heavy ions in RHIC [37],
- Electron-Light Ion Collider [38].

In the first case a low energy (E = 54 MeV), high current electron beam (I = 300 ma = 10 nC x 28 MHz) in an ERL interacts with the heavy ions in the RHIC collider to "cool" the ions. The electron cooling combats the "heating" of the ions by intrabeam scattering and thereby increasing the integrated luminosity of RHIC by nearly an order of magnitude. An R&D program to develop the 704 MHz SC linac and the high precision cooling solenoid has recently begun at BNL.

In the second proposal, known as ELIC, a high energy electron beam (E = 5 GeV), obtained from operating the CEBAF recirculating linac in energy recovery mode, is made to collide with a new source of 50-100 GeV light ions for nuclear physics experiments.

Preliminary consideration has also been given to colliding 10 GeV polarized electrons in an ERL with the gold ions in RHIC [39].

SUMMARY & FUTURE OUTLOOK

The operating FEL oscillator ERLs stand as brilliant proof-of-principle experiments which demonstrate many important ERL fundamentals such as:

- CW average currents of 5 ma at 15-50 MeV,
- High rep rate photoinjectors: up to 75 MHz with normalized emittance $\varepsilon_N \sim$ 10-30 μm,
- High efficiency energy recovery ($\eta > 99\%$),
- Preservation of electron beam quality in the arcs,
- Longitudinal phase space manipulation for sub-picosecond electron bunch compression,
- High average power photons (P >2 kW).

These pioneering experiments have laid a firm foundation for ERL based technology and provide the impetus to pursue the R&D necessary to realize the next generation of proposed ERLs which will require:

- high brightness ($\varepsilon_N < 1$ μm) CW electron sources capable of high average currents (I ~ 100 ma),
- long lifetime cathode materials and robust laser sources for CW photoinjectors,
- optimization of SC RF frequency, number of cells per cavity, gradient and HOM extraction,
- control of the electron beam halo,
- shorter photon and electron pulses ($\tau < 100$ fs),
- beam stability and feedback systems to transform ERLs into state of the art user facilities.

The next decade should be an exciting one for ERL development as existing machines will be upgraded to yield even higher performance, critical R&D issues will be explored and some new proposals will likely begin construction.

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