ENERGY RECOVERED LINACS*

G. A. Krafft#, Jefferson Lab, Newport News, VA 23606, U.S.A.

Abstract

In the last decade, stimulated by the success of the energy recovered free electron lasers, many projects have been initiated exploring the applications and limitations of beam energy recovery in recirculated linear accelerators (linacs). In this talk the performance of many existing energy recovered linacs is briefly reviewed. Looking forward, potential applications of energy recovered linacs such as recirculated linac light sources, high energy beam electron cooling devices, and electron beam sources for high energy colliders have been pursued with varying degrees of effort. The types of new technology that must be developed for applications, and more broadly, some of the open issues regarding this technology, are discussed.

RECIRCULATED AND ENERGY RECOVERED LINACS

Over the course of the last decade, there has been a growing interest in developing accelerators using the idea of beam energy recovery. This paper presents a review of the work done on energy recovery to date. In brief, applying the technique of beam energy recovery allows the construction of electron linear accelerators that can accelerate average beam currents similar to those provided by storage rings, but with the superior beam quality typical of linacs. Such an ability to simultaneously provide both high current and high beam quality can be broadly utilized. For example, high average power free electron laser sources may be built yielding unprecedented optical beam power, light sources extending the available photon brilliance beyond the limits imposed by present day synchrotron light sources may be designed, electron cooling devices may be possible which would benefit from both high average current and good beam quality to ensure a high cooling rate of the circulating particles in a storage ring collider, or, as a final theoretical possibility, the electron accelerator in an electron-ion collider intended to achieve operating luminosity beyond that provided by existing, storage-ring-based colliders may be based on an energy recovered linac (ERL).

In the following, we compare recirculating linacs to two more common types of accelerators: single pass linear accelerators and storage rings. We then discuss energy recovery conceptually, and review the work to date on this technique, primarily in the energy recovered free electron lasers. Most of this introductory material is a condensed paraphrase of material in an earlier review of energy recovered linacs [1]. Please consult this reference for a more detailed discussion.

In the past, two types of particle accelerators (Fig. 1) have been used. Among the electron accelerators, the first class of accelerators consists of the high-energy electron linacs. In such accelerators, the electron beam has a definite beginning and a definite end. Usually, the beam propagates along a nearly straight line, and there is a substantial length of RF beam-acceleration devices.

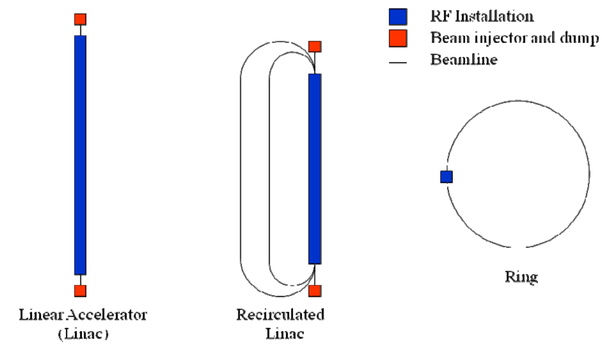

Figure 1: Main accelerator types.

Some main features of an electron linac are: first, an individual electron resides in the accelerator only briefly, certainly for times that are short compared to any relevant radiation damping times. Second, if a laser-driven photocathode gun is used as the electron source, it is relatively easy to load, or program, the beam current or beam polarization delivered to users by controlling the duration and polarization of the lasers that stimulate electron production at the gun. Third, the emittance, of the electrons in a typical beam tends to be set by phenomena in the low-energy electron source region, and this emittance may be well preserved during the acceleration to high energy. Fourth, the pulse duration, and more generally the longitudinal phase space distribution, is relatively easily manipulated by using standard beam-rf and electron beam optical techniques. Having long distance between the end of the linac and the beam dump is easy to arrange in a linear geometry.

The second class of high-energy electron accelerators is the synchrotron-like storage ring. In an electron storage ring, the electrons are bent on a roughly circular orbit. Because transversely accelerated electrons radiate copious amounts of electromagnetic radiation, to achieve a long-term equilibrium it is necessary to supply energy to the circulating electrons. Energy is supplied, as in linacs, with RF cavities but they subtend a small portion of the total machine circumference. After the beam is injected into the ring, the electrons rapidly settle into an equilibrium where the synchrotron radiation losses are made up by the energy transferred from RF to beam. The equilibrium characteristics point to the main limitations of storage rings. The equilibrium beam emittance, and hence the

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#krafft@jlab.org

beam sizes in the storage ring, are given by a competition between the radiation damping, which tends to drive the electrons onto the closed orbit at the correct accelerating phase, and the quantized radiation emission, which tends to excite transverse and longitudinal oscillations. Formulas for the equilibrium size are well known [2]; here, it is sufficient to point out that both the emittances and the equilibrium pulse length in an electron storage ring can not be arbitrarily small.

Recirculating linacs are accelerators in which, as in linacs, there is substantial RF accelerating the beam and the beam has a definite beginning and ending (i.e., there is no closed or equilibrium orbit), but, as in a storage ring, the beam goes through the accelerating cavities more than once (Fig. 1). Such a hybrid arrangement, by applying beam energy recovery, allows one accelerator to feature some advantages of both of the usual arrangements.

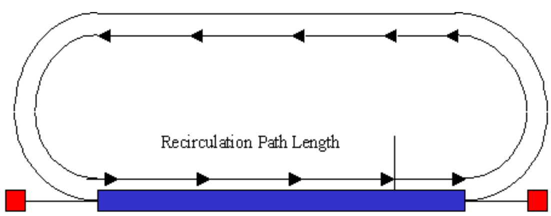

Figure 2: Traditional recirculation geometry.

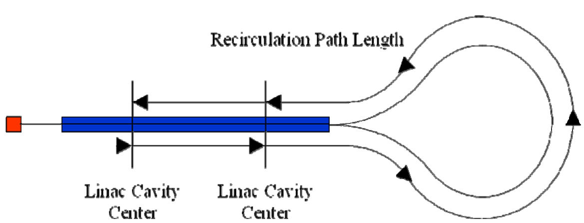

Figure 3: Reflex or herring-bone geometry.

Figures 2 and 3 define possible beam recirculation geometries. In the more traditional, and more utilized, geometry of Fig. 2, the recirculation path length is chosen to be approximately and integer plus one half RF wavelengths for energy recovery. By this choice, if the first pass beam is accelerated by the RF field, the second pass beam is decelerated by the same RF field because the RF phase has reversed sign when the second pass beam arrives. This geometry has the advantage of relatively easy phasing and no beam-beam collisions, but suffers from the fact that at most locations along the linac, two different beam energies exist. This shortcoming is solved in the reflex or herring-bone geometry of Fig. 3. Here both beam passes have nearly the same energy simplifying beam optical design. The downsides of this geometry are the possibility of beam-beam collisions and the fact that additional constraints must be placed on the linac geometry to ensure that the recirculation path length is nearly an integer number of RF wavelengths at each cavity. The earliest accelerator utilizing beam energy recovery was built at Chalk River in reflex geometry [3].

In the future, it is likely that electron recirculation will be applied to build recirculating linacs because of their superior beam quality. Recirculating linacs share with linacs the ability to accelerate and preserve the emittance of very-low-emittance injector beams. Because the transit time is short compared to a typical radiative emittance buildup time, no equilibrium is established as in a storage ring, implying that the emittance delivered to the end user may be smaller. Also, as in linacs, one can manipulate the longitudinal phase space of the electron beam to deliver very short beam pulses to the end user. The minimum pulse length is no longer set by radiative effects but by the ability to generate, and precisely manipulate, the longitudinal phase space of the electron beam, as shown many years ago at Jefferson Lab [4]. Applying energy recovery has allowed one to conceive of recirculating linacs with high average currents and efficiencies approaching those in storage rings.

ENERGY RECOVERED FREE ELECTRON LASERS

The combination of high average current and good beam quality is highly desired when a high average power free electron laser is required. Therefore, the first purpose-built energy recovery linacs were constructed as free electron laser drivers. Presently, all the existing energy recovered linacs are FEL drivers.

Stanford Free Electron Laser

The Stanford Superconducting Accelerator (SCA) was upgraded into a 5-pass recirculated linac for nuclear physics research in the late 1970s, and employed in that capacity for several years [5]. However, after free electron laser work was initiated at Stanford in the late 1970s and early 1980s, it was desired to increase the peak current in the beam bunches to increase FEL gain. The RECYCLOTRON bends were replaced with two sets of isochronous bends, one set being mounted on a movable table that allowed the path length of the recirculation arc to be adjusted throughout a full RF wavelength. This flexibility allowed RF power measurements to be performed comparing the RF power required to accelerate 1-pass beam, 2-pass beam in accelerating mode, and 2-pass beam in energy recovery mode. Such measurements convincingly demonstrated the possible efficiency enhancements permissible in a same-cell energy recovered beam [6].

The SCA had a long life as a FEL source of infrared radiation for two decades. Several papers in the proceedings document changes and upgrades to this venerable machine as it begins its new life in Monterey, CA as an energy recovered FEL [7].

Jefferson Laboratory 10 kW Free Electron Laser

This devise represents the state of the art in high average current energy recovery in a superconducting linac. A parameter list for this device appears in Table 1. The free electron laser has, during conditions where the beam power was 1 MW, produced up to 14.2 kW optical power, a world record for continuous operation. The free electron laser presently employs moderate bunch charge, about 135 pC, and a relatively high repetition rate of 75 MHz to achieve high average power. Because the FEL operates in the IR region of the electromagnetic spectrum, the emittance requirement in this device is lax compared to some of the ERLs contemplated for the future. A new, 100 kW optical power free electron laser will be built by the U. S. Department of Defence and is being bidded on by U. S. industrial firms. Jefferson Lab scientists are assisting in proposal development for the bids and can be expected to have greater or less participation in the final projects, depending on the firm awarded the contract. It may be expected that a large portion of the power increase will be obtained by increasing the beam bunch repetition rate above 100 MHz. It is not expected that the energy recovered linac has to change much to support this jump to higher power operation.

Table 1: Jefferson Lab 10 kW FEL beam parameters.

Electron Beam Parameters	IR FEL	UV FEL
Energy (MeV)	80-150	150
Accelerator Frequency (MHz)	1500	1500
Charge per Bunch (pC)	135	135
Bunch Repetition Rate (MHz)	75	37.5
Average Current (mA)	10	5
Beam Power (kW)	1500	750
Energy Spread (%)	0.4	0.2
Normalized Emittance (mm mrad)	<10	<8
Induced Full Energy Spread	12%	6%

JAEA Free Electron Laser

The JAEA Free Electron Laser consisted of a 230 keV thermionic cathode gun, acceleration by superconducting cavities to 2.5 MeV for injection, and 2 500 MHz 5-cell superconducting cavities for acceleration to 17 MeV in the beam reciculation loop. The recirculation arcs consisted of three bend achromats that could be adjusted to non-zero momentum compaction. Much recent work focussed on providing maximum bunch compression at the free electron laser by varying the compaction. Within a beam macropulse, the average power of this device was at the 1 kW level, but at a longer wavelengths than at Jefferson Lab. The three bend achromat could be tuned up to 15% energy acceptance, and the FEL extraction efficiency was measured to be up to 2.8%. After highly successful beam running, the facility was shut down in April of 2008 and the superconducting cavities were returned to KEK.

ALICE/ERLP

Construction of the first energy recovered linac in Europe, the ERL Prototype (ERLP) at Daresbury, UK, is nearing completion. Because of the changing emphasis in the project away from ERL development and into experimental applications, the facility has been renamed to Accelerators and Linacs In Combined Experiments (ALICE) [8]. Gun commissioning is proceeding with the result that the longitudinal emittance of the extracted beam agrees well with ASTRA simulations. The transverse emittance has been higher than expected; present effort is focussed on understanding the discrepancies. First beam energy recovery experiments will be completed this fall, without the FEL. First light, and first energy recovery with the FEL completely in place will take place in Spring of 2009. A very complete review and status report was provided to the conference by D. Holder [9].

BINP Energy Recuperator

The Budker Institute THz FEL is unique in several particulars of its design. Most prominently, the injector and linac consist of normal conducting 180 MHz accelerating cavities that are operated in CW mode. The linac provides approximately 15 MeV beam energy gain. The two-pass THz FEL is laid out on a vertically oriented plane with the accelerating cavities close to the ceiling and the THz optical cavity on the floor. Because low frequency cavities were utilized with very large apertures, this design is highly robust and reproducible. There is very little beam loss on recirculation, and this device has energy recovered the largest average current to date, at 40 mA beam current. Because of the large apertures, it is reasonable to upgrade to a multiple pass version of the accelerator. A four recirculation loop, eight-pass accelerator upgrade has recently been completed. On passes two and four there will be infrared free electron lasers; all of the recirculation beam lines are on a horizontal plane passing through the linac axis near the ceiling. As of the recent FEL conference, 9 mA beam had been transported and energy recovered through two loops of the upgraded machine, but without going through the FEL yet. During the coming months one anticipates completing the full 4-pass circuits and running the free electron lasers at high optical power.

APPLICATION TO X-RAY SOURCES

Storage ring x-ray sources operate by having a high average current, high energy electron beam interact with the bend magnets of the ring, or with a series of insertion devices deployed throughout the ring where the x-rays are produced. The performance of these machines is constrained by fundamental processes, which ultimately limit the quality of the electron beam. Producing electron beams with superior characteristics for generating synchrotron radiation may be possible via photoinjector electron sources and a high-energy energy recovered linac. Relatively simple considerations lead to an understanding of the possible beam modes.

The brilliance of x-rays originating on a typical insertion device goes as

$$B = \frac{I}{\varepsilon^2} = \frac{fQ}{\varepsilon_{th}^2 + AQ^p}$$

where I is the average current, Q is the bunch charge, ε_{th} is the beginning emittance, and a hypothetical power-law model for the emittance growth between source and insertion device is assumed. Because of the rapid increase with Q of the denominator for a power law greater than ½, it is easy to show that the greatest brilliance occurs at a condition where the two terms in the denominator are of similar order. But usually the emittance at the insertion device is at least an order of magnitude beyond the beginning emittance. Thus, as a function of Q, the maximum brilliance occurs with high frequency low charge bunches. More thorough analysis of this problem including the diffraction effect of the x-rays leads to the conclusion that for 1300 MHz operation with every accelerating bucket filled, the optimal brilliance occurs at around 20 pC bunch charge [10], which has somewhat less average current than the comparable storage ring.

Table 2: ERL X-ray source beam parameters.

Electron Beam Parameters	**High Flux**	**High Coherence**
Energy (GeV)	5	5
Accelerator Frequency (MHz)	1300	1300
Charge per Bunch (pC)	77	19
Bunch Repetition Rate (MHz)	1300	1300
Average Current (mA)	100	25
Beam Power (MW)	500	100
Energy Spread (%)	0.02	0.02
Normalized Emittance (mm mrad)	<0.3	<0.1

Because of the smaller inherent energy spread in a recirculated linac beam [11] than in a storage ring, it is possible to raise brilliance by considering longer insertion devices with a larger number of magnetic periods. A rule-of-thumb that has been found useful in evaluating the brilliance of ERL x-ray sources is that the optimized brilliance of an ERL source is about 3 orders-of-magnitude above present day storage rings. About an order-and-a-half of this improvement is due to the superior beam emittance, and an order-and-a-half is due to the possibility of long undulators. To obtain conditions suitable for high-flux experiments, beam currents comparable to those in storage rings are supported by higher charge-per-bunch operation. Unfortunately, it may be difficult to arrange simultaneous high-flux and high brilliance running without some sort of RF beam separation system to divide the ERL beam to various users.

Since being initially proposed, and being strongly advocated by scientists from Novosibirsk [12], many groups considered the possibility of energy recovered x-ray sources. Cornell University is building and commissioning an ERL demonstration injector as a first step toward a follow-on many GeV light source. It is based on a DC photocathode source followed by beam bunching and acceleration to 10 MeV by 5 two-cell superconducting RF cavities. This prototype will demonstrate full current injection with the required beam properties, acceleration to 10 MeV, and if successful will be the first device to clearly demonstrate emittance compensation in a DC gun system [13]. It will also be highly influential for evaluating future projects because so much of the utility of the ERL light source idea is dependent on superior beam emittance being produced at low charges. New technology, especially in the area of drive laser pulse shaping, is being developed to meet this challange. Over the summer the ERL injector yielded its first beam. Presently, various commissioning studies are happening. The review talk at this conference provides much more on plans and recent accomplishments [14].

APPLICATIONS TO HIGH ENERGY AND NUCLEAR PHYSICS

Energy recovered linacs are being considered for applications in high energy and nuclear physics because of their unique ability to provide high average current beams with superior beam quality. Two potential applications are as an electron source for beam cooling schemes and as an electron beam source for an electron-ion collider.

Electron Cooling

In electron cooling, a relatively low-energy electron beam is merged with a relatively high-energy ion beam, the electron-beam energy being chosen so that the average longitudinal velocity of the two beams is the same. The electron beam acts as a heat sink, removing thermal energy from the ion beam. Collisions with cooled beams are possible at higher luminosity than in the same collider without cooling. The cooling rate is proportional to beam average current.

High-energy electron cooling with high cooling rates may be possible now that ERLs have demonstrated technical feasibility. Again, the main development is the high-average-current source. Such a design may be even more difficult than for the light sources because the bunch repetition rate, to match, for example the RHIC beams, must be reduced to 9 MHz, and to obtain the same average current, the charge per bunch must be increased to ~10 nC. Recent successes in utilizing stochastic beam cooling in RHIC have reduced interest in developing this device as a cooler for RHIC. But ERLs may find use as drivers for coherent electron cooling devices.

Electron-Ion Colliders

Finally, energy recovered linacs have been studied for electron-ion colliders for nuclear and/or particle physics research. An ERL would replace the more typical electron storage ring. A *gedanken* experiment indicates why such an arrangement is advantageous and may produce higher luminosity. Assume for the moment that one has designed a stable ring-ring collider. If the electron ring is stable, any current-limiting instability growth rate must be slower than one ring damping time. Then, the electrons are confined to at least one damping time, or about 1000 revolutions.

Suppose now one designs an ERL collider with an identical ion-storage ring and an identical set of electron beam parameters to the ring-ring collider above. Because the electron-beam parameters are the same, the ion beam stability is assured, even if one increases the *ion* bunch charge and luminosity. Increasing the ion bunch charge will increase the disruption of the electron bunch by the beam-beam effect. However in the ERL it is no longer necessary to confine the electron beam for 1000 turns, only a few turns. Estimates of the emittance increase and the maximum deflection angle generated by a few beam-beam collisions show that there may be room to considerably increase the ion bunch charge, and the luminosity, before energy recovery becomes difficult.

Two projects have considered ERL collider drivers. The first is eRHIC, an electron-ion collider based at RHIC, and the second is ELIC, an electron--light-ion collider based at CEBAF. In the eRHIC proposal, one of the RHIC rings is used to contain the ions and a new ERL is built. In ELIC, CEBAF is upgraded to a higher-energy ERL, and a new ion-storage ring is constructed.

Table 3: BNL ERL prototype beam parameters.

Electron Beam Parameters	High Current	High Charge
Energy (MeV)	20	20
Accelerator Frequency (MHz)	700	700
Charge per Bunch (nC)	1.4	5
Bunch Repetition Rate (MHz)	700	9.4
Average Current (mA)	500	50
Beam Power (kW)	1000	150
Energy Spread (%)	0.5	1
Normalized Emittance (mm mrad)	2.3	5.3

The parameters required by these ERL proposals are an extrapolation from today's demonstrated performance by one to two orders of magnitude in average current. Because of the difficulty in constructing a high average current polarized electron source, the ELIC project has migrated back to a ring-ring design using the upgraded CEBAF accelerator as a full energy injector.

Supporting the development of very high average current ERLs, Brookhaven National Lab is assembling an ERL prototype. Potential operating modes of this device are shown in Table 3. D. Kayran presented a poster summarizing the status of this project [15].

CONCLUSIONS

Energy recovered recirculated linacs are a new class of accelerators with the potential to produce unique beam properties. The field of ERL-based free electron lasers continues to grow and the performance of devices continues to improve. Higher peak and average brilliance may be possible in ERL-based x-ray sources than is possible in storage rings at the same beam current. Many new ideas are being explored in a broad range of applications. This field seems to be thriving and there is no shortage of interesting problems to work on.

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