HIGH BRIGHTNESS BEAM APPLICATIONS: ENERGY RECOVERY LINACS*

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In the first part of the paper some general statements are made regarding applications suitable for utilizing energy recovered linacs (ERLs) by contrasting their potential performance to that of single pass linacs and storage rings. As a result of their potential for extremely good beam quality in combination with high average beam current, ERLs have been used and considered as drivers of both free electron laser and partially coherent photon sources, from THz through X-rays; as a suitable technology for high energy electron cooling; and as a continuous or semi-continuous electron beam source for high energy colliders. At present, beam requirements tend to be highly matched to end use requirements. By reviewing some of the many examples which have either been reduced to practice, or are being explored presently, one can develop an appreciation for the wide range of parameters being considered in ERL applications.

1. Introduction

Recently, energy recovered linacs have been considered for a wide variety of purposes, well beyond their initial development as drivers for high average power free electron lasers. These developments have led to new and interesting problems in the field of high brightness beams as new high average beam power electron sources must be developed in order to drive the ERL, and some of the applications require very low emittance in addition. In this paper the recent progress in energy recovery linacs will be reviewed, with particular emphasis on the electron sources that have been built and that are being contemplated for these applications.

In brief, the paper begins with a description of the beam energy recovery process. Next, energy recovered linacs are compared and contrasted to the usual workhorses in electron accelerator physics: the single pass linacs and the storage rings. This discussion leads naturally to a review of the presently existing ERLs, which up to now have been developed as free electron laser (FEL) drivers. Next we discuss the types of electron sources being proposed for ERLs. In

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contemplating the requirements on the electron injectors for ERLs, it becomes obvious that the brightness requirements depend very heavily on the application, the most stringent being for anticipated recirculated linac X-ray sources. Therefore, the primary end use applications will be discussed in turn, referring to the most recent ideas concerning the electron sources for the energy recovered linac. Their implications on high brightness beam sources will be addressed.

2. Beam Energy Recovery

Beam energy recovery can be most simply explained by reference to Figures 1 and 2, which present the idea in the simplest case of a two-pass recirculated linac with a single accelerating pass and a single decelerating pass. Figure 1 provides a schematic diagram of the more common "front-to-back" beam recirculation geometry, where "front-to-back" refers to the fact that the second pass beam proceeds from the front of the linac to the back of the linac. Suppose a two-pass linac exists, with the recirculation path length, as defined in Figure 1, chosen so to be an integer plus ½ accelerating mode RF wavelengths long. Suppose further that there is no beam loss between passes. Because the current load phasors are equal and opposite, there is no RF beam load on the cavities within the recirculation loop. Physically, the energy for acceleration of the first pass beam no longer comes from the incident RF power on the accelerating cavity, but is transferred directly out of the decelerating second pass beam via the RF field of the cavity. That this transfer can be done very efficiently, and almost all of the decelerating beam energy passes to the accelerated beam is demonstrated by recent experiments involving superconducting recirculated RF linacs.

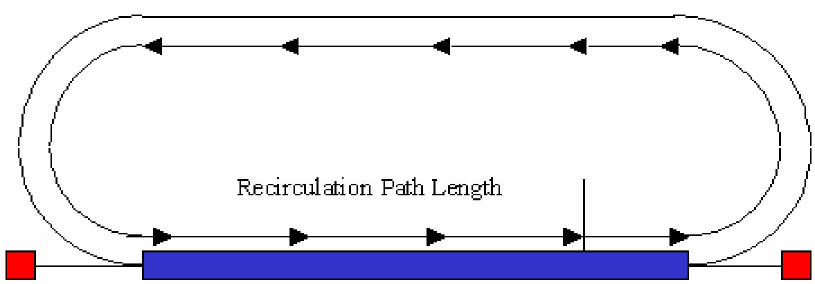

Figure 1. Two pass recirculated linac in "front-to-back" beam recirculation arrangement. Beam energy changes depending on the pass number.

There is another way to achieve perfect energy transfer between the accelerating beam passes and the decelerating beam passes, as shown schematically in Figure 2 [1]. Rather than having the beam load phasors cancel by a 180 degree difference in the RF phase between accelerating and decelerating beams, one could just as well have the beam load cancel by having the beam velocities oppositely directed with the arrival timed to be on the same phase on the two beam passes. In order for this situation to be achieved the recirculation path length as defined in the figure must be an integer number of RF wavelengths to the center of each accelerating cavity. Such “back-to-front” or reflex beam recirculation was actually used on the earliest recirculated linac where energy recovery was performed [2].

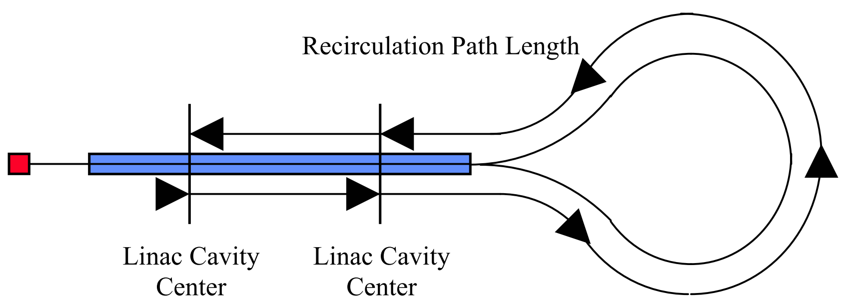

Figure 2. Two pass recirculated linac in “back-to-front” or reflex beam recirculation geometry. Here, the beam energy is the same for both passes between the accelerating cavities.

A convenient way to characterize the benefit of the beam energy recovery is in terms of the RF-beam multiplication factor, discussed more thoroughly in [3] and [4]. The multiplication factor

$$k = P_{ave,beam} / P_{RF}$$

gives the ratio between the average beam power at its end use and the RF power required to accelerate the beam. By the first law of thermodynamics, any single pass linac has $k < 1$. If one considers normal conducting recirculators, the multiplication factor is less than 1 because of the large RF power needed to maintain the accelerating field in the RF cavities. For superconducting accelerating structures, because of the possibility to operate at high loaded Q

values, one has the possibility of having the multiplication factor close to 1 even in non recovered linacs such as the CEBAF accelerator at Jefferson Lab [5], where the multiplication factor is about .995 for a perfectly matched beam current, and it is usually about 0.8 at more common operating beam loads. The first recirculated linac with a multiplication factor that exceeded 1 on a continuous basis was the superconducting Jefferson Lab IR DEMO FEL [6], with a multiplication factor around 16. This device has recently been upgraded and operates with a multiplication factor around 30. A storage ring with superconducting accelerating cavities has a multiplication factor around 1000.

Table 1 presents a comparison between the beam properties possible in single pass linacs and the beam properties possible in storage rings. One notices an advantage to single pass linacs in that the ultimate electron emittance may be better and the achievable beam pulse lengths may be much shorter than in storage rings, whereas the electron storage rings have a large advantage in their ability to handle high average current beams. Recirculated linacs that are energy recovered, because of the possibility to achieve high multiplication factors, are quite interesting because they contain the possibility of combining the good emittance and short pulses of linacs with the high average current capability of storage rings, all in a single technology. The arrows in this table extend from present experience to numbers that have been proposed in various ERL projects.

Table 1. Comparison of Accelerator Types.

	High Energy Electron Linac	High *k* Super-conducting Linac	Storage Ring	Unit
Accelerating Gradient	>50	10-20	NA	MV/m
Duty Factor	<1%	1	1	
Average Current	<1	10→100	1000	mA
Average Beam Power	0.5	1→1000	3000	MW
Multiplication Factor	<1	33→200	1000	
Normalized *rms* Emittance	1	1	4	mm mrad
Pulse Length	0.1	0.1	20	psec

3. Existing and Planned ERL Free Electron Lasers

Early work on beam energy recovery was performed at Stanford University on the Superconducting Accelerator [7]. A primary motivation of this work was to provide a path to higher average beam current and higher average power free electron lasers utilizing the higher efficiency possible at higher multiplication factor. Their early work did not include operating the FEL oscillator inside the beam energy recovery loop, but the work did anticipate many of the problems later encountered when the FEL oscillator was included in the loop.

It took more than a decade before an oscillator was enclosed inside the recirculation loop of an energy recovered recirculated linac, at the Jefferson Lab IR DEMO FEL, followed sometime later by the Japan Atomic Energy Research Institute (JAERI) FEL at Tokai [8]. These devices achieved several kW average photon beam power from devices handling of order 200 kW average electron beam power. More recently, a similar average beam power has been achieved at much higher average beam current in a normal conducting energy recovered linac at Budker Institute of Nuclear Physics [9]. Higher beam powers of order 1 MW have recently been used to drive a 10 kW scale FEL laser oscillator utilizing superconducting accelerating cavities [10].

These successes have led to a veritable plethora of more advanced FEL projects. The furthest along is the 4GLS project at Daresbury [11], which proposes, in addition to a non-energy recovered IR FEL, to construct a non-energy recovered DUV-FEL of a conventional SASE type and an energy recovered DUV light source. A small-scale energy recovered linac, including an enclosed oscillator, is being built at Daresbury as a prototype. The Korean Atomic Energy Reseach Institute (KAERI) has plans to build an energy recovered IR FEL similar to the device at JAERI, and the National High Magnetic Field Laboratory at Florida State University plans an ERL based on the IR DEMO FEL parameters, but featuring more advanced beam optics designs. Also, there is a French proposal for an ERL based roughly on the 4GLS model, in a less complete state of development. Of course, plans are being developed to extend the average power in the FELs to the 100 kW level with 10 MW average electron beam power drivers.

Because of the long wavelength of the operating oscillator FELs, the emittance requirements for the devices are relatively modest. For example, the Jefferson Lab FELs operate at of order 10 mm mrad normalized *rms* emittance, JAERI has an emittance of 40 mm mrad, and MARS has an emittance of 20 mm mrad. Because of the relatively modest emittance requirements of present devices, because of the prior existence of DC photocathode guns that could without much further development provide the requisite beams for the FEL, and because DC guns may be easily run in a "CW" mode, the Jefferson Lab FEL and its likely offshoots are based on DC photocathode gun technology. JAERI and MARS have utilized the usual thermionic emission sources coupled with high extraction voltage in the formation of their beams. 4GLS, at least for the present, has chosen to base their sources for the IRFEL and ERL ring on the DC photocathode sources, copying development work being done at Cornell University to extend the performance of DC guns into new brightness regimes [12].

4. Electron Source Technology for ERLs

Because beam for the energy recovered linac must be continuously provided in high duty factor applications, there is a great need for developing advanced high average current electron sources to drive the ERL. Many technologies have been explored to solve this problem, and it is fair to say that no clearly obvious "winning" technology has emerged to the point that future discussion on this topic is fruitless. Actually, this situation accounts for some of the interest and excitement in the field generally. In this section the possibilities will be discussed, with their advantages and disadvantages. In the following sections of this paper, where some of the potential applications of ERLs are discussed, the technology choices being made will be related to the application.

The types of guns being studied presently fall into 4 broad categories: DC photocathode guns, RF photocathode guns, SRF photocathode guns, and hybrid DC-SRF photocathode guns. As mentioned in the previous section, all of the present ERLs have been driven by DC electron sources, and the IR DEMO FEL was driven by a DC photocathode source. Advantages of this technology choice include: natural integration into CW ERLs because of the DC accelerating field; existing sources performing at the 10 mA, 100 pC bunch charge level; good thermal emittance of the photocathode; and a natural upgrade path in average current by increasing the photocathode drive laser power by increasing the pulse repetition rate. A primary disadvantage of this choice at present is that it has never achieved transverse emittance, and hence brightness, comparable to the best RF photocathode sources. This situation may soon change, as a 5-15 MeV ERL electron source is being constructed at Cornell University that is expected to have markedly better emittance than previous DC photocathode guns. Interestingly, an essential element of this design is the application of emittance compensation techniques similar to those that have been applied in RF photocathode guns for a number of years [12].

Normal conducting RF photocathode guns have been developed, built, and operated over a number of years. The best RF guns have the best beam brightness from photocathode guns, accounting for their overwhelming predominance throughout this conference. However, these best results have been obtained only in low duty factor pulsed RF guns. Pulsing the RF allows the accelerating field in the cavity to be greater than may be possible in ERL applications requiring CW operations. The highest duty factor normal conducting RF gun was operated for the Boeing FEL [13], at 25%. Here, the average accelerating gradient was 5 MV/m and the normalized *rms* emittance was several 10s of mm mrad, only comparable to the present DC data. However, an advanced normal conducting RF gun is being developed by Los Alamos and AES [14] as an FEL driver. It is anticipated that the average accelerating gradient will be 7 MV/m and the emerging normalized *rms* emittance will be 6.5 mm mrad with 100 mA of average beam current.

Given the inherent limitations in the accelerating gradient of CW RF guns tied to ones inability to cool them beyond a certain point, it is natural to contemplate removing such limitations by using superconducting RF (SRF) acceleration cavities instead normal conducting RF cavities. This should allow one to operate at higher accelerating fields, with better extracted emittance. The main difficulty of such an approach is that one must integrate, in a single device, both the photocathode, and any preparation activities needed to keep the photocathode emitting, and the relatively touchy (e.g., the surface must be free of contaminants) superconducting material forming the accelerating cavity. On the other hand it should be stated there is broad recognition among practitioners that the ideal source for many ERL applications would be an RF photocathode gun based on superconducting accelerating cavities. Work in this direction was covered in talks by Stefan and Sekutowicz at this conference, where many of the difficulties in and progress towards achieving an SRF gun were reviewed. Unfortunately for applications to projects being planned now, SRF guns are the least developed path, even though substantial progress is being made.

5. Future Applications

The future applications of ERLs that are presently being contemplated fall into four broad categories: higher average power FELs, photon sources in the DUV and X-ray wavelength bands, sans the FEL, electron coolers, and electron-ion colliding beam accelerators for high energy and nuclear physics experiments where the electron beam originates in an ERL.

In addition to the projects mentioned in Section 3, work will continue on producing higher average power FELs by increasing the electron beam power energy recovered to the level of 10 MW, corresponding to photon beam powers of order 100 kW. Compared to the present experience, this jump in performance should be relatively straightforward to achieve by increasing the beam current to the level of 100 mA by increasing the bunch repetition rate in the FEL. In particular, the bunch charge does not have to increase much beyond 100 pC to provide the requisite average current. Such a low bunch charge is well within the present operating experience of CW electron sources. In the further future, to achieve 100 MW beam power, it will be necessary to increase the charge-per-bunch substantially, to levels commonly investigated within the X-FEL community. As seen in more detail below, designs at higher levels in charge-per-bunch have tended to take advantage of the good impedance characteristics of superconducting cavities with lower operating frequency and larger physical size.

Because of the relative ease in scaling up the beam current in an energy recovered recirculated linac to the 100 mA level with existing DC photocathode sources, and because the beam current in typical storage ring radiation sources is also around 100 mA, it is natural to ask whether energy recovered linacs might be used in order to produce a recirculated linac light source with unique properties [15, 16]. This idea is being vigorously pursued at Cornell University [17] and 4GLS [11], and with varying degrees of seriousness at other laboratories around the world.

For high average X-ray brightness and flux in this application, there is a requirement for CW operation of the electron source. To maximize the X-ray brightness, as in X-FELs, one would like to minimize the electron beam emittance in both transverse planes in the ERL. Thus one is led to photocathode electron sources and large initial accelerating gradients. The fact that every accelerating phase may be populated with a beam bunch means that at 100 mA beam current only relatively modest charge-per-bunch, less than 100 pC, is needed, along with beam emittances around 1 mm mrad normalize *rms*. It is presently perceived that both DC photocathode guns and normal conducting RF photocathode guns may be able to produce beams with the required properties in the near term, and the hope, as a result of the development efforts mentioned previously, SRF photocathode guns will become excellent electron sources.

Compared to normal conducting RF or SRF photocathode guns, more modest developments are required to produce DC photocathode guns with emittance characteristics superior to those in the present CW FELs. By capitalizing on the lower thermal emittance inherent in GaAs photocathodes, by applying emittance compensation and drive laser pulse shaping techniques similar to those used in X-FEL guns, and by optimizing the placement of individual beam-line elements by application of an “evolution” optimization algorithm, the calculated normalized *rms* beam emittance from an injector designed for the Cornell ERL has 0.1 mm mrad at 80 pC beam charge [12]. The

ERL gun at Cornell is being assembled presently and should be producing its first beam soon [18], and should produce high average brightness electron beams well beyond the requirements of the large recirculated linac light source.

At this point one should mention that there is a long-term proposal to energy recover the spent beam from an X-FEL [19, 20]. The main benefit of this approach is that it is now possible to run the repetition rate of the beam bunches up to 1 MHz, allowing the average brilliance to be increased by a factor of 10^5 in a machine that retains the huge peak brilliances of an X-FEL. Here, a major development task is found in producing the high average electron beam power source retaining the exceptional beam quality required for the X-FEL. The beam line for recovering the energy of the DESY FEL is presently laid out in a reflex geometry, implying that rather elaborate collision avoidance beam optics be installed throughout the linac. To the best of the author's knowledge, no one has explored the perhaps more natural design, which features front-to-back recirculation and the X-FEL undulator in the return straight of the recirculation loop, although 4GLS has a similar geometry for their non-energy recovered DUV-FEL.

Till now, electron beam coolers have been based on DC electron beam technology, including spent electron beam energy recovery by suppressed collector voltage operating modes [21]. It has not been necessary to operate the coolers at beam energies beyond several MeV. With the advent of the RHIC, whose luminosity might be increased by the application of electron cooling, it becomes necessary to consider arrangements at higher beam energy. Because the application requires beam energies higher than a few MeV and because the electron cooling rate is higher the higher the (average) electron current, it becomes natural to consider a CW RF linac as a beam energy source and an energy recovered linac as a means to achieve the high average electron current, no longer limited by the CW RF power required in a single pass arrangement. Plans of this sort are being pursued at Brookhaven National Lab, where electron coolers based on ERLs at around 50 MeV and up to 0.1 A average current are being developed.

There are several special features required of the electron sources of this application. In contrast to the FEL and light source applications, where high average current is obtained by filling every accelerating phase with a relatively low charge bunch, because the ion bunch repetition rate in RHIC is only about 30 MHz, it makes no sense to accelerate with an electron bunch repetition rate of the cooler exceeding this same frequency. To obtain high average current, a charge-per-bunch of 4 nC has been chosen for this application. Therefore, by comparison to the previous applications, much greater care must be taken in dealing with the usual single bunch collective phenomena, for example wakes, coherent synchrotron radiation, and space charge effects, that afflict high charge-per-bunch beams. An example, dealing with injecting such beams onto the linac axis is provided in a separate contribution to this conference [22].

For this reason, and separately because, SRF cavities of lower frequency and larger physical size have less transverse and longitudinal impedance, and higher thresholds against multipass beam breakup instability, the cooler linacs are anticipated to operate at 800 MHz, a frequency where previous SRF development work has occurred yielding SRF cavities with suitable performance characteristics. For a RHIC cooler the source should have a normalized *rms* emittance at 10s of mm mrad normalized *rms* emittance and an average beam current of 100 mA. Cooler development efforts have centered on building an SRF electron source for the ERL.

In the further future, electron-ion colliders based on an energy recovered linac for the electrons are being considered for nuclear physics facilities. There are two basic ideas being explored presently. In the first idea called eRHIC, an ERL would be added at the Brookhaven site, colliding off the ion beam stored in one of the RHIC ion storage rings [23]. In the second idea called ELIC, the present Jefferson Lab nuclear physics accelerator would be upgraded to make an energy recovered linac and two figure eight storage rings added [24]. The first ring would be added as an electron circulater ring, the second would act as an ion storage ring. It is felt that by utilizing electron cooling to maintain high ion densities in the ring, and by allowing the electrons to be more highly disrupted by their beam-beam collisions with the ions than is possible in storage ring colliders, it may be possible to increase the luminosity by one or two orders of magnitude beyond that possible from a more conventional storage ring collider.

Another advantage of the ERL-ring collider is the relative ease with which the beam polarization can be manipulated, at the ERL electron source, by comparison to a storage ring. The present Jefferson Lab accelerator performs experiments with 80 percent electron polarization, the beam polarization being produced by the circular polarization of the incident drive laser on a strained GaAs photocathode electron source. But, this source operates at much lower charge-per-bunch and average current than would be required for a high luminosity collider. As beam polarization manipulation and control seems a highly desirable feature of these advanced colliders, there is a requirement to develop highly polarized high average current electron sources with beam properties comparable to those emerging from the best current photocathode sources.

A little thought shows that in collider applications it may be possible to reduce the average current required from a source, polarized or otherwise, at the cost of an additional "circulater ring" with its fast beam injection and ejection systems. The circulater ring is designed not to store an electron beam for a long time, say exceeding many radiation damping times as in a storage ring, but to store the electron beam for a time that is short compared to the radiation damping time, say 100 turns of a typical-sized storage ring. If one could store and collide the electron beam for 100 turns in the circulater ring without so much degradation of the electron beam properties that the beam energy in the circulating beam can not be energy recovered, then one has the means of reducing the average current needed from the source by a factor of 100. This reduction may be accomplished because the electron source would need to be delivering beam for one turn to completely fill the ring, but then can be off during the period of the 99 = 100 – 1 turns when the subsequent collisions during the fill occurred. The spent beam is extracted and energy recovered in the conventional way, making sure that the decelerating and accelerating beam for the next filling pulse are co-incident on the ERL simultaneously.

A concise summary of the source requirements for the eRHIC collider is of order 10 nC of charge at 30 MHz repetition rate, with emittances at around 10 mm mrad normalized *rms*. It is anticipated that some form of advanced polarized SRF gun will be utilized as the electron source. The ELIC beam parameters are of order 1 nC at 1 GHz repetition rate with similar *rms* emittances to eRHIC. The high average current of order 1 A needed from a CW electron source for ELIC may be reduced to the level of around 10 mA by the application of a 100 turn circulater ring. In this case, similar charge-per-bunch and macropulse currents are needed during a macropulse length equal to the ring filling time. By applying the circulater ring, the average current requirements are within reach of DC photocathode guns.

6. Summary

In this paper, the idea of an energy recovered linac has been introduced and its potential properties compared and contrasted to single pass linacs and storage rings. Energy recovery linacs have provided an elegant and powerful means to achieve high average power in free electron lasers. The pioneering energy recovered linac driven FELs have established many of the fundamental principles of ERLs. The multitude of ERL projects and proposals worldwide promises an exciting next decade as:

1. The three currently operating ERL-FELs will reach higher performance.
2. At least five more ERLs are in serious planning stages and will likely be constructed.
3. New advanced concepts are being explored; most of the applications need new high average brightness electron beam sources.

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