RECIRCULATED AND ENERGY RECOVERED LINACS*

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Linacs that are recirculated share many characteristics with ordinary linacs, including the ability to accelerate electron beams from an injector to high energy with relatively little (normalized) emittance growth and the ability to deliver ultrashort bunch duration pulses to users. When such linacs are energy recovered, the additional possibility of accelerating very high average beam current arises. Because this combination of beam properties is not possible from either a conventional linac, or from storage rings where emittance and pulse length are set by the equilibrium between radiation damping and quantum excitation of oscillations about the closed orbit, energy recovered linacs are being considered for an increasing variety of applications. These possibilities extend from high power free-electron lasers and recirculated linac light sources, to electron coolers for high energy colliders or actual electron-ion colliding-beam machines based on an energy recovered linac for the electrons.

1. Introduction

Superconducting recirculated linacs have been developed for high duty factor nuclear physics accelerators and as drivers for high average power free-electron lasers (FELs). Extending and applying this technology in new parameter regimes is likely to yield accelerators with highly novel capabilities. In this paper the current state-of-the-art in recirculated and energy recovered linacs is reviewed, and some current thinking on possible future projects based on high average current energy recovered linacs is presented.

First, beam recirculation and beam energy recovery are presented in general terms. Next, the main applications of superconducting beam recirculation up to the present are reviewed, culminating in a discussion of the properties of the Jefferson Lab recirculated linac CEBAF [1], a continuous-

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wave (CW) nuclear physics accelerator with high average current. This discussion is followed by a review of applications of beam energy recovery, which is most fully developed in the infrared demo free-electron laser (IR DEMO FEL) at Jefferson Lab [2], because this accelerator has energy recovered the highest average beam current to date. Both these devices give performance information relevant to future plans, and some aspects of their performance are summarized.

There are many ideas, being pursued with various degrees of seriousness, about future applications of beam energy recovery. One can anticipate higher average power free-electron lasers in the very short term, and light sources based on GeV-scale linacs roughly the same size as CEBAF in the near term. In the farther future, there is great interest to build high energy electron coolers to increase the luminosity of Brookhaven's Relativistic Heavy Ion Collider (RHIC), and to design and build electron-ion colliders where the electron beam is accelerated continuously in an energy recovered linac (ERL). All of these projects involve extrapolations beyond the present state-of-the-art. The major extrapolations will be pointed out within the text.

Figure 1. Main accelerator types.

2. Beam recirculation and beam energy recovery

The main accelerator types are displayed in Figure 1. If one focuses on electron accelerators, the first class of accelerators, perhaps best exemplified by the Stanford Linear Accelerator Center (SLAC) linear accelerator (linac) [3], are the high energy electron linacs. In such an accelerator, the electron beam has a definite beginning in an injector, and a definite end in an electron beam dump. The linac is usually timed so that maximum beam acceleration and maximum beam energy are obtained at the dump. However, it should be noted that one could just as easily choose to decelerate the electrons if the electrons actually arrive at the cavities time shifted by 180 degrees compared to the accelerated case.

Some main features of an electron linac are: (1) An individual beam electron does not reside in the accelerator for much time at all, and particularly it resides in the accelerator for times that are short compared to any radiation build-up times present. (2) Assuming a photoinjector electron source, it is relatively easy to load, or program, the beam current or beam polarization delivered to users by controlling the intensity and polarization of the lasers which stimulate electron beam production in the injector. (3) The emittance, or transverse beam phase-space area, of the electrons in a typical beam tend to be set by phenomena in the low energy electron source region, and the normalized emittance (???) is nominally preserved in accelerating to high energy. This means that the emittance at the point of delivery depends mainly on performance in the injector. (4) 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. It should be noted that having long regions between the end of the linac and the beam dump, for experimental or other purposes, is easy in a linear geometry.

The second class of high energy electron accelerators is the synchrotron-like storage ring [4]. In an electron storage ring the electron beam is bent around on a roughly circular orbit. Because transversely accelerated electrons radiate electromagnetically, it is necessary to supply energy back to the electrons to achieve a long-term equilibrium. Energy is typically delivered with RF cavities that subtend a small portion of the total machine circumference. After beam is injected into the ring, the electrons rapidly settle into an equilibrium where the synchrotron radiation losses are just made up by the energy transferred from RF to beam. The relevant time scale is of the order of one radiation damping time $(E_{max}/\eta E)t_{rev}$, where E_{max} is the beam energy, ηE is the energy loss per turn, and t_{rev} is the time it takes to make one revolution. The

ratio of the damping time to the revolution time is a number typically of order 10^3 .

Some properties of storage rings are: (1) the emittances of electrons circulating in an electron storage ring cannot be designed to be arbitrarily small, because of quantum excitation of betatron oscillations, (2) the equilibrium pulse length in the storage ring is, likewise, not arbitrarily small because of quantum excitation of synchrotron oscillations, (3) the beam lifetime is set by beam-beam interactions in colliding-beam storage rings or by Toushek scattering in storage ring light sources, and (4) storage rings are highly efficient in transferring RF power into beam power. Because they are highly efficient, storage rings may operate at much higher average currents than has been possible in single-pass linacs.

Recirculated linacs are accelerators which share with linacs the facts that there is a substantial RF linac accelerating the beam and that there is a definite beginning and ending of the beam (i.e., there is no closed or equilibrium orbit), but as in a storage ring, the beam transits the accelerating cavities more than once. Such a hybrid arrangement allows one to meld in one accelerator some of the advantages that both of the traditional arrangements have separately.

Application of beam recirculation to electron accelerators is an old idea [5]. The first accelerators to employ beam recirculation were the microtrons [6]. These devices use a resonance between the RF frequency of an accelerating cavity and the relativistic cyclotron frequency in a uniform magnetic field, to develop a phase-stable accelerator where the electron orbit enlarges by an integral number of RF wavelengths on each pass through the cavity. To incorporate more substantial linear accelerators in the recirculation path, and to go to higher energy, racetrack microtrons were developed [7-11]. As still higher energy was desired with time, it was completely natural to evolve away from the limitations imposed by the large end magnets of racetrack microtrons, and in a direction where different energy beams had completely different orbits, as in the classical recirculated linac. Jefferson Laboratory's CEBAF machine is the largest extent recirculated linac, achieving almost 6 GeV beam energy and 200 nA of beam current [1].

Till now, the usual *raison d'être* for beam recirculation, extending even to the CEBAF design, was economic. Given that beam recirculation systems tend to be much cheaper to build than additional RF linac, it makes sense to reuse the expensive beam acceleration systems as many times as possible to achieve as high an energy as possible at a given RF installation. As supporting examples of this statement, there have been two instances, at MIT Bates [12]

and at Stanford [13], where front-to-back electron recirculation was used to upgrade the energy reach of an existing linac.

In the future, it is likely that electron recirculation will be applied to build recirculated linacs because of their superior beam quality. Recirculated 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 build-up 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 has the ability to 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 one's ability to generate, and precisely manipulate, the longitudinal phase space of the electron beam, as shown many years ago at CEBAF [14]. Such advantages of the recirculated linac might not be so interesting, except for the application of beam energy recovery. This idea has allowed one to conceive of recirculated linacs with high average currents and recovery efficiencies approaching those in storage rings.

An early suggestion for the use of beam energy recovery appears in a paper by Maury Tigner [15]. In this paper Tigner explored the possibility of basing a particle physics colliding beam machine on an energy recovery linac. While not stimulating a collider project, the idea spread throughout the accelerator community, even if not directly used. The basic idea of energy recovery in a recirculated RF linac is that the RF fields, by proper choice of the time-of-arrival of the electron bunches in the higher beam passes, may be used to both accelerate and decelerate the same beam. Consider the simplest case of a single recirculation in Figure 2. Beam is injected into the linac and timed to accelerate on the first pass up the linac. If the recirculation path length is chosen to be precisely an integer plus $\frac{1}{2}$ RF wavelengths, on the second pass through the linac the beam is decelerated by the same RF field which accelerated it on the first pass. For cavities within the recirculation loop, energy is directly transferred, via the RF field, from decelerating beam to accelerating beam. The key point is that these RF power systems do *NOT* need to provide the energy to accelerate the first pass beam. Indeed, the RF power draw becomes almost completely independent of the beam current.

Figure 2. Definition of the recirculation path length for a simple two-pass recirculated linac.

How can one define the efficiency of the energy recovery process? It is easiest to think in terms of the energy in the electron beam, which is being recycled and reused. If E_{max} is the total beam energy at the point-of-use, and if E_{rec} is the total energy that may be removed from the electron beam and/or reused again, define a recovery efficiency $\eta_{rec} = E_{rec}/E_{max}$. The energy that must be provided for acceleration, per electron, is proportional to $1 - \eta_{rec}$; the total power that must be supplied in order to accelerate a beam of current I_b is $I_b E_{max} (1 - \eta_{rec})/e$, where e is the fundamental charge. This power may be considerably less than the beam power $P_b = I_b E_{max}/e$ in an ERL, and is smaller the closer η_{rec} comes to 1. In some contexts, particularly in comparing different accelerators, the recovery efficiency is inconvenient for quantitative work. One may define a recovery factor $k_{rec} = 1/(1 - \eta_{rec})$ as more convenient. A recovery efficiency of 99% corresponds to a recovery factor of 100; as discussed above, for storage rings the recovery factor is about 1000. It is useful to define the multiplication factor [16] $k = P_b/P_{rf}$, where P_{rf} is the power incident on the RF cavities accelerating the beam. This quantity is useful for distinguishing the ultimate energy recovery limits in practical accelerators. For a superconducting recirculated linac, P_{rf} is only slightly above $I_b E_{max} (1 - \eta_{rec})/e$; the multiplication factor may approach the recovery factor. For normal conducting linacs, because the wall losses are so large compared to $I_b E_{max} (1 - \eta_{rec})/e$, the multiplication factor tends to fall far short of the recovery factor. By the first law of thermodynamics, $k < 1$ for single-pass linear accelerators that are not energy recovered. Modern superconducting ERL designs can have k of order 100 or higher.

There are challenges associated with choosing to build a recirculated linac. There is an additional linac beam instability possible, called multipass beam-breakup instability, roughly corresponding to multi-bunch beam instabilities in storage rings [5,17,18]. The designer must assure that the RF cavity high-order

modes (HOM) that are deflecting have enough damping to prevent the appearance of this instability. The turn-around optics in recirculated linacs are a bit more involved than in linacs or storage rings. In particular, the transverse beam dynamics tend to be affected appreciably by the longitudinal beam dynamics designs. Most significant of all, one must develop high average current injectors because the electron beam must be continuously supplied to the accelerator. Some details of the design depend strongly on the application requirements and will be discussed at the appropriate location below.

3. Recirculated Superconducting RF Linacs

In this section the development of superconducting recirculated linacs is briefly reviewed. Before continuing, it should be noted that much of the historical information presented here may be found more thoroughly presented in Rand's excellent book *Recirculating Electron Accelerators* [5], along with a discussion of the various normal conducting recirculated linacs that have been proposed and/or built. Many standard techniques in the field have been developed first at normal conducting machines and will be appropriately referenced in this paper, but time considerations prevent an extensive review of normal conducting recirculated linacs here.

Figure 3. The second Illinois superconducting racetrack microtron MUSL II [8], ? 1977 IEEE.

The first recirculated linacs developed were the so-called racetrack microtrons. As shown in Figure 3, in a split-field racetrack microtron, two uniform-magnetic-field bend magnets are used to bend the electron beam through 180 degrees and the electron beam makes several passes through the linear accelerator structure. Such a design choice allows greater flexibility in parameter choice and, by cascading, allows one to accelerate to beam energies far above those possible in conventional microtrons. High duty factor normal conducting racetrack microtrons have been built at Mainz [9,10] and the National Bureau of Standards (now the National Institute of Standards and Technology) [11]. However, the first split-magnet racetrack microtron was also one of the first applications of RF superconductivity. The University of Illinois built two superconducting racetrack microtrons, dubbed MUSL I and II (for Microtron using a Superconducting Linac), the first of which was completed in 1974.

MUSL I was a 6-pass microtron that produced 5 μ A average beam current at 19 MeV beam energy and 50% duty factor [7]. The state-of-the-art in superconducting cavity performance at that time was about 2 MV/m, and such an accelerator was interesting for nuclear physics applications because of the high duty factor operation possible. MUSL I was upgraded to an 80 MeV racetrack microtron MUSL II by improving the superconducting accelerator and by increasing the magnetic field in the 180 degree bends closer to their allowed maximum [8].

The next superconducting recirculated linac developed, a classical independent orbit recirculator, was at Stanford University about a decade later. It was constructed using the pre-existing Superconducting Accelerator (SCA), originally built for nuclear physics research. In an independent orbit recirculator the separate beam energies in the accelerator travel along completely decoupled beam orbits. Thus microtron-like resonance conditions are not utilized in the accelerator design. The beam from the SCA was recirculated through one orbit in order to increase the energy reach of the linac, and was used in the first demonstration of “same cell” beam energy recovery at a superconducting linac [13]. This device will be described in more depth below.

The SCA was followed by the superconducting S-DALINAC at TU Darmstadt [19,20], also developed primarily for nuclear physics applications. This device features relatively high frequency 3 GHz cavities and 3-pass beam recirculation. Typical beam parameters for nuclear physics running are CW beam energies up to 87 MeV, and beam current up to 50 μ A in a 0.017 pC

bunch charge at 3 GHz bunch repetition rate. Because the recirculated linac provides excellent beam quality, this device was upgraded to provide FEL laser light. In this operating mode 5 pC bunches are provided in a 10 MHz stream. Two especially noteworthy achievements demonstrated at this accelerator were precision RF control of the accelerating field and amplitude at a relatively high fundamental-mode loaded quality factor of 3×10^7 , and isochronous recirculation, i.e., the recirculation time was independent of the energy in its early operation.

The largest example of an independent orbit recirculated linac is the 5-pass Continuous Electron Beam Accelerator Facility (CEBAF) accelerator at Jefferson Lab. This accelerator, one of the flagship accelerators in the United States Department of Energy's nuclear physics program, was explicitly developed to extend and explore electro-nuclear scattering at beam energies and event rates much greater than those at any of these predecessor facilities. A beam energy of 4 GeV and a beam current of 200 μ A CW were initially specified as operations goals for the accelerator. Because of cavity processing developments during and after the project was completed, it has been possible to extend the average operating gradient of CEBAF beyond the 5 MV/m design goal to 7.5 MV/m, yielding a machine that operates almost to 6 GeV.

This accelerator is designed and operated in a way that produces excellent beam quality. For example, the injector compresses the electron bunches to very short durations before acceleration [14,21]. Because the recirculation arcs are isochronous there is very little change in the bunch duration as the beam is accelerated. The linacs are operated on crest phase, yielding as small an energy spread as possible, and the multiple beam passes are verified to be very precisely near to an integer number of RF wavelengths long [22].

CEBAF has yielded a wealth of information about operating large superconducting RF (SRF) linacs. An example is the RF control of large numbers of superconducting cavities. CEBAF's tolerances for phase and amplitude errors have always been more stringent than is typical in storage rings. This requirement, coupled with the desire to have an extremely high fraction of the cavities operating properly at all times, compels one, in the end, to have highly automated systems that continuously monitor and adjust cavity tuning, and that can be invoked to place the cavities on their initial tune after an extended period of down time. Robust automatic procedures of this type were developed as part of the commissioning process at CEBAF.

Several other examples were new beam diagnostics developed to facilitate and expedite machine setup. For example, as part of injector setup, phase transfer function measurements, which give linear and higher-order

longitudinal transfer maps, have been highly developed [21]. Such measurements allow one to precisely diagnose and control the longitudinal phase space of the compressing bunches, and allow one to routinely deliver ultrashort bunches ($\sigma_t < 200$ fsec) in standard operations mode [23]. Another example is the path length systems, which are used to insure that the path length of each pass is an integral number of RF wavelength. Gross path length checking is completed using relative time-of-flight analysis of beam-generated signals from longitudinal pickup cavities [24]. For very fine tuning and continuous monitoring of the beam phase, lock-in systems that generate slight phase modulations in each of the linacs separately, coupled with simultaneous energy analysis at the lock-in frequency, yield the deviation of each of the beam passes from perfect cresting in each linac separately [25,26]. Fast feedback systems have been developed to simultaneously correct the position, angle, and energy of the beam being delivered to the end nuclear physics users [27]. The order of magnitude of the residual fluctuation levels is 10^{-5} m *rms*, in position, 10^{-5} rad *rms* in angle, and about 10^{-5} *rms* in energy. These three preceding achievements have allowed the measured *rms* energy spread of the beam delivered to users to be at the 3×10^{-5} level for extended run periods [22].

4. Energy Recovered Superconducting RF Linacs

The first energy recovery experiment to employ a superconducting recirculating linac occurred more than two decades after Tigner's early paper, and was driven by the needs of the free-electron laser community. "Same-cell" energy recovery, i.e., energy recovery in which both accelerating and decelerating beams traverse the same accelerating cavity, was accomplished at Stanford University's SCA in the mid-1980s. By this time the SCA was principally used as an FEL driver because of the good quality of the accelerated beam. A single pass through the superconducting linac yielded sufficient energy to produce an IR FEL. In order to produce shorter FEL radiation, down to about $0.5 \mu\text{m}$, the beam was recirculated through SCA on a second pass. In this configuration, the superconducting linac took the beam energy from 5 to 50 MeV on the first pass, was recirculated with a path length of an integral number of RF wavelengths, and accelerated from 50 to 95 MeV on the second pass through the linac. The other main parameter of interest, 150 μA of beam current, was provided by a stream of 12.5 pC bunches at 11.8 MHz repetition rate.

Because the beam recirculation system allowed the path length to be varied through a full RF wavelength, choosing to shift the path length by $\frac{1}{2}$ an RF wavelength allowed energy recovery to proceed. Detailed RF power

measurements and comparisons between accelerating and energy recovering modes, and between beam present and absent on a second pass, showed that only 10% of the RF power needed to accelerate a single beam pass, was needed to maintain the RF field at the same gradient when the same current was energy recovered [13]. Consequently, even in this first attempt the recovery efficiency was greater than 90% and the multiplication factor was about 0.6. In speculating about future applications to increase the efficiency of FELs by applying energy recovery, the increased difficulty of recovering a “spent” FEL beam was noted. In the interest of properly attributing priority, it should be noted that nearly a year earlier a same-cell energy recovery experiment was successfully performed at Bates Laboratory on a normal conducting linac [28].

During the period 1990-1994 a beam recirculation experiment was completed on the CEBAF SRF injector at Jefferson Lab [29]. This injector was capable of accelerating in excess of 200 μ A beam current from 5 to 50 MeV, the beam being a continuous stream of 0.12 pC bunches at 1497 MHz. This experiment was primarily developed to demonstrate beam stability against beam-breakup instability; this instability was worst in energy-recovered recirculation because the average beam energy is lowest then. The best performance obtained in this device was 30 μ A in energy recovery mode and between 64 and 215 μ A in accelerating mode, the current depending on the beam optics of the recirculator. The recovery efficiency was $40/45=89\%$, and because the SRF systems were not optimized for energy-recovered operation and the beam current recovered was so low, the multiplication factor was only 0.2.

Figure 4. The Jefferson Lab IR demo free-electron laser.

The final example of an energy-recovered SRF linac is the Jefferson Laboratory IR demonstration FEL, which has energy recovered the highest average current to date. Referring to Figure 4, beam originates in a 5 MeV injection region, yielding a stream of 65 pC, 75 MHz bunches (5 mA). The electron beam is merged onto the linac axis, accelerated to 35-50 MeV (depending on the FEL operating wavelength), bunch compressed and delivered to the wiggler where the FEL interaction takes place. After the FEL interaction the longitudinal phase space is highly degraded as the relative energy spread has increased. The electron beam is recirculated using a beam optical system first used at Bates Laboratory. This recirculation system features an energy acceptance that is quite large [12]. After reinjection into the linac on the decelerating phase for the second pass through the linac, the low energy beam is split off and dumped in a conventional water-cooled beam dump.

This device has experimentally demonstrated quite a number of important features of energy recovery [30]: (1) almost lossless (>99.98%) beam recirculation, including the effects of the energy spread generated by the FEL [2], (2) world's best multiplication factor up to now of about 16, (3) manipulation of the longitudinal phase space of compressing and decompressing electron bunches [31], (3) RF stability in a high current energy recovery configuration [32], (4) beam-breakup stability measurements [33], (5)

detection of HOM cooling load in the cryogenic systems of SRF cavities [33], and (6) high power optical beam handling.

5. Future Projects

To the present, superconducting recirculating linacs have operated at beam currents far below the carrying current limit imposed by HOM heating and beam-breakup stability. Many groups have started exploring the kinds of applications that might arise if one devised recirculating linacs, especially those that are energy recovered, where the average current is much closer to these limits [34]. At present, the applications fall into three broad categories: still higher average power FELs, recirculated linac light sources, and colliding-beam accelerators where the electron beam is continuously accelerated in an energy recovery linac instead of being stored in an electron storage ring. Each of these possibilities will be discussed in turn.

5.1. High Average Power FELs

In the near term, at least two FEL projects will continue to push up the average recirculation current achieved to date. The JAERI FEL has operated as a single-pass SRF FEL driver for a number of years [35]. Because of limited refrigerator capacity, the duty factor of the device has remained under 3%. However, within the beam macropulse the current is 5.3 mA, in a stream of 510 pC 10.4 MHz bunches. This yields an FEL performance comparable to that of Jefferson Lab's IR DEMO within the macropulse. Recently, the recirculation loop on their IR FEL has been closed and energy recovery has been demonstrated. By upgrading the electron beam injector to produce 40 mA beam current in 1 nC 40 MHz bunches, this device will be able to produce 10 kW output optical power within the beam macropulse [36].

Jefferson Lab is replacing the IR DEMO device with one that will operate at roughly an order of magnitude higher optical power, greater than 10 kW average power. This will be accomplished by doubling the bunch charge to 130 pC and beam current to 10 mA, roughly tripling the beam energy to 160 MeV maximum, and increasing the outcoupled fraction of optical power by roughly a factor of two [37]. This final change will increase the relative energy spread of the spent beam, allowing one to further explore the limits of energy recovery as energy spread is increased. This device is nearing completion presently.

The upgrade path for the farther future is fairly clear. Another factor-of-ten in electron beam power (and hence optical beam power in the 100 kW range) is simply obtained by filling every RF bucket in the superconducting linac. This

increases the bunch repetition rate from 75 MHz to 1497 MHz at maximum if CEBAF superconducting cavities are used in the application. The resulting average current of 200 mA is far above the BBU stability limit of the present CEBAF cavities, but improvements in the HOM damping and HOM cooling designs are anticipated to allow operating at such high average current. To continue still further will require the bunch charge to increase from the 100 pC scale to 1 nC or so, in the regime of present-day SASE sources. To make this step, in addition to continuing to improve the HOM damping and cooling still more, one will have to come to grips with the myriads of single-bunch collective effects that start to afflict high charge-per-bunch beams. The desire to reduce single-bunch collective effects will likely cause MW-scale optical power FELs to be built at lower SRF frequencies, in the range 350-750 MHz.

5.2. *Recirculated Linac Light Sources*

As mentioned in the introduction, and in the preceding paragraph, one may anticipate that the average current-carrying capacity in a recirculated linac will approach the average current of present-day storage ring light sources. Thus, it is natural to ask whether recirculated linacs, and particularly those that are energy recovered, would make interesting light sources. Because of the possibility of short-pulse-length radiation, because of the possibility of smaller beam emittance and energy spread than in storage rings, which leads to higher photon brilliance, and because of the possibility of round sources, there is much present activity in designing such light sources. Some of this activity is summarized in a recent ICFA publication [38].

The idea of generating short-pulse radiation from a recirculated linac developed gradually. Early work on SASE-generated deep ultraviolet (DUV) photons from a recirculated linac arrangement was completed in an exploratory way early in the CEBAF project [39]. Also, when ideas about short-pulse SASE sources were first being developed, it was natural to ask whether the CEBAF linac, or a recirculated version of the CEBAF linac, could serve as an X-ray source [40]. Because of the long time-scale for development of SASE sources, and their large expense, various groups began exploring whether alternate sources of short-pulse X-ray radiation were possible. Thomson scattering sources have been used to produce short-pulse radiation, and recent possibilities in storage rings have centered around so-called femtoslicing methods. In such a method one uses the fact that femtosecond optical pulses already exist, and by illuminating a storage ring beam with such an optical pulse, one can manipulate the beam to radiate short X-ray pulses [41]. One disadvantage of such a method is that only a small portion of the storage ring beam actually

radiates usefully. Because the total pulse length can be made short at delivery out of a recirculated linac, and because the average current of even existing recirculated linacs is close to the emitting current in the femtoslicing methods, it makes sense to suggest that one obtains short-pulse X-rays directly from a recirculated linac [42]. The idea that superior beam emittance and energy spread from a recirculated linac [1] lead to higher ultimate photon brilliance, has been advocated for several years by a group from Novosibirsk [43]. They have begun a multipass normal conducting energy recovering linac as a result [43,44].

Aside from this Russian work, all of the other proposed projects assume that a superconducting recirculated linac will be used. The main proposals at present are the Cornell/Jlab energy recovery linac (ERL) proposal [45,46], Brookhaven's PERL proposal [47], LBNL's LUX project [48,49], Daresbury's 4GLS proposal [50], and University of Erlangen's ERLSYN proposal [51]. There is some effort in Japan too, but no serious proposal as yet.^a In the Cornell/Jlab proposal and Brookhaven's PERL, the bunch structure is very much as in the 100 kW FEL above. The Cornell/Jlab proposal has 77 pC with a bunch repetition rate of 1.3 GHz yielding 100 mA in its high flux mode. PERL has twice the bunch charge and twice the average current. Both of these projects posit an injector that produces very small normalized emittance of less than 2 mm-mrad compared to around 10 mm-mrad in the existing IR DEMO source. According to the numerical modeling, this small emittance should be possible given the present understanding of emittance growth in photocathode sources. LBNL's LUX proposal has a much larger charge-per-bunch, around 1 nC, which is comparable to that of SASE sources, and a much lower maximum repetition rate of 10 kHz. Daresbury's 4GLS develops a superconducting linac first as a SASE source, and then closes the recirculation loop to provide a high brilliance CW source optimized for DUV wavelengths. Erlangen has an energy recovery linac, with parameters very similar to those of Cornell, as the second phase of a project whose first phase is to build a third-generation storage ring source.

Cornell and Jefferson Lab have proposed an ERL demonstration prototype as a first step to a follow-on CEBAF-scale light source. This prototype would demonstrate full current injection with the required beam properties, acceleration to 100 MeV, and high efficiency energy recovery. The issues to be

^a As the proofs for this paper were being corrected the author became aware of a proposal document, published in Japanese, on a recirculated linac light source for Japan [52].

demonstrated include producing low injector emittance; preserving the emittance on acceleration; showing that adequate photocathode longevity is possible; manipulating the longitudinal phase space properly to achieve adequate beam bunching; achieving adequate HOM damping, low beam loss, the highest fundamental mode quality factor possible to reduce the size of the cryogenics plant for the follow-on machine, and the highest fundamental mode loaded Q possible to increase system efficiency by reducing the required RF power; and developing high average current beam diagnostics. These results will be important for the accurate design of all the follow-on projects.

5.3. Applications to Colliding-Beam Machines

Two types of applications of energy recovery are anticipated in high energy accelerators: beam cooling and high-luminosity colliding beams. In order to apply the beam cooling technique called electron cooling at the Relativistic Heavy Ion Collider (RHIC) and increase its luminosity, it is necessary to provide intense 50 MeV electron beams. As the cooling rate increases with the average electron current, one would like to accelerate a high average current with a bunch structure that overlaps with the RHIC bunch structure in time. Because a recirculated linac may provide such a repetitive beam at high average current, it is a natural candidate as an electron cooling device. Such a device becomes particularly attractive and efficient if energy recovery is applied. The second type of application is to replace the electron storage ring in a ring-ring electron-ion collider with an electron energy recovery linac. As discussed below, it may be possible to obtain high luminosity out of such a configuration because the beam-beam problem is reduced when only one beam is stored.

Brookhaven National Lab has completed a conceptual design of a beam cooler [53]. This device originally had average current similar to the IR DEMO FEL. The main novelty in the design is that for the cooling application it is preferable to debunch the electron beam before the cooling interaction. There is a debunching system before and a rebuncher after the cooler solenoid magnet to provide for clean energy recovery. Aside from the beam optical design, and because of the enhanced cooling rate with current, there is a very real desire to increase the average current in the recirculated beam beyond the FEL experience. As discussed above, to increase the beam-breakup stability threshold to high values, one must make sure that all of the transverse deflecting HOMs are damped to suitable levels, i.e., Q values much smaller than at present, or if this proves difficult, a feedback system, similar to those used now in high current ring colliders, must be developed that can control the instability. Because the HOM cooling load will increase with the average

current, it will be necessary that the load terminations occur at high temperature in order to keep the dynamic heat load from the HOMs to a manageable level. Because a relatively high bunch charge will be needed, it will be advantageous to consider lower frequency superconducting cavities to reduce single-bunch collective effects.

The final idea to be discussed in this paper is to have an electron beam in an ERL colliding with a proton or other ion beam in a storage ring [54]. A simple *gedanken* experiment shows why such an arrangement might be advantageous, and produce higher luminosity. The luminosity of a collider is

$$L = \frac{f N_e N_i}{2\pi \sigma_{ex}^2 \sigma_{ix}^2 \sigma_{ey}^2 \sigma_{iy}^2}$$

where f is the collision frequency, N_e is the number of electrons in the colliding bunch, N_i is the number of ions in the bunch, and the *rms* beam sizes of the two colliding beams (assumed unequal) are given by the σ 's. Assume that a stable ring-ring collider design, limited by any phenomena you chose to consider, is given, and in particular we know all the inputs to the luminosity formula above. For the electron ring to be stable, any current-limiting instability growth must be slower than one ring damping time, as otherwise the ring would not be stable. This means that the electrons have to be confined up to one damping-time's worth of revolutions, i.e. about 1000 revolutions.

Suppose now one has an ERL collider design with an identical ion storage ring, and an identical set of electron beam parameters as the ring-ring collider design above. Because the electron beam parameters are the same, the ion beam will continue to circulate stably, even if one increases the ion bunch charge and luminosity considerably. Increasing the ion bunch charge will increase the disruption of the electron bunch by the beam-beam effect, but it is no longer necessary to confine the electron beam for 1000 turns, only a few turns in the ERL. Easy 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 N_i before energy recovery becomes difficult.

Detailed initial parameter lists, covering two collider schemes, have been worked out. The first is eRHIC, an electron-ion collider, based at RHIC [54,55], and the second is ELIC, an electron-light ion collider based at CEBAF [56,57]. 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 make a higher-energy ERL, and a new ion storage ring is constructed.

Two main obstacles, one technical and one conceptual, must be overcome in order to construct credible proposals. The technical obstacle is that a CW 1 A polarized electron gun is about 4 orders of magnitude in average current beyond present experience. The conceptual obstacle is to precisely quantify the luminosity advantage going from storage ring to ERL by thorough simulation and luminosity comparisons between ring-ring and ERL-ring collider designs.

6. Conclusions

In this talk the ideas of beam recirculation and energy recovery have been introduced. How these concepts may be combined to yield a new class of accelerators that can be used in many interesting applications has been discussed. Some historical information about the development of recirculating SRF linacs has been given as well as performance information on the CEBAF machine and on the IR DEMO FEL. The present knowledge on beam recirculation and its limitations in a superconducting environment leads one to think that recirculating accelerators of several GeV energy, and with beam currents approaching those in storage rings, are possible.^a Cornell University and Jefferson Laboratory have proposed to the United States National Science Foundation to build a prototype high current superconducting energy recovery linac to investigate in depth some of the limitations of energy recovery linacs.

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The author thanks the program committee for the opportunity to present this paper, as the subject matter is somewhat outside the topic of linear accelerators. It is anticipated that continued activity in this field will lead to new results and new applications of this highly interesting type of accelerator.

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^a Recently, a team at Jefferson Lab has successfully energy recovered a low-average-current beam accelerated from under 50 MeV to above 1 GeV in CEBAF [58].

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