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Concepts and Applications of Energy Recovery Linacs (ERLs)

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Abstract. Energy Recovery Linacs are being explored as next generation synchrotron light sources. The fundamental x-ray beam properties from storage ring sources, such as the source size, brilliance, and pulse duration are limited by the dynamic equilibrium characteristic of the magnetic lattice that is the storage ring. Importantly, the characteristic equilibration time is long, involving thousands of orbits around the ring. Advances in laser-driven photoelectron sources allow the generation of electron bunches with superior properties for synchrotron radiation. ERLs preserve these properties by acceleration with a superconducting linac, followed by transport through a return loop hosting insertion devices, similar to that of a 3rd generation storage ring. The loop returns bunches to the linac 180° out of accelerating phase for deceleration through the linac and disposal. Thus, the electron beam energy is recycled back into the linac RF field for acceleration of new bunches and the equilibrium degradation of bunches never occurs. The superior projected properties of ERLs beams include extraordinary brilliance and small source size, with concomitant high transverse coherence, x-ray pulse durations down to ~100 femtoseconds, and flexibility of operation. ERL projects are summarized. ERLs will be capable of hosting practically all experiments now being carried out at storage rings while also enabling new types of experiments.

PURPOSE OF THIS DOCUMENT

The development of ERL technology is being very actively being pursued by the accelerator and synchrotron radiation research communities. Although there is already a sizable literature on the subject, much of this information is only available in conference proceedings and on web-sites and is, therefore, difficult to locate. The primary purpose of this document is to present an overview of the ERL technology and to indicate where ERL information may be found.

ERL CONCEPT

Essentially all present hard x-ray synchrotron radiation facilities are based on storage ring sources. The accelerator physics of storage rings is highly evolved and reasonably well understood[1]. Storage rings are highly constrained by the requirement that the electron (or positron) bunches be able to circulate for hours with minimal losses. In general, it is desirable to maximize the flux and brilliance of the x-ray beams while minimizing the source transverse size and the temporal length of the x-ray pulses. These characteristics follow directly from the bunch transverse and longitudinal emittances and dimensions, and the total current circulating in the storage ring [2]. At the same time, the circulating electrons are subject to a variety of perturbations arising from the magnetic forces of the lattice that comprises the storage ring, the emission of synchrotron radiation, electron-electron interactions, and periodic acceleration through RF cavities. The result is an equilibrium characteristic of the lattice that determines the bunch dimensions, emittances, and ring current. Significantly, this equilibrium sets in relatively slowly, typically over milliseconds, corresponding to thousands of turns of a given bunch around the ring. While storage ring technology continues to improve and further advances may be expected, the consensus in the accelerator physics community is that the technology is at the point of maturity and only small additional improvements are believed possible. Further dramatic improvements are unlikely without the use of enormously large rings [3,4].

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Although it is possible to use laser-driven photocathodes to produce bunches that initially have superior bunch dimensions and emittances, these bunches cannot be stored without degradation as the storage ring equilibrium sets in. However, bunches can be accelerated in linacs without emittance degradation. This suggests an alternative approach wherein a high duty factor photoinjector is used to feed a linac to produce high energy bunches. These are passed through undulators to produce highly brilliant synchrotron radiation. The difficulty with this scheme is that a high flux of hard x-rays requires both a reasonably high current and high energy, resulting in an enormous beam power (e.g., 100 mA at 5 GeV is a beam power of 500 MW). It is impractical to produce such beams continuously unless the beam energy is somehow recovered or stored.

A way around this dilemma follows from the observation that linacs can also serve as decelerators by converting electron beam power to RF power in the linac cavity. Tigner noted [5] that the Q of superconducting RF cavities can, in principle, be sufficiently high that this recovered energy may be stored in the cavity long enough to accelerate new particles. This leads to the ERL concept shown in Figure 1.

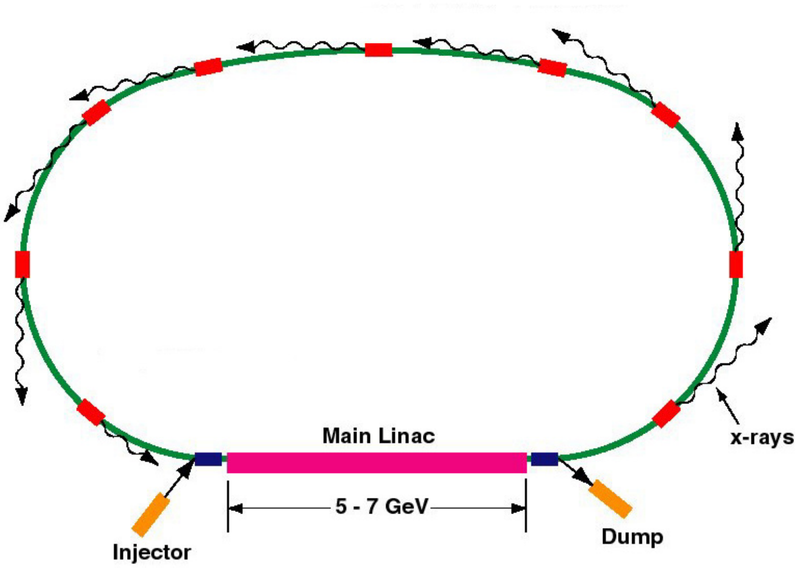

FIGURE 1. A schematic design of an x-ray ERL. An injector produces very low emittance bunches which are then accelerated to high energy in a superconducting linac. These high energy bunches are passed into a transport loop, similar to a section of a 3rd generation storage ring, that includes undulators for the production of x-rays. Because the time to equilibrium is long the bunch properties are not appreciably degraded in a single passage around the loop. The loop length is carefully adjusted so the bunches arrive at the linac 180° out of accelerating phase. The bunches then decelerate through the cavity while transferring the bunch energy to the linac RF field. The energy depleted bunches emerge from the linac and are deflected by a weak dipole magnet to a beam dump. Note that accelerating and decelerating bunches may be interleaved one after the other, since they are at different phases of the RF field, so bunches may emerge at the frequency of the cavity, e.g., ~ 1 GHz.

STATUS OF ERL PROJECTS

The basic principles of ERL operation were demonstrated in the late 1980's [6] and first applied to a low-energy dedicated machine at the Thomas Jefferson National Accelerator Facility (Jlab) in the last half of the 1990's [7]. The key technological advances that enabled the Jlab machine were improvements in superconducting linacs and in high-duty cycle laser-driven photoinjectors. By 2000, it had become clear that ERL technology was advancing rapidly and offered very attractive possibilities as a hard x-ray source. Cornell University started serious consideration of an x-ray ERL [8] and soon CHESS and the Cornell Laboratory for Elementary particle Physics (LEPP) entered into a collaboration with Jlab to do a design study [9]. The Cornell/Jlab study concluded that an x-ray ERL was feasible, but would require prototyping in order to fully reap the potential benefits as a superior x-ray source. ERL development efforts were also announced elsewhere in the U.S., England, Germany and Japan. A compilation of world-wide ERL efforts may be found at the Cornell ERL web site [10]. This site also has pointers to ERL literature. A large number of additional ERL papers were presented at the 2003 Particle Accelerator Conference [11].

CONCLUSION

As opposed to storage rings, ERL technology is very new and the ultimate limits of ERLs are not known. Initial studies indicate that ERL sources should be able to outperform existing storage rings in significant ways. ERL sources promise to have sufficiently high brilliances so as to be fully transversely coherent in the hard x-ray region. ERLs allow bunch manipulations that exceed what can be done with storage ring operation, such as bunch compression down to at least 100 femtoseconds. ERL sources may be round and small, thereby optimizing throughput with x-ray optics. Importantly, many critical ERL parameters are limited by the photoinjector, a relatively small part of an full-scale high energy ERL source, thereby providing a relatively inexpensive upgrade path to lower emittance operation as injector technology improves. As opposed to x-ray free electron lasers, ERLs are continuous duty machines with individual pulses that are sufficiently small that most samples will not suffer instantaneous destruction due to coulomb explosions. Most experiments now possible at storage ring sources could be performed in the same way at an ERL source. Thus, ERLs offer the advantages of advanced storage rings while simultaneously promising new capabilities. The development of ERL source technology will be both exciting and challenging.

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