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Energy recovery linacs as synchrotron light sources

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Abstract

Pushing to higher light-source performance will eventually require using linacs rather than storage rings, much like colliding-beam storage rings are now giving way to linear colliders.

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Synchrotron radiation sources have proven to be immensely important tools throughout the sciences and engineering. In consequence, synchrotron radiation usage continues to grow, assuring the need for additional synchrotron radiation machines well into the foreseeable future. Storage rings, the basis for all major existing hard X-ray synchrotron facilities, have inherent limitations that constrain the brightness, pulse length, and time structure of the X-ray beams. Since large synchrotron X-ray facilities are expensive and take many years to bring to fruition, it is important to consider if there are alternatives to storage rings that offer advantages. The Energy Recovery Linac (ERL) is a proposed alternative synchrotron radiation source that will extend synchrotron radiation science into new realms not possible with storage rings while still being able to serve most existing storage ring applications.

The usage of synchrotron radiation has become more specialized and sophisticated. Although no single source will meet every need, the trend is towards higher brilliance and intensity, and shorter bunches. These trends are driven by a desire to study smaller and smaller samples that require more and more brilliance, because tiny samples tend to have both low absolute scattering power and require micro-X-ray beams. An increasing number of experiments also require transversely coherent X-ray beams. It can be shown that transverse coherence increases with the brilliance of the source. Another trend is towards examination of time-resolved phenomena in shorter and shorter time windows. The time resolution of many experiments is ultimately limited by the duration of the X-ray pulse. If the time envelope of the X-ray pulse is sufficiently short and the source is sufficiently brilliant, it can be shown that an increasing number of X-rays will also be longitudinally coherent, that is, in the same quantum mode. So the optical characteristics generally desired from synchrotron radiation sources are brilliance and short pulses.

These desired characteristics immediately translate into requirements on the electron bunches. The average brilliance scales inversely to the bunch transverse emittances and linearly with the average

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current. Peak values scale inversely with the bunch length. Thus, the most desired characteristics of a synchrotron radiation source are a high average current of very short, very low emittance bunches. With this in mind, let us look at the characteristics of storage rings and linacs as sources of bunches for synchrotron radiation.

All existing hard X-ray (that is, photon energies greater than about 5 keV) synchrotron radiation sources rely on storage rings. Storage ring technology is well understood and is near fundamental limits of minimum transverse emittances, intensity and bunch length (see other articles in this issue). The limits arise from the requirement that the particles be stored in stable equilibrium orbits, despite energy and momentum perturbations arising from the emission of synchrotron radiation, the radio-frequency acceleration system, intrabeam scattering (Touschek effect), and small errors in the magnetic bending and focusing systems, or their alignment, leading to coupling between the horizontal and vertical orbits. These perturbations, which are specific to the given lattice of magnetic optical elements that comprise the storage ring, damp the initial bunch emittance, cross-sectional distribution, and bunch length to equilibrium values in a time which is typically milliseconds long, that is, many thousands of revolutions around the ring. While the equilibrium damping behavior endows storage rings with excellent stability, it also decouples the critical characteristics of stored bunches from those of the initially injected bunches. That is to say, bunches which are injected into the storage ring with smaller emittances or lengths than characteristic of the lattice will equilibrate to the larger values typical of the storage ring. As examples, values for some state-of-the-art synchrotron radiation facilities are given in Table 1.

The long damping times of storage rings suggest a way around the equilibrium limitations of the lattice, namely, use the bunches to produce synchrotron radiation long before equilibrium is attained. In this case, the bunch properties, and therefore the quality of the synchrotron radiation will be limited not by the lattice, but by the electron source itself. Modern radio-frequency and direct-current photocathode-based injectors can produce bunches which are both short and have small emittances in all dimensions. Moreover, properly designed linacs can accelerate bunches with very little emittance degradation. An obvious approach is then to couple a suitable photoinjector with a high-energy linac to produce a stream of bunches which can then be passed through an undulator to produce brilliant synchrotron radiation. The drawback to this idea is that significant currents (~ 100 mA) and energies (~ 3–8 GeV) are usually needed to obtain adequately intense synchrotron radiation with state-of-the-art undulators. These values represent enormous beam powers; for example, a continuous 100 mA, 5 GeV beam (such as a hypothetical continuously operating linac might deliver) would carry 500 MW of power, equivalent to the power output of a large commercial electrical generating station. It would be economically unfeasible to consume this much electrical power on an ongoing basis (Table 1).

In a storage ring, the requirement of continuously supplying such a high power is circumvented by storing the high-energy particles and replacing only the power lost to synchrotron radiation, which is typically $\sim 10^{-4}$ of the power in a continuous beam, such as the linac example

Table 1
Basic parameters

Machine	Energy (GeV)	Ave. current (mA)	Horizontal emittance (nm rad)	Bunch length (ps fwhm)
ESRF	6	200	4	35
APS	7	100	4	73
SPring 9	8	100	6	36
ERL (low emmitance)	5.3	100	0.15	0.3
ERL (very low emmitance)	5.3	10	0.015	0.3

Some basic parameters of a few existing third generation storage rings compared to a possible ERL in high- and low-current modes.

described in the preceding paragraph. Therefore, it is only necessary to provide a relatively small amount of radio-frequency power to replace synchrotron radiation losses. Of course, it is possible to couple a low duty cycle photoinjector, with concomitant low average current, to a high-energy linac, because the average power scales with the average current. This is exactly what will be done at the X-ray Free Electron Laser (XFEL) sources now being contemplated (see Claudio Pellegrini and Joachim Stöhr in this issue).

Yet there is a way to use high duty cycle, high-energy linacs without consuming large amounts of power: superconducting (SC) linacs may be efficiently used as both linear accelerators and decelerators—an idea suggested by Maury Tigner in 1965. When used as an accelerator, the electron bunch gains energy at the expense of an electromagnetic (EM) field resonant in the linac; when used as a decelerator, the EM field gains energy from the bunch. The distinction between the linear accelerator and decelerator is simply one of bunch position relative to the phase of the resonant traveling EM wave. For relativistic bunches, which by definition always have speeds close to the speed of light, this distinction is simply one of carefully timing the arrival of the bunch at the entrance of a linac relative to the phase of the radio-frequency wave. In order to efficiently store the energy recovered from the bunch, it is necessary that the resonant Q of the linac be very high, usually in the range of 10^{10}. This requires the use of an SC linac to circumvent the wall losses of normal conducting linacs, such as the SLAC linac.

Fig. 1 shows a schematic layout of such an ERL and illustrates how it can be used as a superior synchrotron radiation source. A brilliant electron injector is used to obtain relativistic (say, 10 MeV) bunches with very low transverse and longitudinal emittances. These are then accelerated in an SC linac to energies in the range of 3–8 GeV. The resultant bunches are then guided around a transport loop, very much like a section of a third generation ring, consisting of a lattice of

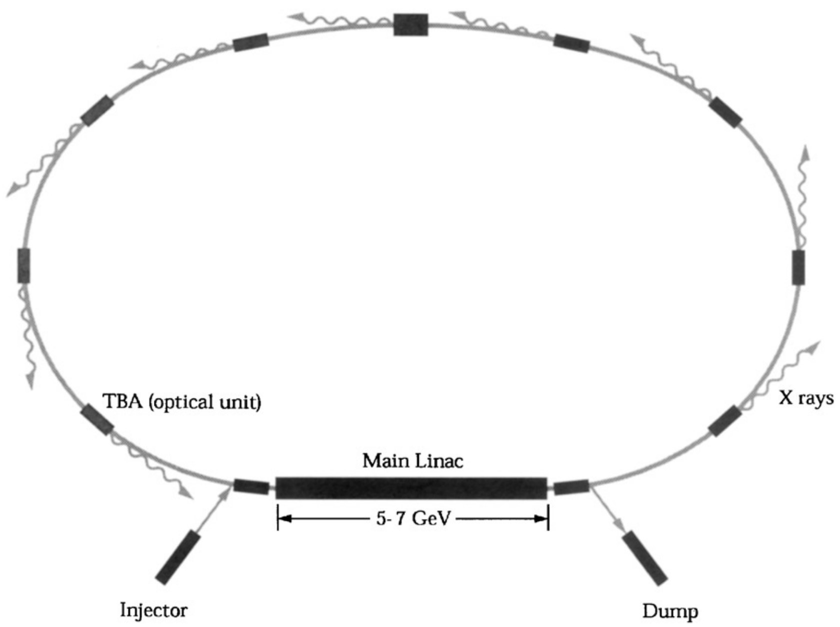

Fig. 1. A schematic layout of an ERL synchrotron light source. Ten-mega-electron-volt electrons made in the injector are bent by a weak bending magnet into a few hundred meter long SC linac and brought to full energy in a single pass. The electrons are then guided around a one-turn arc made, for example, of triple bend achromat (TBA) magnets with undulators producing the X-rays. The electrons have a path length such that they return out of phase with the linac and their energy is recovered before being steered to the dump at an energy of about 10 MeV by another weak field magnet. The low energy at which the electrons are dumped greatly reduces the problem of residual radioactivity generated in the dump.

electron-optical elements interspersed with undulators to produce synchrotron radiation. The loop length is carefully adjusted so the bunches arrive back at the linac 180° out of accelerating phase. They then decelerate through the linac and emerge with the original injection energy, less synchrotron radiation losses. These low-energy bunches are bent aside by a weak dipole magnet and sent to a beam dump. Disposing of the electron beam at very a low energy results in much less induced radioactivity in the beam dump—an important advantage of energy recovery. The essential distinction between an ERL and a storage ring, then, is that the electrons are recycled in a storage ring whereas only the electron energy is recycled in an ERL. This allows bunch manipulations in an ERL which would be unfeasible in a storage ring.

But can energy recovery be made to work on a practical basis? A pioneering experiment was done in the mid-1970s with a SC linac at the Illinois superconducting microtron. Experiments at other labs followed in concert with increasingly sophisticated SC linacs and SC radio-frequency structures developed, for example, at Cornell and Stanford. The CESR storage ring at Cornell, the CEBAF machine at the Thomas Jefferson National Accelerator Facility (Jefferson Laboratory), and LEP at CERN, all of which are driven by SC radio-frequency structures, have proven the practicality of SC accelerating structures for large machines.

The most convincing demonstration of ERL technology, however, has been the commissioning in the last few years of a 48 MeV, 5 mA ERL at Jefferson Lab as a driver for an Infrared Radiation (IR) Free Electron Laser (see Fig. 2). This user facility produced > 1 kW of IR power on a routine basis. Its energy recovery efficiency is better than 99.97 per cent. (It may be a good deal better. The actual efficiency has never been measured to higher accuracy.)

ERLs have tremendous potential as synchrotron radiation sources. As opposed to storage rings, the essential bunch characteristics are determined primarily by the injector, not by the entire ring. This greatly eases the task of upgrading the facility as injectors improve. Since bunches are not stored, there is no decay of a fill. Complex bunch trains can be readily implemented by programming the timing of the laser illuminating the photocathode electron source. Another major advantage is the ability to control the cross-sectional properties of the bunch. In storage rings, the bunches tend to be flat in cross-section and have a vertical emittance which is orders of magnitude smaller than the horizontal emittance. By contrast, the beams in an ERL are naturally round with equal emittances in the horizontal and the vertical, which can be very advantageous for certain X-ray optics. As discussed below, ERL sources are being contemplated with flux and brilliance exceeding all existing storage rings.

ERLs also lend themselves to the production of very short X-ray pulses. Studies of phenomena on the 100 fs time-scale are rapidly emerging as one of the next frontiers of X-ray science. Our understanding of the initial events in chemical and solid-state systems has been revolutionized within the last decade by spectroscopies with femtosecond optical lasers. What is lacking is the associated

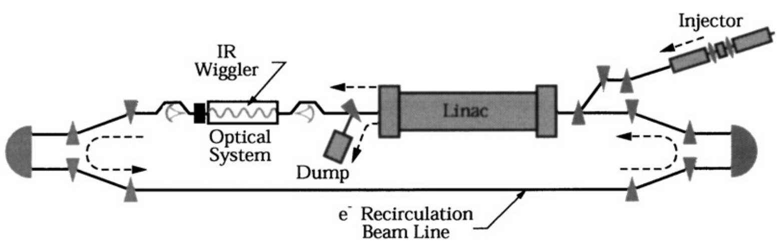

Fig. 2. Jefferson Laboratory IR-FEL. The Jefferson Laboratory IR-FEL is also a single-pass machine. Electrons from the injector are brought up to energy in the linac and then pass through a wiggler magnet to create the IR. Mirrors at the ends of the wiggler magnet intensify the IR beam. The electrons circulate around the rest of the lattice before their energy is recovered in another pass through the linac, after which they are sent to the dump. (*Source*: Jefferson Laboratory web site).

structural information. This may be obtained by pump–probe experiments in which systems are pumped with an optical laser and then probed, after an adjustable time delay, with a very short X-ray pulse. Typical storage ring bunches are some 20–100 ps long, which severely limits experiments on faster time scales. By contrast, the bunches out of an ERL photoinjector may be only a few picoseconds long. Moreover, ERLs allow phase-space manipulations with bunch compressors to create very short bunches. As an example, the CEBAF machine, which is based on a multi-pass SC linac, has achieved bunches shorter than 100 fs rms.

Many novel possibilities are made feasible by the ability to adjust the charge and timing of bunches with appropriate manipulation of the laser system driving the photocathode. For example, the minimum emittance of a photoinjector is limited by space charge effects near the photocathode electron source. The emittance of the photoinjector can be decreased by sacrificing photocurrent. Thus, one can envision operating an ERL in a high-flux, relatively low-brilliance mode or a lower-flux, higher-brilliance mode simply by reprogramming the laser illuminating the photocathode. (As indicated in the next two figures, in both modes, the flux and brilliance can still be extraordinary.) As another example, the repetition rate of pump–probe experiments with femtosecond lasers is frequently limited to low values (say 10 kHz) by the laser. In these cases it is desirable to have a very short, high-charge (for peak intensity) bunch at 10 kHz. One can imagine operating a general purpose ERL with small charge bunches at very high repetition rates (for example, GHz) interspersed with high-charge bunches at 10 kHz. A "buffer zone" of a microsecond with no bunches on either side of the large bunch would allow isolation of the X-ray pulse from the large bunches at the appropriate experimental station. Most other users with time-integration windows exceeding a few milliseconds would be insensitive to this bunch pattern.

Although consideration of ERLs as synchrotron sources has been going on for only a few years, they have already generated a great deal of excitement in the synchrotron radiation community. Nikolai Vinokurov and Gennady Kulipanov and colleagues at the Budker Institute of Nuclear Physics in Novosibirsk had suggested a specialized ERL machine in the mid-1990s. Geoff Krafft and David Douglas at Jefferson Laboratory and Maury Tigner at Cornell, and perhaps others as well, were also thinking about the possibilities of more general purpose ERL synchrotron radiation sources. By late 2000, ERL synchrotron radiation projects were being seriously considered at Cornell University (in collaboration with scientists at Jefferson Laboratory), at Brookhaven National Laboratory (BNL) and at Lawrence Berkeley National Laboratory (LBNL). The focus of the Cornell effort is on a general-purpose synchrotron radiation source; the BNL efforts are on ERLs for both synchrotron radiation and heavy-ion physics applications; and the machine being considered at LBNL is specialized for the generation of short X-ray pulses at low duty cycle. Interested readers may find articles on all three efforts in the March and May 2001 issues of *Synchrotron Radiation News*. The Cornell web site (http://erl.chess.cornell.edu) has descriptions of the Cornell/Jefferson Laboratory work, as well as links to other ERL web sites. The projections given below are based on the ERL being designed by Cornell and Jefferson Laboratory staff.

Figs. 3a and b show the average brilliance and coherent flux vs. X-ray energy for various machines and for a 5.3 GeV ERL for reasonable assumptions of photoinjector emittances and undulators. The curves show the expected ERL performance under two modes of operation: a high-current, "low-emittance" (100 mA, 0.15 nm rad) mode and a lower-current, even lower-emittance (10 mA, 0.015 nm rad) mode. It is assumed that the SC linac operates at 1.3 GHz with every radio-frequency bucket filled, which corresponds to bunches of 77 and 8 pC, respectively. The advantage of high repetition rate operation is that a reasonable average current can be achieved with low-charge bunches, which is desirable since space charge is the primary mechanism for emittance growth at the photocathode. These bunches are considerably smaller than the ~1 nC bunches required by XFELs. For most users, the ERL will seem like a continuous

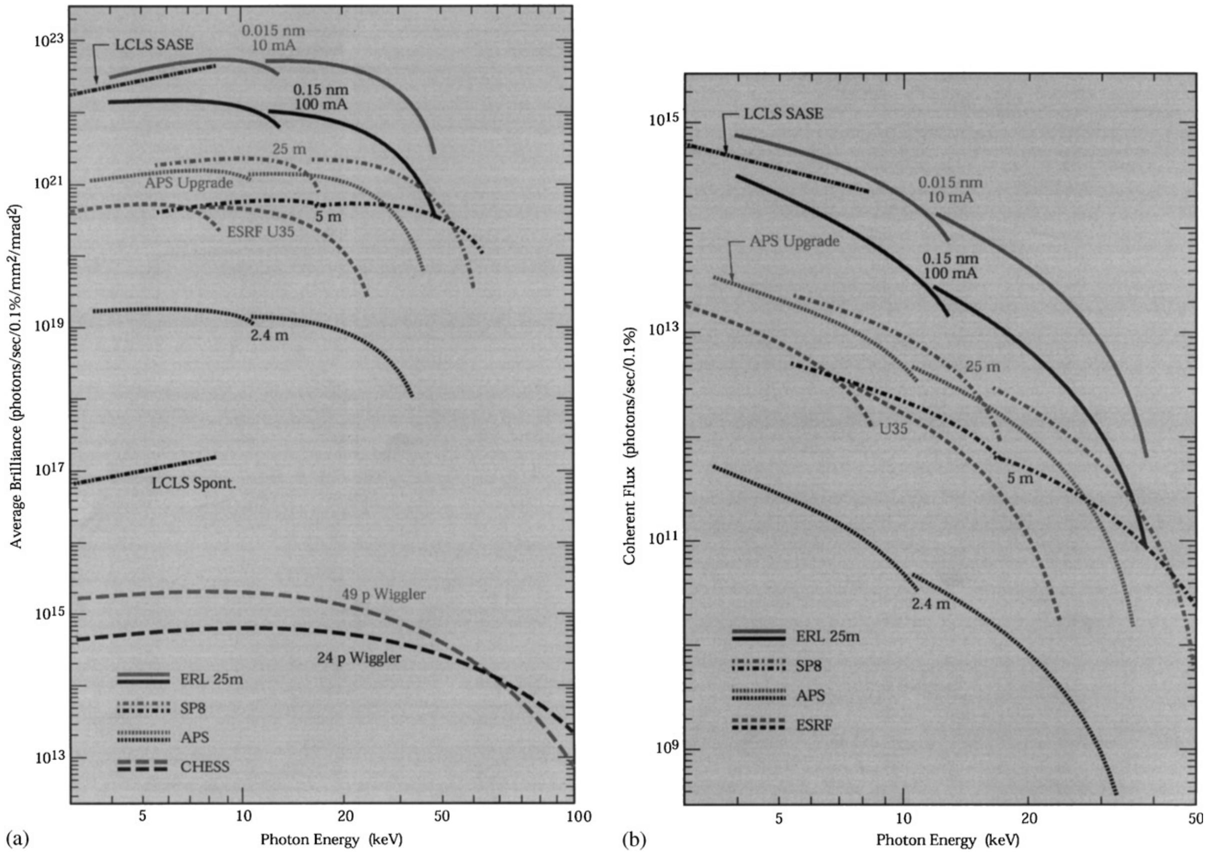

Fig. 3. Expected average brilliance (a) and coherent flux (b) for an ERL based on the Cornell/Jefferson Laboratory design described in http://erl.chess.cornell.edu/Papers/ERL_Study.pdf. The ERL may be operated either in a high-flux mode (100 mA, 0.15 nm emittance) or, by reducing the photocathode current to decrease the photoinjector emittance, in a lower flux mode with very high brilliance (10 mA, 0.015 nm emittance).

source of X-rays. Larger bunches at lower duty cycle—and with lower brilliance—are likely to be possible for special applications. The great advantage of an ERL is that beams for these special applications can be quickly implemented by simply reprogramming the photoinjector.

There are numerous challenges to building an ERL to these performance levels. These issues were explored in a workshop at Cornell University in August 2000. No ERL has ever been constructed to operate at these simultaneous values of energy, average current and emittance. Likewise, a photoinjector with the requisite specifications has never been built. The shortest pulses will present special challenges, as will the X-ray optics required to realize the full potential of the synchrotron radiation beams. Significantly, the workshop concluded that the requisite performance levels can be achieved by straightforward improvements of existing technology and that no new breakthroughs or radically new technology will be required. However, there are many issues—beam stability, halo control, the negative effects of coherent synchrotron radiation, photoinjector design, and photocathode lifetime—which will require prototyping before an optimum large ERL facility can be confidently designed. Fortunately, almost all of these questions can be addressed with a small, low-energy (for example, 100 MeV) ERL prototype. Cornell University has proposed building a small prototype to address such issues for the community at large.

ERLs and XFELs are both based on linac technology, both are limited by photoinjectors, both will optimally utilize long undulators and both will deliver short bunches. How do these two synchrotron radiation sources differ? From a physics point of view, the biggest difference is that the self-amplified spontaneous emission (SASE) process to generate synchrotron radiation is fundamentally different from the spontaneous synchrotron radiation process so far considered for the ERL. In order to achieve SASE in the hard X-ray, higher-energy linacs, bunches with higher peak current and far longer undulators will be required.

From a user point of view, however, ERLs of the Cornell or BNL designs and an XFEL of the LCLS or TESLA designs could not be more different. The first difference is that almost all the applications now being performed at storage rings sources are directly transferable to the ERL. For these users, the design of the beam lines, and the way in which the experiments are carried out, will be very similar to those at storage ring sources. The extra few orders of magnitude improvement in beam characteristics will, however, have significant consequences for the experiments that can be performed. The more brilliant beams will allow smaller and weaker scattering samples to be examined. For instance, the practical limits of photon correlation spectroscopy experiments will be pushed into faster time regimes. Inelastic scattering experiments may well be extended to the sub-meV regimes, thereby greatly expanding the kinds of experiments that can be done. The round source size will extend the limits of what can be done with microbeams. With improved X-ray optics, ERLs may make feasible 10–30 nm diameter hard X-ray beams. Thus, ERLs automatically have a huge natural constituency of advocates, namely, almost all users of existing storage rings when these users begin to demand more and better synchrotron radiation resources. Of course, there will also be applications that take advantage of the distinctive characteristics of ERL synchrotron radiation beams, such as short pulses, as discussed earlier.

By contrast, XFEL beams will be so intense that single-pulse specimen and X-ray optics damage become over-riding issues. As opposed to the ERL, few experiments can be transferred from storage rings to the XFEL without big changes in the way in which the experiments are performed. The community will have to develop new ways of doing practically every kind of synchrotron radiation experiment. The peak intensity of the XFEL pulses is so high for many experiments that a new sample, or a new illuminated area of sample, will be required for each pulse. Yet the number of photons available per pulse ($\sim 10^{12}$ for a single sub-ps pulse from the SLAC LCLS, about equivalent to 0.1–1.0 s of monochromatic beam at the APS) will limit the information available from a given sample. Thus, the emphasis at an XFEL will shift to developing techniques to average and merge data from different samples. The extreme properties of the X-ray beams (for example, enormous peak electric fields, full transverse coherence) will enable unique areas of investigation, which is very exciting. But at the same time, it is safe to predict that the learning curve in utilization of XFELs will be long. One of the most interesting cultural changes in synchrotron radiation usage in recent years is the growing number of users who are not X-ray experts. The use of XFELs by these communities will likely come years after XFELs first turn on.

Finally, we cannot resist pointing out that a high duty cycle XFEL will consume an enormous amount of electrical energy, unless, of course, it is also an ERL. The potential benefits of merging ERL and FEL technology, already demonstrated in the Jefferson Lab IR-FEL, are likely to become compelling.

For more than 30 years, the focus of the synchrotron radiation community has been bigger and better storage rings; now the ultimate storage ring is in sight (see article by Pascal Elleaume in this issue). ERLs and XFELs are emerging as alternative synchrotron radiation sources with interestingly different properties. The first three generation sources were primarily incremental improvements of a single technology, namely storage rings. The future of next generation sources is likely to be much richer than in the past. ERLs and XFEL are both more appropriately termed alternative technology synchrotron radiation sources, since they utilize linacs rather than storage rings.

ERLs, XFELs, and, no doubt, synchrotron radiation machines not yet invented, are the creative fruits of an emerging new generation of accelerator physicists. Culturally, accelerator physics has been the sibling of high-energy physics activity, because new high-energy physics experiments required new accelerators. Yet accelerators are but one tool towards the end of understanding the fundamental constituents of Nature. The trends in recent years are leading science in new directions. High-energy physicists are increasingly looking to the skies to understand the fundamental constituents. And accelerator physicists are increasingly finding other science areas challenging and attractive. In a very real sense, both ERLs and XFELs are consequences of a maturation of accelerator physics designed specifically from the very start to expand what can be done with synchrotron radiation. We look forward to the next decade when ERLs and XFELs will take the frontiers of synchrotron radiation to new vistas.

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