Energy-recovery linac project at Cornell University†

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There is considerable interest in using superconducting electron linacs with energy recovery as synchrotron radiation sources. Such energy recovery linacs (ERLs) would open new regimes of X-ray science because they are capable of producing ultra-brilliant X-ray beams [$>5\times10^{22}$ photons s^{-1} (0.1% bandwidth)$^{-1}$ mm^{-2} mrad^{-2} at 10 keV], maintaining a very small source size ($\sim$3 µm r.m.s.) suitable for micro X-ray beams, and making very intense fast ($\sim$100 fs) X-ray pulses. Each of these characteristics would permit the execution of experiments that are not feasible with existing synchrotron sources. Many technical issues must be satisfactorily resolved before the potential of a full-scale ERL can be realised, including the generation of high average current (10 to 100 mA), high-brightness electron beams (0.015 to 0.15 nm rad emittances, respectively); acceleration of these beams to energies of 5–7 GeV without unacceptable emittance degradation; stable and efficient operation of superconducting linear accelerators at very high gradients *etc.* Cornell University, in collaboration with Jefferson Laboratory, has proposed to resolve these issues by the construction of a 100 MeV, 100 mA prototype ERL. The intention is to then utilize the information that is learned from the prototype to propose the construction of a full-scale ERL light source.

Keywords: particle accelerators; energy recovery; linacs; X-rays; light sources.

1. Introduction

Synchrotron radiation has become one of the most important tools in the physical and biological sciences, as well as engineering. The synchrotron radiation user community consists of many thousands of scientists and engineers. There is no evidence that the growth of this user community is slowing down, as evidenced by graphing the number of publications per year citing synchrotron radiation on the INSPEC database, or by the accelerating number of depositions per year of protein structures into the Protein Data Bank, most of which involve synchrotron radiation. Given that growth in demand will continue to require more synchrotron radiation sources, one may reasonably ask: why not simply build more storage rings? The answer is that there is a need not only for more sources but also for sources of synchrotron radiation with greater capabilities.

2. Ideal synchrotron radiation source

What do we ideally want from a synchrotron radiation source? The list of qualities includes:

(i) Flexible pulse structure: (*a*) programmable pulse trains (interval, bunch charge); (*b*) variable pulse lengths down to 100 fs and below.

(ii) Very high average and high peak: (*a*) brilliance [photons s^{-1} (0.1% bandwidth)$^{-1}$ mm^{-2} mrad^{-2}]; (*b*) brightness [photons s^{-1} (0.1% bandwidth)$^{-1}$ mrad^{-2}]; (*c*) flux [photons s^{-1} (0.1% bandwidth)$^{-1}$].

(iii) Small X-ray source size of a desired shape, *e.g.* circular.

(iv) Flexibility of source operation: (*a*) no fill decay; (*b*) stability and robustness; (*c*) upgrades easily incorporated.

(v) New technology that encompasses the techniques and successes of third-generation synchrotron radiation sources.

The properties of synchrotron radiation are directly related to basic electron beam and undulator properties. For standard undulator radiation, the insertion device of choice for most experiments, the flux, coherent flux, peak brilliance and the photon degeneracy (number of photons per pulse that are both transversely and longitudinally coherent) are simple functions (Kim, 2001) of fundamental parameters. If we examine the formula, we discover that (Shen, 2001) the X-ray flux in the nth undulator harmonic is

$$F_n = 1.431\times10^{14} N_u Q_n I\,[\mathrm{A}],$$

where F_n is measured in units of photons s^{-1} (0.1% bandwidth)$^{-1}$, and N_u is the number of undulator periods, Q_n is a parameter ($\sim$1), I is the beam current and n is the undulator harmonic number.

Brilliance is the photon flux per unit transverse phase space volume and can be expressed as

$$B = \frac{F_n}{(2\pi)^2\bar{\varepsilon}_x\bar{\varepsilon}_y} \simeq \frac{I}{\bar{\varepsilon}_x\bar{\varepsilon}_y},$$

where B is measured in units of photons s^{-1} (0.1% bandwidth)$^{-1}$ mrad^{-2} mm^{-2}, and the bar on the emittances denotes the addition of radiative terms to the true r.m.s. electron beam emittance. The peak brilliance, $\hat{B}$, in photons per pulse ($F_p = F_n/f$) in six-dimensional phase space, including the longitudinal dimension, is

$$\hat{B} = \frac{F_p}{(2\pi)^3\bar{\varepsilon}_x\bar{\varepsilon}_y\varepsilon_E} = \left(\frac{2.35^2}{2\pi}\right)\frac{B}{\tau f} \simeq \frac{I}{\bar{\varepsilon}_x\bar{\varepsilon}_y\tau},$$

where τ is the full width at half-maximum pulse length and f is the pulse frequency. The coherent flux is given by

$$F_c = 10^{-8}\big(\lambda\,[\mathrm{\AA}]/2\big)^2 B \simeq \frac{I}{\bar{\varepsilon}_x\bar{\varepsilon}_y},$$

where λ is the X-ray wavelength. The photon degeneracy, δ_D, is the number of photons per pulse both transversely and longitudinally coherent, and scales as

$$\delta_D = \hat{B}\frac{\lambda\,[\mathrm{\AA}]^3}{1.2\times10^{24}} \simeq \frac{I}{\bar{\varepsilon}_x\bar{\varepsilon}_y\tau}.$$

Thus, maximization of the flux, coherent flux, peak brilliance and the photon degeneracy involves maximizing the beam current, I, while minimizing the transverse emittances of the electron bunch, $\bar{\varepsilon}_x$ and $\bar{\varepsilon}_y$, and the longitudinal bunch length, τ.

What determines these bunch properties in a storage ring? The answer is the dynamical equilibrium characteristic of the machine lattice. For a given ring current, in a few milliseconds, *i.e.* many passes of the electron bunch around the ring, the equilibrium dynamics determine the minimum emittances and bunch length. They also determine the transverse bunch shape, and the fill decay, *i.e.* essentially all the factors that are important for the production of synchrotron radiation X-ray beams. Unfortunately, storage-ring

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technology is highly evolved and approaching in-principle limits, so there is no expectation of being able to get around the equilibrium ring behavior. The best one can do is to optimize many of the fundamental bunch properties by making storage rings of ever increasing radius.

Let us take a different approach towards making an X-ray source. In principle, injectors can be built to produce very brilliant e^- beams and linacs can accelerate these beams with very low emittance growth. Why not simply combine a brilliant high-average-current injector with a high-energy linac to produce the electron beams for synchrotron radiation directly? Once the beam is used to generate synchrotron radiation, it can be dumped before the equilibrium dynamics destroy the desired bunch properties. The drawback to this approach is that the cost of power would be too high to operate such a machine: a beam of 7 GeV at 100 mA contains 700 MW of power, equivalent to the electrical output of a large generating station. Storage rings overcome this problem by using the same high-energy bunches many times, so it is not necessary to accelerate the bunches to high energy every time they are used to generate a burst of synchrotron radiation. The solution to this dilemma is to employ energy recovery, a principle that was first proposed by Tigner (1965), and really demonstrated to work at the IR Free Electron Laser (FEL) facility at Jefferson Laboratory (Jlab) (Neil *et al.*, 2000). Other groups are considering using this ERL principle worldwide.† There is also the intriguing possibility that bright injectors coupled to linacs may be combined with long undulators and higher peak current injectors to make unique X-ray sources (Emma, 2002; Arthur *et al.*, 2002; Materlik & Tschentscher, 2001; Kulipanov *et al.*, 2001).

Fig. 1 shows a conceptual layout of a future machine, as envisioned by the Cornell/Jlab group. It is based on a high-energy superconducting linac and X-ray undulators of up to 25 m in length installed in the beam return path. A laser-driven DC photocathode gun is used to create low-emittance electron bunches at high frequency (1.3 GHz). The photoinjector includes a booster stage to accelerate the bunches to ~10 MeV. These are merged into the main superconducting linac ($Q_o \simeq 10^{10}$) and accelerated to 5–7 GeV, after which the bunches make only one circuit around a return arc generating synchrotron light as they pass through X-ray undulators. The bunch energy is then reclaimed, as the return beam path length is made to deliver the bunches 180° out of phase with the accelerating beam as they pass through the linac a second time. Efficient storage and reclamation of the bunch energy is made possible by use of a superconducting linac with an external Q above 10^7. The energy-depleted bunches emerge from the linac at just below 10 MeV and are diverted to a beam dump (Gruner *et al.*, 2001, 2002). Accelerating and decelerating bunches may be interleaved in every RF cycle, *i.e.* each RF bucket in the linac may be filled. It appears feasible to produce brilliances in excess of 5×10^{22} photons s^{-1} (0.1% bandwidth)$^{-1}$ mm^{-2} mrad^{-2} for 10 keV X-rays. Higher brilliances are likely with further injector development work.

The operating current will be in the range from 10 to 100 mA with 0.015 to 0.15 nm rad emittances, respectively. Flexible pulse structures with pulse widths in the vicinity of 100 fs r.m.s. are planned (although perhaps at the cost of some brilliance). The beam size can be down to a few micrometers r.m.s. (3.2 µm for 2 m long ID) for making ideally round microbeam sources and exceedingly high-brilliance beams. An attractive feature of the ERL technology is that the performance is primarily limited by the photoinjector, which is only a small part of the overall machine. Thus, ERLs can be readily upgraded as photoinjectors improve, without rebuilding the entire machine lattice.

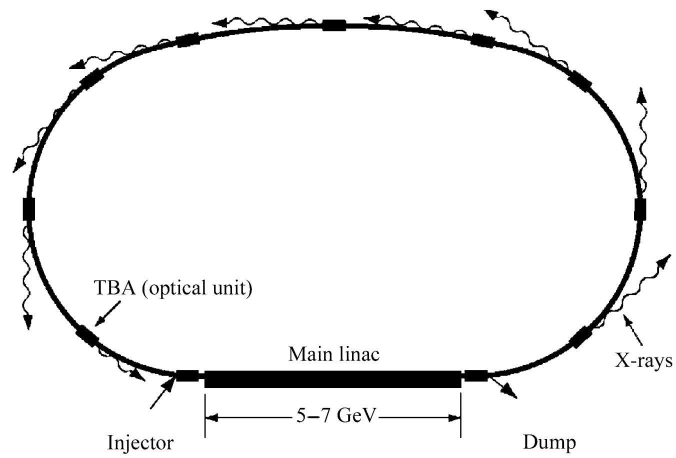

Figure 1
Conceptual layout of a future ERL phase II machine based on a superconducting main linac and X-ray undulator of up to 25 m in length installed in a single turn-around arc. A laser-driver DC gun plus superconducting (SC) cavity injects beam at between 5 and 15 MeV into a main SC linac. A triple-bend acromat (TBA) lattice plus insertion devices guide and produce the X-rays. The magnetic elements to compress (and decompress) the bunches to ~100 fs are not shown. After energy recovery, the beam is steered to a low-energy beam dump.

Many scientific applications will really benefit from the ERL technology, including femtosecond X-ray studies of solids, molecules and proteins; microbeam experiments; coherent imaging and microscopy; photon correlation spectroscopy; nuclear resonant scattering; polarized X-ray beam studies; resonant scattering and circular magnetic dichroism studies *etc.*‡

3. ERL machine physics prototype

The ERL principle has been validated at the Jlab IR FEL at a current of 5 mA and a normalized emittance of around 10 mm mrad in CW operation. The bunch repetition rate was as high as ~75 MHz, and the bunches were compressed to ~400 fs before entering the FEL wiggler. These values define the current practice.

To achieve a significant improvement in synchrotron radiation production, higher beam currents of 100 mA (20× current practice), smaller emittances of 2 mm mrad (0.2× current practice) and r.m.s. bunch lengths of less than 100 fs (0.25× current practice) will be required. The purpose of the proposed ERL prototype is to stably and reproducibly achieve these values. This will involve: excellent compensation of space charge emittance growth in a DC gun; understanding and control of short- and long-range wakes to avoid emittance dilution; understanding and management of coherent synchrotron radiation to avoid six-dimensional emittance dilution; adequate understanding and control or elimination of beam halo; and development and verification of beam simulation codes.

† Jlab IR FEL upgrade (underway), BNL PERL, LBNL short pulse, Daresbury IR-UV, Erlangen eventual synchrotron radiation upgrade, JAERI IR FEL upgrade, BIN P recirculating FEL driver, Budker Institute 'Mars' Recouperator, RHIC electron cooling. More details can be found at http://erl.chess.cornell.edu/WorldwideReferences.htm.

‡ See the proceedings of the SRI2001 workshop on 'Energy Recovery Linac Sources of Synchrotron Radiation' that discussed ERL type of machines at Jefferson National Laboratory (present) and possible future machines at Cornell University, Brookhaven National Laboratory, Lawrence Berkeley Laboratory and Budker Institute of Nuclear Physics, held on 21 August 2001 at Madison, Wisconsin, USA, with viewgraphs posted at http://erl.chess.cornell.edu/sri2001_workshop_proceedings.htm.

The accelerator technology challenges of the prototype ERL machine include: production of $I_{\rm ave} \geq 100$ mA, bunch charge of $\sim$80 pC at 1300 MHz, $\varepsilon_{\rm n} \simeq 1$ mm mrad, with low halo and very good photocathode operational longevity; transport and merging of the injector beam to the main linac without excessive six-dimensional emittance growth; non-invasive measurement of all relevant beam parameters; maintenance of high Q and accelerating field in the linac under relevant beam conditions; extraction of high-order modes (HOMs) from the cryogenic environment with very high efficiency; elimination of beam break-up by strong HOM damping; operation with high external Q for energy economy, *i.e.* control of microphonics and Lorentz detuning; and production and measurement of $\sim$100 fs bunches with bunch charges ranging from $\sim$0.07 to 0.4 nC or higher.

4. Conclusions

The scientific potential of an ERL synchrotron radiation light source is enormous. It extends the very strong case for the most powerful third-generation sources into entirely new regimes while preserving all the advantages of third-generation-type experiments. However, a prototype low-energy ERL machine must first be built to resolve significant accelerator physics and technology issues.

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