Energy recovery LINAC: A next generation source for inelastic X-ray scattering

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Abstract

The Energy Recovery LINAC (ERL) being developed at Cornell should be an excellent source for Inelastic X-ray Scattering (IXS) because it will permit long undulators to operate at high efficiency generating unprecedented spectral flux (photons/second/meV) and brilliance. We discuss several advantages of the ERL for IXS experimentation.
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1. Introduction

IXS experiments benefit when the highest possible spectral flux is delivered to a sample at an incident energy corresponding to backscattering from high-order reflections of diced crystal analyzers. To achieve meV spectrometer resolution incident energy must be above 20 KeV [1]. Third generation synchrotron sources are enabling great progress in IXS, but are even better sources likely to be available in the near future? This paper discusses one new source, the ERL being developed at Cornell University [2]. The ERL is an attractive next generation source because it should generate unprecedented X-ray flux and brilliance while being compatible with most experiments at storage rings today.

The ERL idea, first discussed in 1965 [3], and described more recently in Reference [4], utilizes a pulsed-laser driven photocathode to produce ultra bright electron pulses that are injected into a superconducting radio frequency linear accelerator (scLINAC). The pulses are accelerated to ≥ 5 GeV and pass ONCE through a ring-like array of bend magnets and insertion devices. Electrons return 180° out of temporal phase with the LINAC accelerating fields where energy is extracted and the beam is dumped. Ohmic losses in the scLINAC are less than 0.01% of the circulating energy so that most of the energy is then available to accelerate an interleaved train of bunches. The result is that electron energy is recycled and bunch phase space does not grow to storage ring dimensions [5].

The ERL will impact IXS by producing:

(1) A small round electron source (see Fig. 1) ideal for two-dimensional focusing using zone plates, KB mirrors, and capillaries.
(2) Isotropic transverse emittance $\Rightarrow$ undulator can rotate about the electron beam to optimize X-ray polarization for experiments using large analyzer crystal arrays, long arms, or horizontal scattering [6].
(3) Reduced electron energy spread $\Rightarrow$ long undulators will generate unprecedented spectral brightness.
(4) Ultra high X-ray brilliance
(5) Flexible bunch timing and filling may permit IXS with Mossbauer nuclei.

2. Reduced electron energy spread

Electrons lose energy by radiating photons in travelling around a storage ring. Energy supplied by the RF system is equal to the average radiative loss per turn, but after thousands of turns, finite electron bunch energy spread results from equilibrium between excitation and damping due to the quantum nature of synchrotron radiation. Excitation by photon emission is a stochastic process so energy spread grows in a random walk fashion. However, this spread is limited by radiation damping because the energy radiated by electrons scales as E_e^4 (where E_e is electron energy). However, this
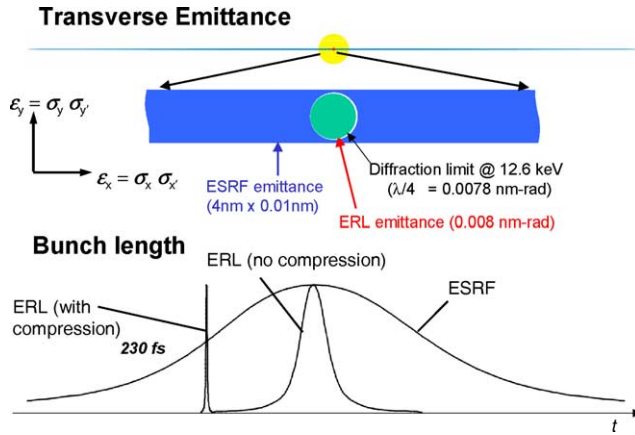
Fig. 1. Provides a schematic comparison of electron bunch size, in space and time, for storage ring and ERL sources. In the lower figure bunch intensity profiles are normalized to unity. 230 fs refers to FWHM (100 fs RMS).

discussion ignores the so called momentum compaction of particles within the bunch. Including this effect, and assuming equal radiation damping and excitation, the RMS energy spread is $\delta\gamma/\gamma = \sqrt{\{C_q\gamma^2/(J_E\rho)\}}$ [7] where $\gamma = E_e/mc^2$, ρ is the average bending radius in meters, J_E is the radiation damping partition number (~ 1 for storage rings) and $C_q = 3.83 \times 10^{-13}$ m. For a 5 GeV light source with average bend radius 80 m, $\delta\gamma/\gamma = 7 \times 10^{-4}$. In typical operation, Advanced Photon Source $\delta\gamma/\gamma = 9.6 \times 10^{-4}$.

Because the ERL does not store electrons, energy spread is largely defined by parameters of the low energy electron source and the RF acceleration system. Energy spread at the electron source is expected to be 1×10^{-3} at ~ 10 MeV (2×10^{-6} at 5 GeV). However, RF cavity accelerating voltage ($V_{RF} \propto \cos \omega_{RF} t$) is expected to increase energy spread because the bunch center is accelerated more than the head and tail. If this dominates, $\delta\gamma/\gamma = (k_{RF}\sigma_z)^2/\sqrt{2}$ where $k_{RF} = 2\pi/\lambda_{RF}$ and σ_z is the RMS bunch length. For the ERL, 2 ps bunches from the injector correspond to roughly $1°$ of RF phase at 1.3 GHz, giving $\delta\gamma/\gamma = 2 \times 10^{-4}$ at 5 GeV [8]. In this case, ERL energy spread has a well-defined cosine dependence on position in the bunch, and it may be possible to reduce energy spread without shortening the bunch length at the injection point [9].

3. Impact of long undulators

At fixed deflection parameter K, peak on-axis spectral flux of the nth odd undulator harmonic increases with the number of periods N and inversely with the energy width of the harmonic. Harmonic width depends on: nN, electron energy spread $\delta\gamma/\gamma$, and the ratio ε/β (ratio of emittance to beta function). An approximation for the width $\delta E/E$ of the nth harmonic based on [10] is

$$\sqrt{\{(nN)^{-2} + (2\,\delta\gamma/\gamma)^2 + (\gamma^2(\varepsilon/\beta)/(1 + K^2/2))^2\}}.$$

In Fig. 2 we calculate third harmonic peak spectral flux vs N for several values $\delta\gamma/\gamma$. The calculation assumes a Gaussian harmonic peak, 20 mm undulator period, K=1,
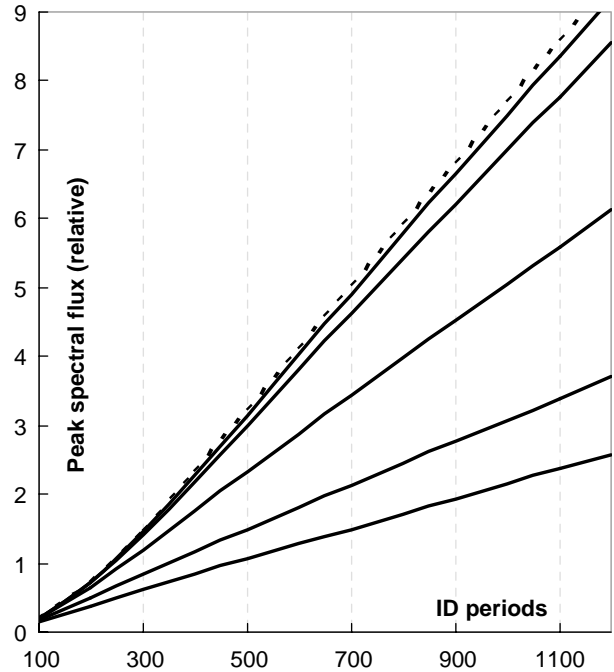

Fig. 2. Undulator peak spectral flux vs number of periods improves significantly with reduced electron energy spread. Solid curves are based on the formula and assumptions in the text. They correspond to $\delta\gamma/\gamma = 0.15\%$ (lowest curve), 0.1% (typical 3rd generation value), 0.05, 0.02 (proposed ERL), and 0.01%. For the dashed curve $\delta\gamma/\gamma = 0$ so the finite electron emittance limits peak flux. See [12] for additional machine parameters.

$\varepsilon = 10^{-10}$ m-rad, and $\beta = ½$ the ID length. The figure suggests the performance of long undulator should improve with smaller $\delta\gamma/\gamma$. For the ERL, a 20 meter undulator should deliver approximately 20 times the spectral flux available at the best IXS beamlines today.

4. ERL undulator brilliance

With small isotropic transverse emittance and reduced electron energy spread, the ERL should produce unprecedented X-ray brilliance. This is important for experiments that require focusing (such as microscopy) and/or maximum transverse coherence. Fig. 3 compares time average brilliance calculated for a 25 m ERL undulator with other sources including those discussed in [14]. The APS upgrade curves are based on [15]. ERL machine parameters are conservative based on reference [13].

With higher brilliance, an ERL would likely extend high-pressure diamond anvil cell science and other applications combining high energy resolution and micro-beams.

5. ERL opportunities related to timing

The natural ERL electron and photon pulse length is short (~ 2 ps) compared to storage rings (20–80 ps). However, nominal ERL pulse separation is 770 ps at 1300 MHz. This appears to preclude Mossbauer resonance based X-ray methods
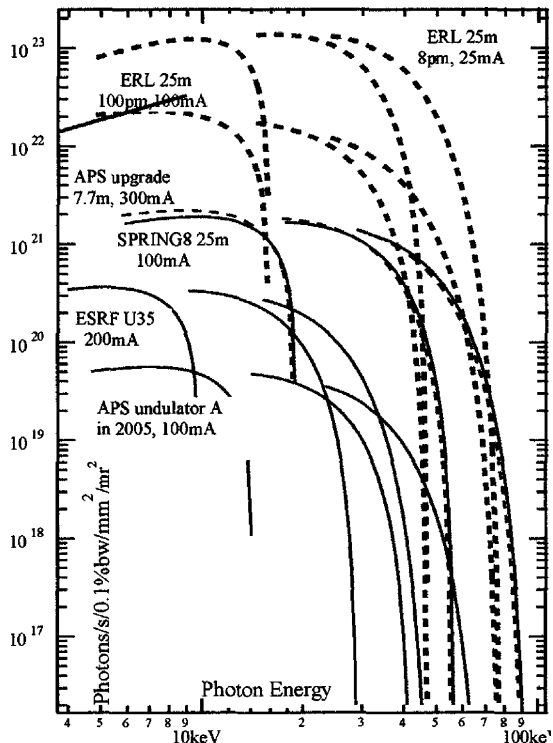
Fig. 3. gives calculated [11] average X-ray brilliance for proposed 25 meter ERL undulator [see 13, 14], existing sources, and proposed APS upgrade [15]. The dark line corresponds to proposed Laser Coherent Light Source where the peak brilliance is expected to be orders of magnitude greater than other sources.

because nuclear decay times are longer (e.g. for Fe^{57} lifetime is 97 ns). However, simulations [13] suggest that special running conditions may permit 'macro-bunch' operation that would not significantly degrade ERL machine performance. For example, a 7.7 ns long pulse train composed of 10 consecutive 0.5 nC bunches separated from neighbor trains by 500 ns yields 10 mA average current. This is approximately the current available when the APS operates with the hybrid bunch pattern [16] compatible with Mossbauer scattering. A number of technical challenges must be addressed before the ERL can produce short bunch trains of high charge, but this operational mode is not expected to degrade energy recovery by increasing higher mode loss in the scLINAC.

6. Conclusions

The ERL has the potential to be an excellent hard X-ray source for IXS and many other X-ray methods. It should produce unprecedented beam brilliance and spectral flux when compared to 3rd generation sources because the electron source is small in four phase space dimensions: transverse emittance, pulse length, and energy width. The ERL should permit long undulators to operate with high efficiency, and the round electron source and flexible pulse structure are certain to accelerate progress being made at 3rd generation sources in micro-beam science and a range of pump–probe experiments.

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