White Paper

Synchrotron Radiation Sources for the Future

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1. Introduction

Synchrotron sources have proven to be immensely important research tools throughout the biological, physical and engineering sciences. This is illustrated by the fact that most issues of *Science* or *Nature* are likely to contain articles which depended on synchrotron radiation (SR). World-wide, about 70 SR sources are in various stages of operation, construction, or planning, representing a cumulative investment which is estimated to be approaching $10B. This has been driven by a very large and diverse user community which, worldwide, is on the order of 10,000 and still growing rapidly. New, large-scale science initiatives are being planned which absolutely require SR (e.g., structural genomics). SR is here to stay.

Europe, with roughly the same size research community as the U.S., is in the process of building several new rings. Not counting Russia, Europe already has 12 SR storage rings of ≥ 1.5 GeV energy (built or under construction), as against 5 in the U.S. The question is not *if* the U.S. will need more SR sources in the future, but rather *when* the U.S. will need new SR resources. Given the cost and lead-time in designing a new SR machine, we need to start preparing for this need now.

Currently, all major SR sources are based on storage rings. Given the importance of SR, it is important to ask:

- Are storage rings the optimal SR technology for the future?
- Are there alternatives to storage rings which enable new science?

The purpose of this white paper is to suggest an alternative SR machine which offers many potential advantages over storage rings and which opens new paths for future science. To avoid confusion, it is important to understand that this alternative is **not** an x-ray Free Electron Laser (FEL) and fills a very different research need than FELs. These distinctions are discussed, below.

2. Background: SR and Storage Ring Principles.

2.1 Machine Generations, Flux, Brightness and Brilliance

Storage ring technology is an outgrowth of the colliding beam machines designed for high energy physics (HEP). Storage rings use a lattice of magnetic field elements to create stable orbits for ultra-relativistic electrons or positrons. The particles radiate SR when passed through magnetic structures (e.g., dipoles, wigglers or undulators) which cause the particles to experience radial accelerations. Only a very small fraction of the kinetic energy of a particle is radiated on each orbit; this energy is replenished by microwave (RF) cavities in the ring.

SR storage ring technology is very highly developed to optimize characteristics of importance for SR production. The *first generation* SR sources were parasitic upon HEP colliders (e.g., CESR, SPEAR I) and, consequently, were optimized for particle collisions, instead of x-ray production. These were followed by *second generation* storage rings (e.g., the NSLS, SPEAR II) which were dedicated for high-flux production of x-rays using many magnetic dipoles and a few wiggler/undulator sources. These machines were optimized for stable, high-current particle orbits with long lifetimes. *Third generation* machines (e.g., APS, ALS) were additionally optimized for brilliance by further reducing the machine emittance (explained below) and incorporating many more straight sections for IDs. Low emittance storage rings permit use of undulators, which produce very highly collimated x-ray beams, with divergences on the order of 20 μrad. There is now emphasis on so called *fourth generation* machines based on FELs, which would deliver ultra-bright, ultra-short x-ray pulses.

The distinctions between machine generations and the concepts of flux, brilliance, brightness are used inconsistently in the literature and are, therefore, worth reviewing: Consider photon beams spanning a narrow enough range of photon energies to be essentially monochromatic, say, $\Delta E / E =$ 0.1%; this is referred to as 0.1% bandwidth. *Flux* refers to the number of photons/s/0.1 % bw. For a given wavelength, the total beam power is simply proportional to the flux. *Brightness* (photons/s/unit solid angle/0.1% bw) accounts for the divergence of the beam. A beam in which the photons were all traveling absolutely parallel to one another would be infinitely bright, even if the total flux was small. Of course, this never really happens because there is always some divergence to the beam. *Brilliance* (photons/s/unit solid angle/0.1% bw/unit area) additionally accounts for the cross-sectional area of the beam of the source.

So for example, a monochromatic lamp with a 10 watt beam may have a lot of flux, but because of the divergence of the beam, the number of photons/s through a small area a long distance away from the lamp may be small. By contrast, a laser pointer might only output 5 mW of power, but the beam is bright because it has low divergence. So even at a long distance from the source the spot cast by the pointer still has most of the 5 mW of photon power and, therefore, is readily visible. Now imagine comparing two 5 mW laser pointers with identical divergences, but in which the cross-sectional area of the first laser source is half that of the second. Because the two lasers output the same number of photons/s with equal divergences, they are equally as bright. But the smaller area laser is twice as brilliant as the other because it packs in twice as many photons per unit emitting area.

The flux, brightness and brilliance of a photon source refer to the characteristics of the photon beams produced by the source. An integration of the source brilliance over the emitting area yields the source brightness and a further integration over the solid angle yields the flux.

The photons beams produced by SR sources are manipulated by optical elements – mirror, lenses, etc. – and are subject to the limitations of geometrical optics, namely, the best one can do (e.g., by avoiding absorption) is to preserve the product of beam area times the divergence of the beam along its path. Attempts to concentrate the beam into a smaller area will inevitably increase its divergence in a compensatory manner. This means that the product of area and solid angle through a plane cutting the beam anywhere along its path will, at best, be constant and is ultimately limited by the brilliance of the source. Since the purpose of SR sources is generally to maximize the number of photons delivered to specimens some distance from the source, brilliant sources are generally preferred. If one is trying to deliver lots of photons to smaller and smaller specimens, as is increasingly the case in many science areas, high brilliance sources are necessary.

As a rule of thumb, the higher the generation of the SR sources, the higher the brilliance. This is not an absolute criterion and, in fact, obscures essential distinctions between particular machines which determine if the machine is suited for a given application. A full characterization of a SR source involves specification of the brilliance, polarization, spectrum, coherence, and time structure of the emitted radiation.

FELs are called fourth generation SR sources. This may give the false impression that FELs bears the same incremental change in characteristics that marked distinctions between earlier generations of storage rings. In fact, FELs are totally different animals from storage rings, and deliver beams with greatly different coherence and time structure: Whereas FELs deliver c.a. 100 femtosecond pulses of super-bright, highly transversely coherent radiation perhaps a 100 times a second, a storage ring might deliver the same number of photons/s, but in incoherent pulses ~100 picoseconds long perhaps a million times a second. The energy per unit area and time in the focussed beams of proposed hard x-ray FELs is so high that it turns most targets into plasma in femtoseconds. This very narrow time window is the source of both the opportunities and limitations of FELs. There will be enormous technical challenges *both* in building a hard x-ray FEL *and* in learning how to use it. The x-ray community is rightly excited about these challenges and opportunities. But the practical effect is that it will be many years before FELs are ready for applications and, even then, FELs and storage rings will each be best suited for different uses. There is no prospect that FELs will replace storage ring-like sources; rather, FELs will open new science areas. Thus, the development of FELs does not lessen the need to improve ring-source technology.

2.2 Very Low Emittance

The goal is to have a SR source which has both as high a flux and as high a brilliance as possible. Flux and brilliance can always be reduced in applications which do not require it, so a high flux, high brilliance machine is most versatile. The brilliance of a storage ring source is increased by decreasing the *emittance* of the orbiting particle beam, i.e., by keeping cross-sectional area and angular divergence of the particle orbits as low as possible. In a storage ring, the emittance damps to an equilibrium value which typically requires thousands of orbits around the ring to settle in. The sequence of drift spaces, magnetic dipoles, quadrupoles and sextupoles around the ring used to control the particle orbits is called the machine *lattice*. Special lattices are used in storage rings to create as low an equilibrium emittance as possible. There are two key points to be made:

- The emittance and bunch length, and hence the brilliance, are established by a dynamic radiation equilibrium, the minimum value of which is controlled, for a given lattice by the beam energy; the higher the energy, the larger the emittance. The emittance of the best lattices known are now close to theoretical limits and are unlikely to see significant improvement.

- In a well designed linac (linear accelerator) the beam emittance and bunch length are controlled entirely by the emittance and bunch length of the particle *source*. Today's electron sources have inherent emittances less than those achievable in radiation controlled storage rings making higher brilliance possible with linac drivers. This is why the proposed FEL's, which require very low emittance, are based on linacs.

2.3 Energy recovery

Since properly designed linacs do not degrade emittance, why not use a linac to accelerate a very low emittance particle beam which is then passed through an undulator to produce a brilliant SR beam? The difficulty with this idea is that it takes a lot of power to accelerate the high current beam of electrons needed to produce high x-ray flux: A 100 mA beam at 7 GeV (typical of the APS) carries 700 MW of power, which is the output of a large electrical generating station! In a storage ring, this power need is circumvented by using the same electrons over and over again, so the kinetic energy is not wasted. A 100 mA beam in a storage ring involves the same electrons coming by a given point in the ring perhaps a million times a second, in which case the number of accelerated electrons is reduced by a factor of a million for the given current. A continuously operating high current linac is simply prohibitively expensive to operate unless the electron beam energy is recovered.

Fortunately, energy recovery is feasible. Linacs operate by maintaining a travelling electromagnetic wave which exerts unidirectional force on a charged particle. Whether a linac accelerates or decelerates electrons depends on the phase of the electron position relative to the electromagnetic (EM) wave. When a particle is accelerated, it gains energy from the electromagnetic wave. In accelerators, this wave is replenished by klystron amplifiers. Conversely, when a linac is used as a decelerator, the particle kinetic energy is transferred into the EM wave. The stored EM energy can be used to accelerate other electrons.

Linacs are usually made of copper to lower resistive losses in the linac walls. The wall resistance of even copper linacs lowers the quality factor, or Q, to too low a value to store an EM wave for very long. The alternative is to use linacs made of superconducting materials to minimize wall loss and raise the Q. Cornell has pioneered the use of superconducting niobium linacs with Qs of $\sim 10^{10}$ to drive accelerators. CESR, the storage ring used by CHESS, is entirely powered by superconducting RF cavities which are effectively just short linacs. Cornell superconducting linac technology was used to build the CEBAF accelerator facility in Newport News, VA, a 5.5 GeV electron accelerator [Neil, et al., 1998]. CEBAF is powered by hundreds of meters of superconducting linac. CEBAF has been operating very reliably for years. The TESLA x-ray FEL being designed in Germany will also use similar technology, as will the Spallation Neutron Source at Oak Ridge National Laboratory.

A low energy bunch of electrons injected into a superconducting linac can be accelerated and emerge with substantial energy gain. The same bunch can be routed via bending magnets back into the entrance end of the linac, 180º out of accelerating phase, and will be decelerated and emerge with lower energy. This regeneration concept is not new [Tigner, 1965]. Its practical implementation has recently been proven: In 1998 CEBAF commissioned a small, 38 MeV FEL which uses exactly this kind of energy recovery and which has been operating reliably [Neil, et al., 1998] as an infra-red user facility. Even in this first demonstration, the linac energy recovery is about 99%. Advanced SR machines using regeneration have also been suggested [Kulipanov, et al., 1998].

3. ERL concept

We propose to investigate the use of a superconducting linac with energy recovery as an Energy Recovery Linac (ERL), as illustrated in Fig 1. An electron bunch from a low emittance electron source is preaccelerated to low energy, say, ~10 MeV and injected into a superconducting linac. The bunch emerges at high energy (5 - 10 GeV) and is routed via bending magnets into an experimental hall consisting of a series of undulators which produce exceedingly bright, high flux synchrotron radiation. The electron bunch is then routed via bending magnets back into the superconducting linac, but 180° out of accelerating phase. The decelerated beam which emerges is bent out of the way by a weak bending magnet and dumped. The weak bending magnets at either end of the linac serve to deflect the low energy injection bunches and the decelerated bunches, since these have very low energy, but hardly deflect the high energy bunches.

The one pass nature of the ERL principle has important advantages for radiation production: Because the particle beam is not subject to radiation equilibration the particle beam tails can be made very sharp, thereby allowing the use of very long, narrow-gap undulators. For the same reason, the bunch length can be made much shorter, limited only by the source buncher and space charge forces. This feature will make possible high flux timing experiments not possible with storage ring beams. Since the particles in a linac are not preserved, one can change the bunch pattern at will to probe different time intervals without waiting for hours for long fills to end. Undulator changes will also be much quicker since the need for precision adjustment of the magnetic optics for long storage ring lifetimes does not apply.

Numerous advantages and new science opportunities are enabled by the ERL, as described below. The advantages flow from the loosening of the many constraints of storage rings. The most difficult requirement of a storage ring is the need to maintain particles in stable orbits for many hours. The trajectory of a particle in a storage ring is the net result of all the perturbations to which it has previously been subjected, many of which continue to influence the orbit even after numerous additional circuits around the ring. Achieving stable orbital conditions and long lifetimes is very difficult and puts strict constraints on the lattice, on the bunch structure, on vacuum conditions, on apertures in the ring, in fact, on practically every aspect of the ring. By contrast, threading an electron bunch around the ring a single time, as is the case in the ERL, allows far more flexibility in practically all aspects of the machine design. Particle losses/turn around the ring which are insignificant in the ERL would be intolerable in a storage ring.

4. ERL technology case

The technology case for an ERL machine is strong and has many features:

- The ERL is a superior SR source. Most experiments which are performed on storage rings can be better performed on an ERL machine. Calculations of the performance of an ERL machine using present technology suggests that it would exceed the best 3rd generation machines in brilliance and flux (Appendix 1). Although it is premature to specify costs, there is good reason to believe that an ERL machine would be cost-competitive with even mid-size 3rd generation storage rings. We expect ERL-type SR sources, once demonstrated, may become the preferred choice for new high-performance SR machines.

- The ERL uses demonstrated technology. Although an ERL machine of the type we envision has never been built, all the parts are existing technology and have been demonstrated, in one form or another, in other types of machines. While there is much to be done in order to get all the parts to work together at the required currents, we are confident that an ERL machine is viable.

- The brilliance of 3rd generation storage rings is constrained by beam lifetime considerations arising from intrabeam scattering (the Touschek effect). In the ERL, however, particles are not stored, so there is no comparable beam lifetime constraint and making higher brilliance is feasible.

- The ERL provides flexibility and facilitates performance improvements. Brilliance upgrades in the ERL do not require rebuilding the whole machine. In a storage ring, a new machine lattice is required to substantially decrease emittance in order to raise brilliance. This is usually tantamount to building a completely new machine. An example is the SPEAR II to SPEAR III upgrade. However, there is little change in beam emittance in a single circuit around a machine. For this reason the emittance in the ERL is determined rather by the photoinjector, a relatively inexpensive piece of apparatus which can easily fit into a small room. Hence, future brilliance improvements are now contained in a small piece of apparatus; the rest of the machine need not change. Further, smaller emittance, at the expense of flux, can be readily obtained for a given set of experiments without modification of the machine. This enormous flexibility is one of the main advantages of an ERL source.

Very brilliant photoinjector sources have been built. A normalized emittance of one micrometer for bunch charges of more than 10^9 electrons can now be achieved. Ultimate limitations arise from the need for electron guns which have low emittance, high current and good lifetimes. Electron gun technology is constantly improving and is not near in-principle limits. Significantly, electron gun improvements are being driven by many commercial and scientific applications (e.g., FELs) so better guns may be expected. Initial R&D is needed on the most appropriate photoinjector because the photoinjector characteristics will determine the linac required to achieve a given type of x-ray beam.

- The ERL and storage rings are distinguished by their time structures. Because the ERL is not subject to the Touschek effect the bunch filling pattern can be much more flexible than in a storage ring. Thus, one could have bunches with 3nC spaced by 30ns, or ~100 pC spaced at 1ns and have the same average flux. The bunch lengths (lengths of the individual x-ray bursts that make up the beam) can be very short. Current linac collider designs depend on 100 to 400 micrometer (0.3 - 1.2 ps) bunch lengths as opposed to the several centimeter scale (~100 ps) bunch lengths characteristic of most storage rings. Shorter bunches may well be possible. Thus, the ERL could be operated either as more of a continuous x-ray source than a storage ring, or, alternatively, picosecond-long bunches could be spaced a distance apart to allow fast pump-probe timing experiments.

- The ERL particle beam cross-section can be tailored more readily than in a storage ring. Equilibrium considerations in a storage ring result in a stored beam in which the vertical and horizontal emittances are very different and in which there is a near-Gaussian fall-off in density as one moves out from the center of the stored beam. By contrast, the ERL can have nearly identical horizontal and vertical beam profiles, if desired. Moreover, scrapers can be used to remove the tailing edges of the beams. The result is that the beam profile can safely thread through longer narrow-gap undulators than is feasible with storage rings.

5. ERL Science Case

The special characteristics of the ERL enable exciting new science. These characteristics include:

- Extraordinary flux.
- Extraordinary brilliance, adjustable via the photoinjector.
- Picosecond bunch lengths.
- Great flexibility in the timing of bunch sequences.

The numerous science opportunities available with more brilliant, intense SR sources have been examined in detail at numerous conferences (e.g., see the workshop proceedings accompanying Laclare, 1999). Just a few representative examples will be given below.

a). Structural biology, membrane proteins, and genomics advances will be speeded by an ERL machine. The SR demands for structural genomics are projected to be enormous and are likely to saturate existing SR sources in the first few years. The ERL can not only meet future demands, but do so by facilitating challenging crystallography which can have an enormous impact on biology: The rate-limiting step in macromolecular crystallography is in obtaining crystals of sufficient size and quality. Obtaining large crystals is especially difficult for large molecular complexes and membrane proteins, precisely the areas on the cutting edge of structural biology. The high brilliance and flux of the ERL can be used for microbeams which not only allow use of small (c.a. 30 μm) crystals using standard methods, but also allow research into new ways of performing crystallography on even smaller crystals. For example, it may be possible to obtain full data sets by step-scanning a microbeam across a layer of frozen microcrystals thinly spread across a flat support. Each crystal yields a single diffraction pattern before it suffers radiation damage. A full data set is obtained by accumulating and merging hundreds of diffraction patterns from randomly oriented crystals. Microcrystallography will be especially important in detailing the structure of membrane proteins because membrane protein crystals are almost always very small. Brilliant, high-flux SR sources will be required to open up membrane protein structural genomics. The ERL can meet this need.

b) Science with coherent beams

The frontier in SR science involves the use of x-ray beams with a high degree of transverse coherence. Coherent experiments at storage rings usually involves passing an undulator beam through a small aperture to produce a plane wave; this results in greatly reduced flux. A better route to coherent beams is to reduce the machine emittance, ε. Synchrotron radiation is fully transverse coherent if $\varepsilon = \lambda / 4\pi$, where λ = x-ray wavelength [Jackson, 1999]. The ERL design example given in the Appendix is fully transverse coherent for 1.9 nm x-rays, for which the ERL is essentially a diffraction limited x-ray source. Full coherence at even smaller wavelengths is possible by reducing emittance via lower photoinjector current or lifetime. This can be done without changing the rest of the machine and, quite likely, by simply running the photoinjector in different modes. Photoinjector technology is evolving rapidly and photoinjector limits require future R&D. However, it is clear that even with present-day photocathodes, an ERL will provide far more highly coherent hard x-ray beams than storage rings, yet will still deliver a high flux.

An example of a coherent beam application is the extension of Fourier microscopy to non-crystalline materials such as whole cells, nanocomposites, minerals, etc. This idea, first proposed by Sayre, was shown to be feasible in recent demonstration of 75 nm spatial resolution imaging of a non-periodic array of micrometer-sized gold dots by Miao et al. (1999). A high brilliance source is needed, since there is no constructive interference from a crystalline lattice to boost the diffracted intensity at the detector and because a coherent plane wave is used. The test image studied by Miao et al. (1999) involved imaging gold atoms and was taken in a 15 minute exposure with 1.7 nm x-rays from the NSLS X1A undulator source. Replacing the strongly scattering gold atoms with low-z atoms results in a greatly reduced scattering power, so a high flux, high-brilliance source will be required to develop this into a general tool. Miao, et al. (1999) estimate that with a sufficiently coherent source, such as the ERL, ultimate resolutions of 10 to 20 nm may be obtainable on frozen biological samples.

Another example requiring transverse coherence is X-ray Photon Correlation Spectroscopy, or XPCS [Sutton et al, 1991]. Demonstration XPCS experiments have been performed by utilizing radiation from an undulator beam which is passed through a tiny aperture to produce a partially coherent plane wave. XPCS is the direct analog of optical photon correlation spectroscopy, but with the use of x-rays. The short wavelengths of x-rays allows the dynamics of matter to be probed down to molecular length scales and, with sufficient flux, to microsecond time scales. XPCS could be applied to study critical questions about the dynamics, mixing, and phase behavior in polymers, liquid crystals, colloids, and mesophase composites, including the newly developing field of surfactant-templated inorganic composites. XPCS experiments are always flux limited. New experiments would become practical with the high flux and high degree of transverse coherence of an ERL source.

c) Microprobe x-ray experiments. Brilliant sources enable a rapidly growing number of microbeam microanalysis experiments in areas such as microfluorescence, microdiffraction, microAXFS (XANES & EXAFS), microXPS etc. (Riekel, 2000). Microbeams are certain to revolutionize study of structures, materials, and cells which are heterogeneous on length scales ranging from a micron on down. Beam sizes of 0.15 to 1 micron are obtainable at today's premiere SR facilities, but these experiments are all ultimately brilliance limited and require longer exposures as the probe size becomes smaller, both because of the smaller flux and because of the very small sample volumes involved. Probes for even smaller dimensions will be needed in the future.

A good example of an important technological application is the use of microbeams to study nanofabricated materials. X-ray microbeams are already used to study contamination, strain and crystal orientation in integrated circuits. These experiments become increasingly difficult with existing sources as the length scale of fabrication shrinks towards 0.1 microns. The ERL can deliver the requisite beams to go to smaller dimensions.

Another important example is study of individual crystallites and domains in metals and polymers. It is already known that materials properties change dramatically as crystallite sizes shrink to nanometer dimensions. X-ray probes commensurate with the domain size will be needed to fully understand the properties of these materials.

Yet another application requiring microbeams is the analysis of materials at very high pressures. The highest pressures (Mbars) are obtainable in diamond anvil cells, but only for volumes of micron dimensions. Study of interfacial regions between crystallites at very high pressures is, to date, practically impossible because of microprobe limitations.

d) Timing experiments: The example given in Tables 1 & 2 is for 3 ps wide pulses occurring every 0.77 ns. The inter-bunch period is short and if all RF buckets are loaded the ERL will nearly look like a DC source that varies little with time. Since there is continuous injection, always at the same current level, there will be no decay of beam with run length and the machine will be designed to be just a stable "lamp" with negligible changes over time. Thus beam position monitors will always see the same steady beam current (no nonlinear effects with decay of beam current), heat loads on optics will not change with time, etc. This will contribute, we believe, to a machine stability that will exceed the performance of even today's best storage rings. Extreme stability will be especially important for optimal utilization of microbeams and coherence effects.

The great flexibility in the way bunches are loaded into the ERL can be utilized for timing experiments. The ERL bunches are up to a hundred times shorter than those typically found in storage rings, (e.g., 1 ps vs. 100 ps), enabling timing experiments with picosecond resolution for synchronized pump/probe experiments. The inter-bunch period is very flexible and can be lengthened if required, albeit with some compromise in flux. This opens new areas for the study of laser heating of materials and for study of chemical dynamics. Even shorter times ($\leq$ 0.1 ps) will be obtained with x-ray FELs, but at far lower repetition rates and with far greater single-pulse radiation damage. It will be necessary to substantially reduce the specific FEL intensity in order access the plentiful, interesting science in picosecond regimes, lest the sample be destroyed. In combination with the low repetition rates of FELs, the experiments may become awkward. Thus, the different machines may be best suited for different time windows.

6. What is needed to get started?

Efficient development of the ERL concept will require a combination of factors:

- Expertise with superconducting linac technology and accelerator physics
- Expertise in SR optics and in developing a SR facility
- A culture which promotes new ideas and instrumentation development and demonstrated track record of success in such endeavors
- A focus on integrating machine physics and scientific requirements
- Demonstrated ability to cost-effectively develop new projects by thinking "out of the box".

All these factors are present at Cornell, which is an ideal location to develop the ERL concept. The last three factors are especially important if the ERL concept is to be developed at low cost and to be well-adapted for science applications.

Next steps:

- Initiate discussion with the funding agencies.
- Sponsor workshops. The purposes of the workshops are to:
  - Enlist community feedback and participation
  - Critically examine options for an ERL machine

  - Identify technical aspects in need of R&D, both with respect to the machine and with respect to the beamlines
  - Identify appropriate key staff
  - Develop cost estimates.
- Develop a proposal for a demonstration project.

7. Conclusion

SR has matured into a vibrant tool in an amazingly diverse variety of science areas. It is especially significant that both the size of the SR community, and the potential applications continue to grow rapidly. There is wide-spread feeling in the community that SR sources with lower emittance and more transverse coherence are needed; however, development of conventional storage rings to meet these requirements will be very expensive. The development of more inexpensive, higher-performance SR sources would have an enormously beneficial impact on U.S. science. The ERL offers the possibility of both serving existing SR needs and of opening new SR directions at a significantly lower cost than any known alternative. The Cornell community is excited about the prospects of developing an ERL machine and continuing a long tradition of service to the scientific community.

8. References

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Appendix 1. ERL Brilliance and Flux

Lab & Source	**Brilliance** Phot/s/0.1%bw/mm**2/mr**2 Figure 2	**Flux(over opening cone)** Phot/s/0.1%bw Figure 3
Argonne APS	$1x10^{19}$	$1x10^{15}$
Grenoble ESRF	$4x10^{20}$	4×10^{15}
JASRI, Japan Spring 8	4×10^{20} for 4.5 m undulator 2×10^{21} for 25 m undulator	2×10^{15} for 4.5 m undulator 9×10^{15} for 25 m undulator
Cornell ERL	$1x10^{22}$	$1x10^{16}$

Table 1. Comparison of ERL with APS, ESRF & SPring-8

Lab & Source	**Brilliance** Phot/s/0.1%bw/mm**2/mr**2	**Flux(over opening cone)** Phot/s/0.1%bw
Stanford LCLS Phase II	$4.2x10^{22}$ (average) $1.2x10^{33}$ (peak) [Arthur, 1999] [LCLS, 1998: fig 10, sec 3 page 6]	$2x10^{14}$ (average) $3x10^{23}$ (peak) [LCLS, 1998: sec 3 pg 4]
DESY TESLA Phase II	$2x10^{26}$ (average) $2x10^{34}$ (peak) [Nunn & Rossbach, 2000: fig 11]	$5x10^{20}$ (average) $8x10^{27}$ (peak) [Brinkmann et al. 1997: pp 1023 and 1043]
Cornell ERL	$1x10^{22}$	$1x10^{16}$

Table 2. Comparison of ERL to FELs. The ERL fits nicely between 3rd and 4th generation facilities and can appropriately be called a generation 3.5th generation machine.

Calculations for Tables 1 and 2:

The following machine conditions for the ERL were employed in the undulator calculations using program SRW = SR Workshop from ESRF. Note that segmented undulators with focusing in the middle may be required, but the calculations here are just for one continuous undulator.

Assumed ERL conditions:

- 7 GeV, 100 mA
- RF linac frequency = 1300 MHz & max repetition period = 1/f = 0.77 ns. This implies ~ 3ps pulses every 0.77 ns. Since the charge is spread out over many bunches, the charge per bunch is small compared to FEL or storage ring sources. Further, assume
- Beta horizontal = Beta vertical = 12 m (taken from APS-like lattice)
- Emittance horizontal = Emittance vertical = 0.15 nm – radian
- Source size = 42 microns (x and y)
- Electron beam divergence = 3.5 microradian (x and y) and energy spread of 0.1%.

The basics of making brilliance and flux are in the selection of undulator period, undulator gap, and number of poles. The fruitful direction is to make the emittance small so that small beams can go through a small vertical gap. This makes short period undulators possible with excellent radiation characteristics.

Three undulators/machines have been chosen as representative of the current leading edge in SR technology (see Figures 2 & 3. Also see Kitamura, 2000). The bench mark for comparison is the undulator A at the APS, with a 3.3 cm period and a 2.4 meter length at 7 GeV and 100 mA. The ESRF curve is for a 3.4 cm period undulator of 5 m length at 6 GeV and 200 mA. The Spring8 curve is for a 2.4 cm period undulator of 4.5 m length at 8 GeV and 100 mA. The curve for the proposed ERL machine is for a 1.65 cm period undulator of 19.8 m length at 7 GeV and 100 mA. Spring8 is also commissioning a 25m undulator. It's projected brilliance and flux are given in Table 1.

Very long, narrow gap undulators may be considered with the ERL because of the small, sharp-edged electron beam profile. But, even with shorter undulators and larger gaps, the ERL will deliver exceptional performance. Flexibility in undulator design is another example of the flexibility possible when the constraints of maintaining a storage ring are loosened. Of course, R&D will be required to both build such long undulators and to utilize their brilliance.

Note on emittance units: 1 mm-mrad = 1 μ m-rad = 1000 nm-rad. Since the angular factor is dimensionless, it is frequently left unstated, e.g., 1 μ m-rad = 1 micron emittance. The actual or *geometric* emittance decreases purely due to kinematic effects if accelerated to relativistic velocities. The *normalized* emittance is the geometric emittance times γ, which at relativistic speeds is, of course, very close to the electron energy divided by 0.511 MeV, the electron rest mass energy. Unfortunately, it is sometimes ambiguous whether an author is using normalized or geometric emittance.

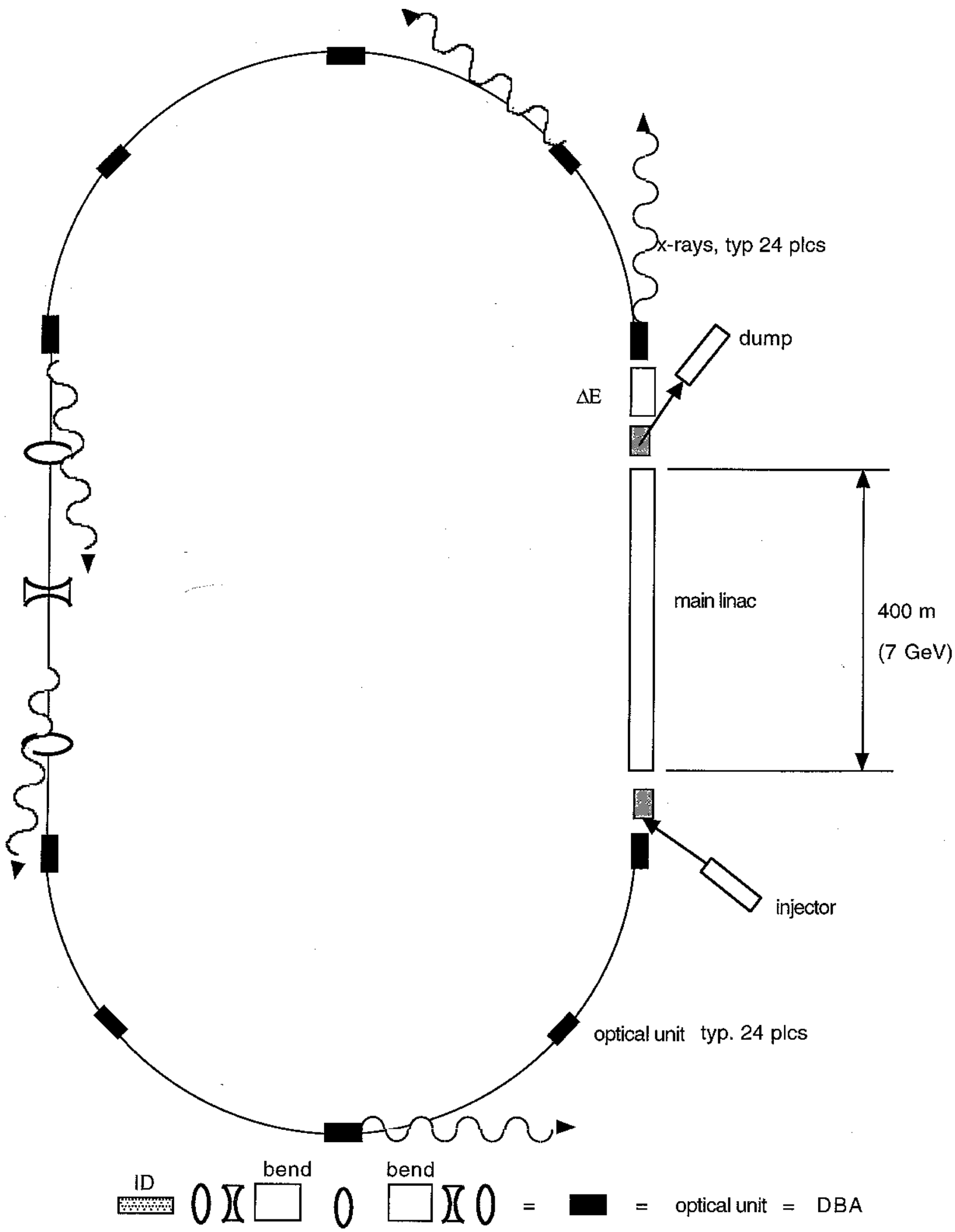


Figure 1. Plan schematic of an ERL. The various parts are not to relative scale. An advantage of the ERL is flexibility in the layout of the ring. Thus, for example, one could imagine putting all the components in an underground tunnel, except for the linear stretch opposite the linac. This part might consist of a herringbone lay-out of long undulator beam lines housed in a ground-level rectangular building. This would permit ground-level access to all the beamlines and a relatively inexpensive beamline building.

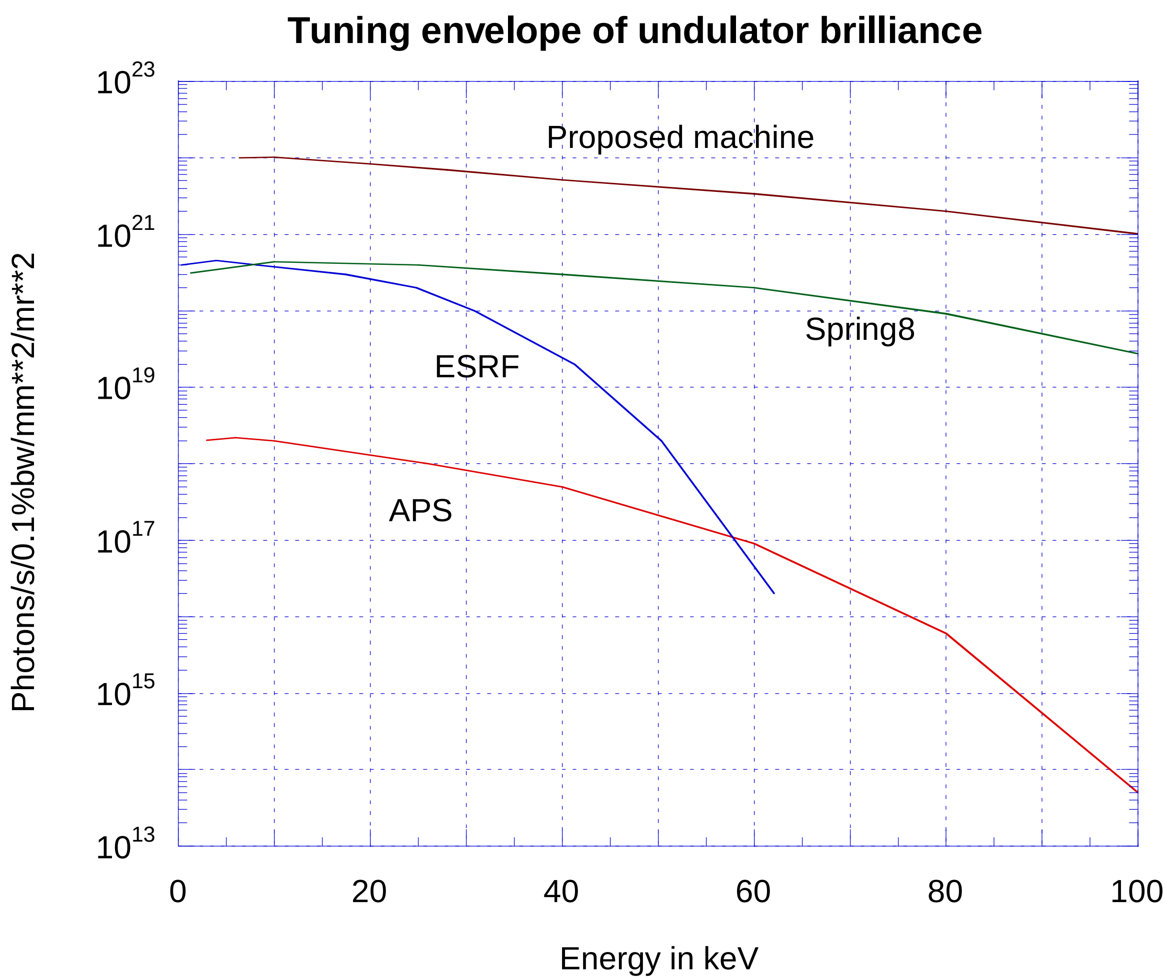


Figure 2. Tuning envelope of undulator brilliance for various undulator sources -- See explanation following the Tables. (Note: Per Dr. Dennis Mills, the peak APS brilliance value has been increased to 10^{19}, as given in Table 1, but not shown in this figure.)

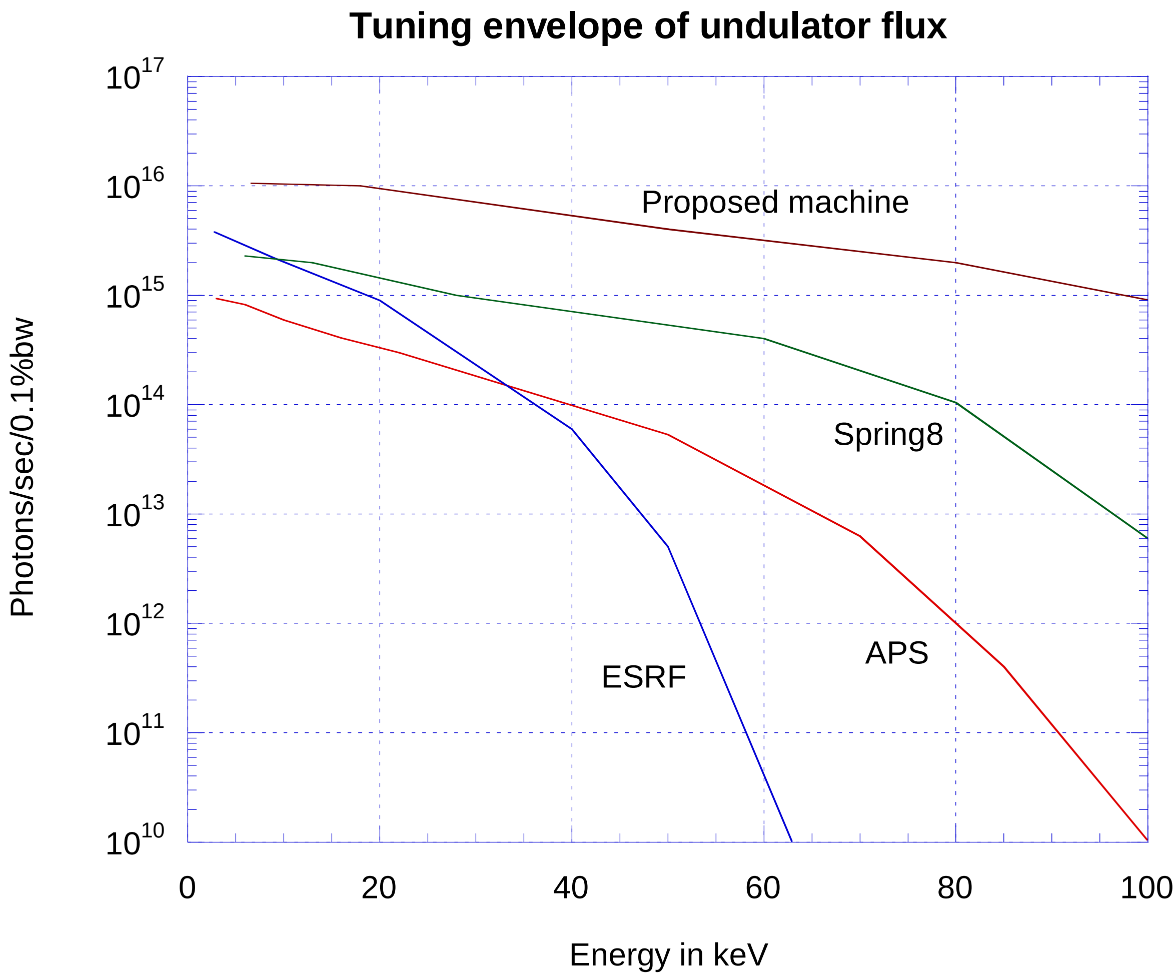
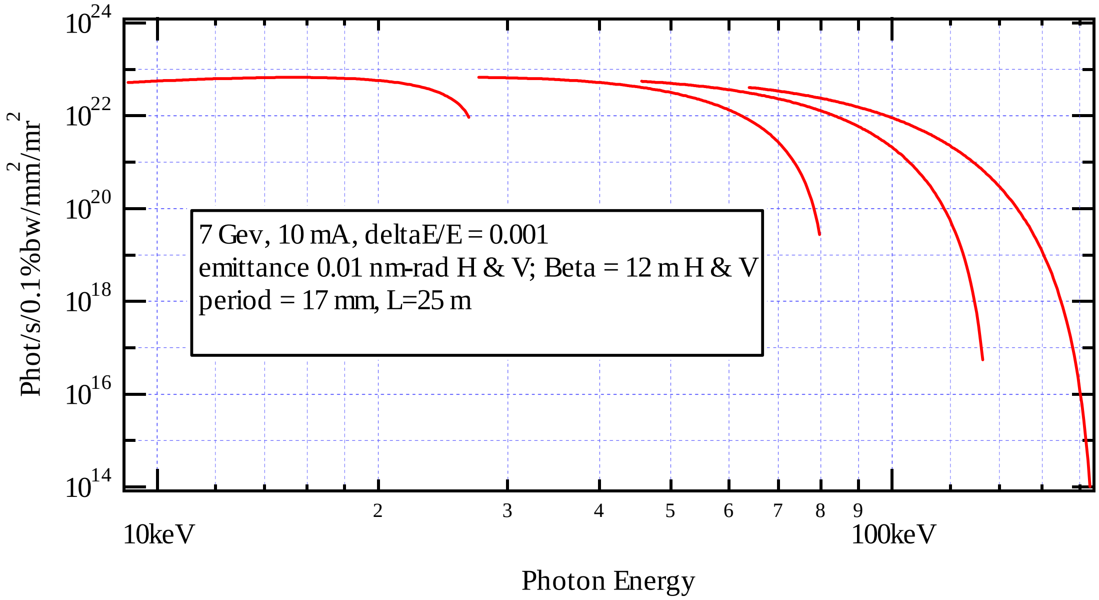
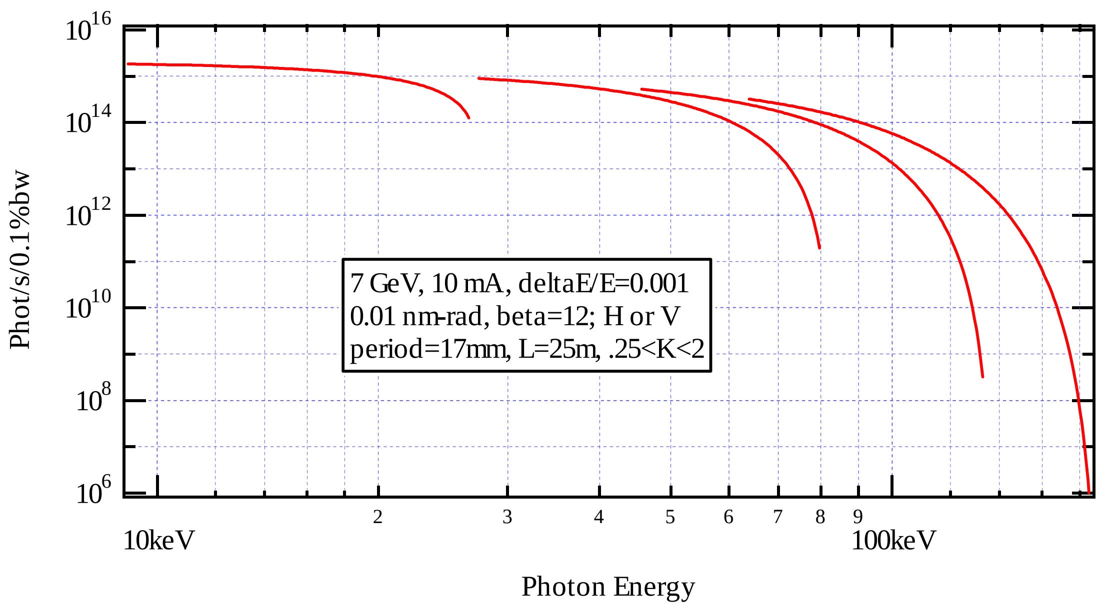


Figure 3. Tuning envelope of undulator flux for various undulator sources -- See explanation following the Tables.

Appendix 2: Low Current, Low Emittance ERL

A major advantage of the ERL is that the machine emittance is largely determined by the photoinjector. Photoinjectors with very low emittances are feasible if the average current is small. The possibilities are stunning. The following examples are for an average current of 10 mA and a geometric emittance of 0.01 nm-rad. This is near the edge of present photoinjector feasibility. Note, however, that at 0.15 nm wavelength, the beams are fully transversely coherent.





By inserting short undulators into low beta (of order 1 to 2 m) sections of the ERL, beam sizes of 3 to 4 microns can be created for microfocusing experiments.