R&D Toward an Energy Recovery Linac at Synchrotron Light Source

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Synchrotron radiation (SR) sources have produced extraordinary advances in fields such as biology, chemistry, materials science, physics, and even in art and history. Storage-ring sources are continually being improved but have inherent limitations from the equilibrium emittances arising from many passes of the electron bunch around the ring. As we described in an earlier *SRN* article [1], an Energy Recovery Linac (ERL) source of X-rays can overcome many of these limitations to produce X-rays of high coherence and short pulse length, which can be focused down to a 1–10 nm round beam size.

The particle bunches from today's rings have a flat pancake shape in contrast to the very small round electron beam of an ERL. Typically for storage rings, the horizontal emittance is one hundred times larger in the horizontal than in the vertical, the bunch energy spread is larger, and pulse length is longer than for bunches from an ERL laser-driven injector, a consequence of the equilibrium conditions in a storage ring. Although undulator insertion devices are highly developed and produce bright X-ray beams, the highest possible spectral brightness is not being realized in rings because a larger,

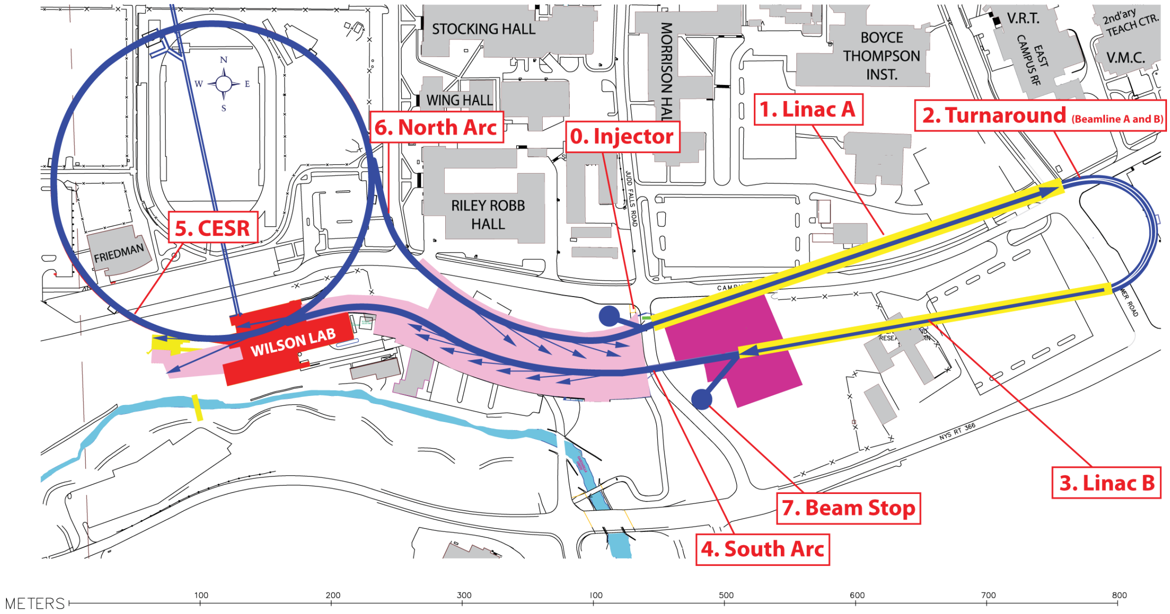


Figure 1: Schematic ERL layout incorporating the existing Cornell Electron Storage Ring (CESR). Electrons are injected (0) and are accelerated to the right through a 2.7 GeV linac (1, Linac A), then looped through a turn-around arc (2) and accelerated to the left through an additional 2.3 GeV linac (3, Linac B) to 5 GeV. Bunches then pass clock-wise around CESR (5). Bunches may be compressed to <100 fs (6) and feed more undulators before being uncompressed, and their energy is recovered in second passes though linacs (1) and (3). Finally, the now low-energy bunches are stopped at a Beam Stop (7) near the end of the second linac. A second injector could provide larger bunch charges at lower duty cycle for accelerator-physics investigation of seeded X-FELS, X-FEL-Os, or other advanced techniques of short X-ray-pulse creation. X-ray beamlines in new buildings (in light pink color) are indicated by blue arrows.

Table 1: ERL operating mode target parameters of high-flux, high-coherence, and short-bunch at high repetition rate

Operating Modes	A High Flux	B High Coherence	C Short Bunch North Arc	 South Arc
Energy (GeV)	5	5	5	
Current (mA)	100	25	25	
Bunch Charge (pC)	77	19	19	
Repetition Rate (MHz)	1300	1300	1300	
Geom. Emittance (pm) h/v	30	8	120/9	11/9
RMS bunch length (fs)	2000	2000	<100	1000
Relative energy spread (1E-3)	0.2	0.2	2	

asymmetrically-shaped electron beam has to be accomodated in the insertion devices (IDs).

Peak spectral brightness many orders of magnitude above that from storage rings is just now becoming available with hard X-ray Free Electron Lasers (XFELs) such as the LCLS [2], the European X-FEL [3], and the compact Japanese CSSC XFEL [4], etc. However, these XFEL beams have very different characteristics from storage rings. The X-ray pulses are extremely short, on the order of femtoseconds, and have exceedingly large numbers of photons per pulse, but with repetition rates many orders of magnitude lower than for rings. X-ray experiments with such beams are generally quite different than those in storage rings, and many focus on time-resolution or on “single-shot” detection that destroys the target and requires replacement with every X-ray pulse.

By way of contrast, ERLs [5,6] have complementary qualities to the XFELs. Superconducting radio-frequency (SRF) cavities are used

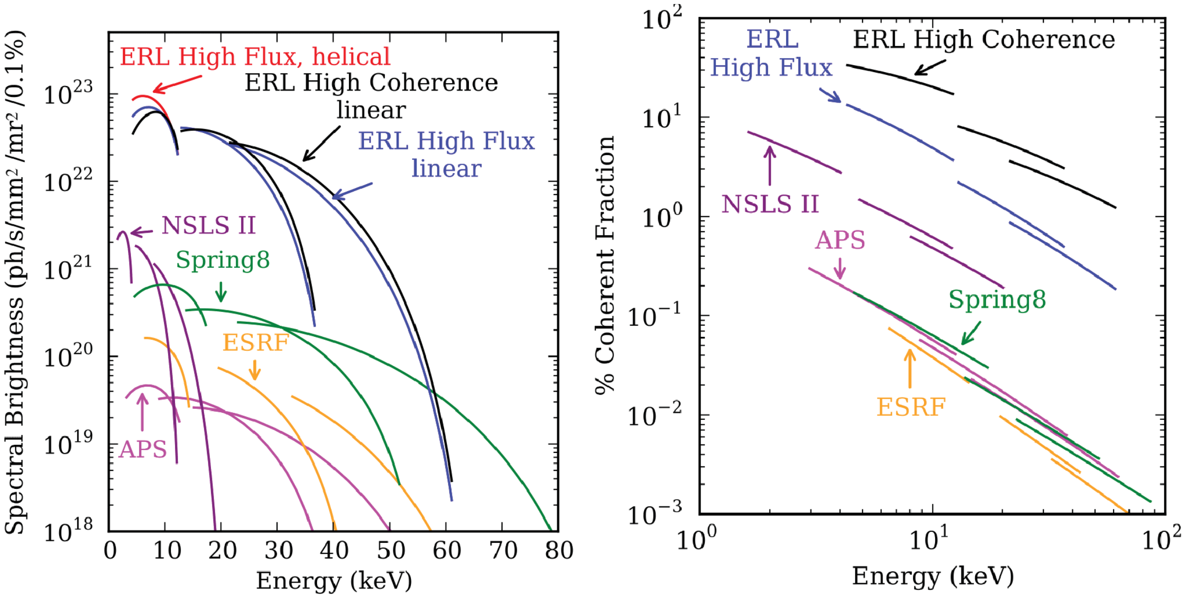


Figure 2: (Left) The average spectral brightness vs. photon energy [19] for the 1) ERL in Hi-flux mode (5 GeV, 100 mA, 30 pm round beam, 22 mm period ID) and ERL in Hi-coherence mode (5 GeV, 25 mA, 8 pm round beam, 22 mm period ID). Even higher brightness may be feasible with advanced undulators or advanced beam collimation; 2) Spring8 (8 GeV, 100 mA, 3.4 nm × 6.8 pm emittance, 3.2 cm period ID); 3) NSLS II (3 GeV, 500 mA, 0.55 nm × 8 pm, 14 mm period SC Undulator); APS (7 GeV, 100 mA, 2.5 nm × 20 pm, 3.3 cm ID). (Right) Coherent fractions vs. X-ray energy for the various sources are indicated.

to both accelerate and decelerate alternating bunches of particles, so the kinetic energy carried by the beam is recycled [7]. Because X-ray pulses occur at rates roughly a million times faster than in XFELs, but with pulses a million times smaller in intensity, the time averaged spectral brightness is comparable to XFELs. In consequence, specimens that suffer an instantaneously destructive 10^5 K rise in temperature per pulse in an XFEL suffer a millionth of this thermal rise per pulse in an ERL, which is a rate slow enough to allow heat to escape and the sample to accumulate a higher dose before it is damaged or destroyed.

In order to have a reasonably short linac, the accelerating field of the cavities must be rather high, and only SRF accelerators can simultaneously produce large fields and continuous operation. It is therefore the recent progress of high-field SRF cavities that makes this the opportune time to develop an X-ray ERL.

ERL experiments can be quite similar to experiments with storage rings, even though ERL technology offers a way around the limitations of storage rings, improving important parameters on many fronts, such as higher spectral brightness, smaller energy spread, more continuous time structure, more flexible electron optics, and shorter bunch lengths. ERLs use undulators to produce X-rays, as do storage rings, but the beam quality in an ERL can be greatly superior. The key attribute of an ERL is that the superb (low) emittance of the electron beam provided by a photoemission gun and an SRF injector linac can be preserved

Table 2: Comparative RMS Source Sizes and Divergences for the ERL extension of CESR and for various rings (from published source parameters) including radiative effects.

Machine	Horiz. Size (µm)	Horiz. Divergence (µrad)	Vert. Size (µm)	Vert. Divergence (µrad)
ESRF (4nm, 0.25% coupling), ID27	61	90	8.6	5.3
APS (2.5 nm, 1% coupling)	224	14.3	10.1	6.2
NSLS II (0.5 nm, 2% coupling)	32	18	5.1	9.2
ERL, 25 m und, hi-flux, 30 pm	13	3.3	13	3.3
ERL, 0.75 m und, hi-coher, 8 pm	1.6	13	1.6	13

because bunches make only one pass around the ERL layout, and thereby do not suffer the emittance degradation process that characterizes storage rings.

Several laboratories, most notably the Thomas Jefferson National Accelerator Facility (TJNAF), have demonstrated the feasibility of energy recovery for a low energy particle beam [8,9]. In 1999, Cornell scientists began exploring the possibility of building a high-energy, hard X-ray source using ERL technology, and by 2000 an international workshop at Cornell concluded that such a source would provide unique capabilities for X-ray-based science [10]. In 2001, a detailed Cornell/TJNAF study [11] began defining an ERL facility and pointed to R&D needed to assess practical feasibility. National Science Foundation (NSF) support for prototyping ERL technology began in February 2005. Simultaneously, a design for extending the existing CESR storage ring into an ERL, as shown in Figure 1, has been developed [12,13]. This accelerator concept has been presented in several international workshops, most notably in the 3rd international ERL workshop held at Cornell in 2009 [14].

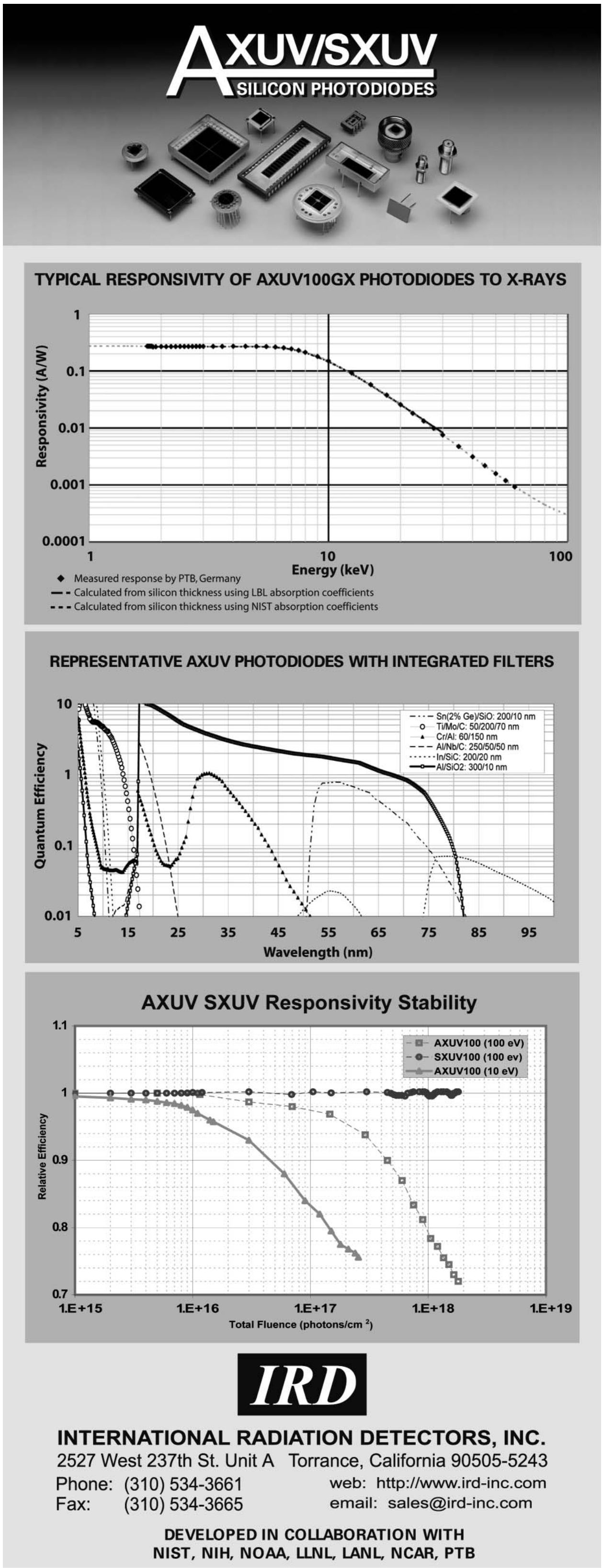
An ERL SR source is inherently very flexible and can be tailored to the requirements of scientific measurements. By its very nature, an ERL source can serve the same functions now served by 3rd generation storage-ring sources, albeit with vastly improved radiation characteristics. These improved characteristics enable experiments not feasible at any existing storage rings.

Outstanding features of an ERL include ultra-low emittance to enable near full transverse coherence, small, round source size, short native pulse length and high repetition rate, as shown in Table 1. The facility is very flexible and several dedicated running modes with specific bunch repetition rates and bunch charges could be envisioned. Here we specify the following three representative modes: (A) high-flux, (B) high-coherence, and (C) short pulse, low-charge modes.

In addition to the operating modes in Table 1, a second injector is envisioned that will work at a lower repetition rate, but simultaneous with X-ray operation in any of the above modes. A fast kicker will pluck specific bunches out from the main stream at 10 kHz. Bunch charge can be up to 1 nC, in which case the geometric emittance (h/v) is simulated to be 2600/37 pm for an RMS bunch length of <100 fs and a relative energy spread of 2×10^{-3}. These non-recovered electron bunches are available for tests on the first beamline in the south arc.

Additionally, the bunch structure can be changed to fit specific X-ray experiments. Because an ERL has linac-quality beams, the energy spread is very low and allows more efficient utilization of a larger number of undulator poles than is generally possible at a storage ring. Furthermore, an ERL does not have to optimize its electron optics for the large dynamic aperture needed to store beam for millions of turns. Consequently, the electron optics in ERL undulators are very flexible, and beam size and beam divergence can be fine-tuned to experimental needs in each insertion device section.

Table 2 compares source size and divergence parameters for two ERL operating modes with two existing and one future high-energy 3rd generation ring sources.



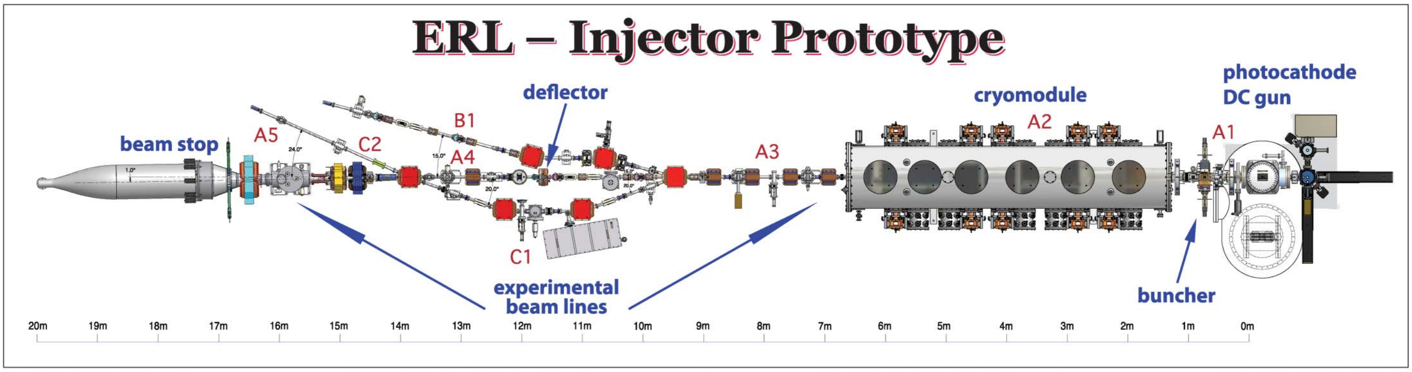


Figure 3: Layout of the now fully assembled Cornell high current injector prototype consisting of a DC photocathode gun, followed by a buncher cavity, and then an injector cryomodule containing five two-cell SRF cavities at 1.3 GHz that can accelerate beam to 5 to 15 MeV. The subsequent beam lines are for electron beam characterization and one ends in a 1 MW-capable beam stop (dump).

The spectral brightness and transverse coherent fraction in Figure 2 both scale inversely with the product of the transverse emittances, which is why small ERL emittance is so significant. Small emittances also facilitate the production of intense nanobeams. Micron X-ray beams have been a great success of 3rd generation SR sources [15]. However, storage rings are limited by beam emittances that are much larger horizontally than vertically, as shown in Table 2, making their beam diffraction limited only in the vertical direction and producing typical intensities of order 10^{12} X-rays/sec per square micron. ERLs, on the other hand, are nearly diffraction limited in both directions. With suitable X-ray optics now under development in several labs, potential exists at the ERL for hard X-ray beams with ~10^{11} to 10^{12} X-rays/s per square nanometer [16], a potential million-fold gain in flux density [17].

The one-pass nature of the ERL avoids destruction of injector beam properties. The native bunch length from the electron photoinjector of approximately 2 picoseconds is already much shorter than for existing storage ring sources and will be available simultaneously to all X-ray beamlines at an ERL. In addition, magnetic bunch compressors could be used to provide much shorter pulses at selected north-arc stations, as noted in Figure 1 and Table 1.

In 2006, scientists from across the globe assembled for six science workshops (high pressure science, ultra-fast phenomena, difficult materials science, soft matter and nanoscience, biology, and opportunities with nanometer beams) to explore potential applications for an ERL hard X-ray source [18]. It was concluded that there are outstanding possibilities in each area. We propose to

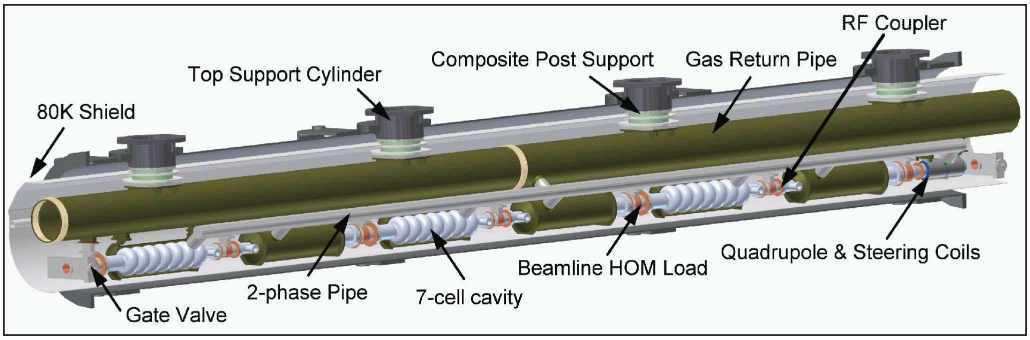


Figure 4: A cut-away CAD model showing the main features of the 9.8-meter-long Cornell ERL Main Linac cryomodule. There are 6 cavities in series (three of which are visible in this cut-away sketch) with 7 cells making up each cavity. The cryomodule is being designed to operate at 1.8 Kelvin and for 16 MeV/meter accelerating gradients. The design will benefit greatly from the developments accomplished for the soft X-ray FEL, FLASH, and the European XFEL at DESY.

continue the scientific dialog by holding a series of six two-day workshops on the Cornell University Campus in 2011 to explore the scientific potential of a continuous-duty (or CW) source of greater than a 1 MHz repetition rate, coherent (fully diffraction-limited), hard ($\lambda \le 1.5$ Å) synchrotron X-ray source.

A recent paper [19] highlights some strengths of ERLs relative to X-FELs in a variety of coherent and nanobeam experiments where the sample must be repetitively probed or where the samples are unique and the requisite scattering information cannot be obtained with a single X-FEL pulse. ERL technology is young. The parameters presented in Table 1 may be expected to improve as the technology develops.

The main ERL development work so far has been funded by the National Science Foundation, Cornell University, and New York State. We report below on this specific R&D progress for the key required ERL technologies: 1) DC photo-cathode guns, 2) SRF injectors, 3) CW linacs, and 4) X-ray undulators.

DC photocathode gun and laser development

A DC photocathode gun (Figure 3) operates by using a laser-driven photocathode to produce electron pulses that are then accelerated to relativistic speed by a constant electrical potential between the gun's cathode and ground potential. The Cornell photo-cathode gun is an extension of the TJNAF design, and presently is operated at 350 kV. A new gun insulator is being constructed, which is expected to extend operation to 600 kV for better control of space charge and to keep the beam size small. The main limit to high voltage in DC guns is field-emission. Field-emitted electrons that strike the ceramic insulator that serves as both electrostatic and vacuum barrier might lead to local charging and heating of the material, and might result in ceramic puncture and vacuum leaks.

Two solutions to this problem are known: metal-shielded segmented ceramics, which preclude field-emitted electrons from reaching the ceramic segments in the first place, and an inverted gun in which the ceramic is no longer the main vacuum envelope. Cornell and KEK are

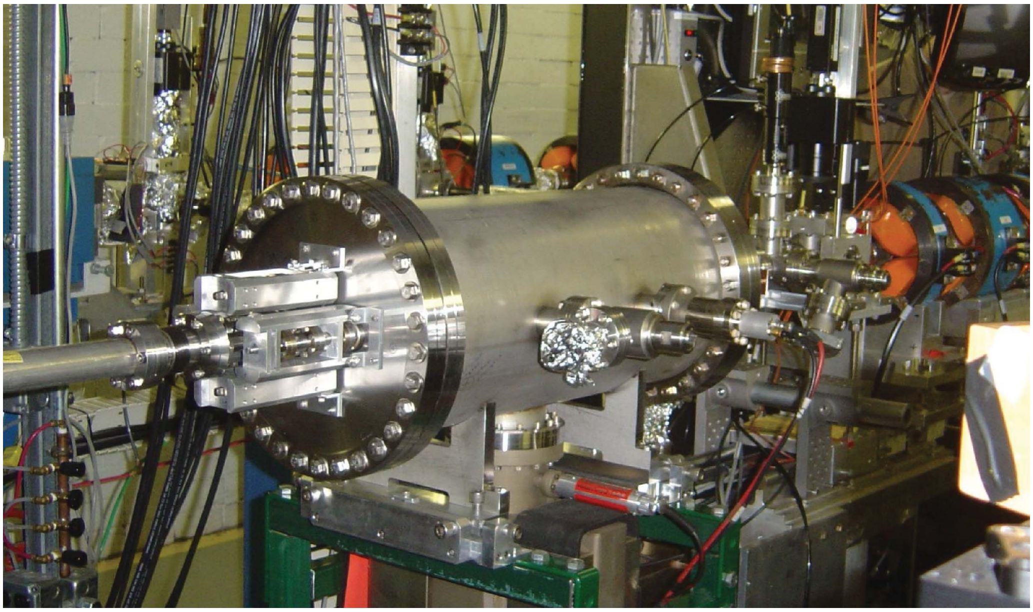


Figure 5: Cornell's prototype in-vacuum Delta undulator shown on the BNL ATF test stand. The test with 60 MeV electrons successfully produced circularly and linearly polarized infrared radiation as predicted.

pursuing the first approach, while TJNAF is exploring the inverted gun option.

Low-emittance photocathodes are the key to generating bright electron beams. Cesiated GaAs is known for low thermal emittance, and initial operation has used this material. Other prominent choices include multi-alkali photocathodes, such as CsK_2Sb, which are known to have greater longevity, albeit at a higher thermal emittance.

A Yb-fiber based laser oscillator and amplifier system offers the best possibilities to produce the 1300 MHz, high average power optical pulse train that is needed for the ERL. Yb-fiber lasers are only now beginning to come onto the commercial market, and none of these presently meet the requirements, so Cornell is developing its own laser system. The laser must deliver transverse and longitudinal-shaped high power optical pulses at 1.3 GHz. A 50 MHz fiber laser is now in routine operation, and the 1.3 GHz system is just now being commissioned. The goal is a photocurrent of 100 mA.

Superconducting Radio Frequency Injector

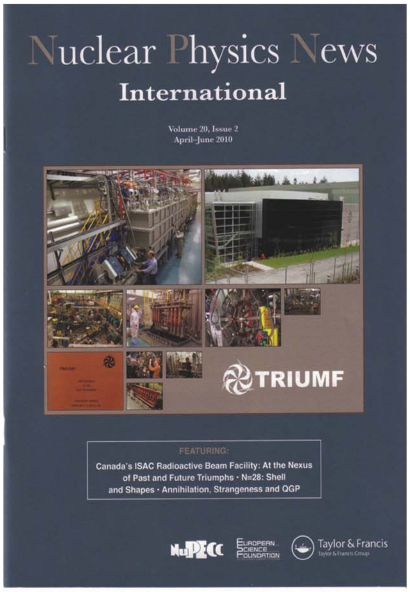
The SRF injector cryomodule is designed to accelerate the electron beam from the photo-cathode gun to 5 to 15 MeV in a prototype injector (Figure 3). The accelerating beam power is limited by symmetrical power couplers attached to the cavities, each capable of handing 50 kW. These are driven by custom klystrons capable of 120 kW of CW output power at 1.3 GHz. Five pairs of couplers allow beam currents of up to 100 mA at 5 MeV and up to 33 mA at 15 MeV. So far beam currents up to 25 mA have been achieved unbunched behind the DC gun, and 13.5 mA have been bunched and accelerated through the SRF injector linac for short periods of time, limited by instabilities of the HV gun power supply. An improved HV supply is now installed and is being commissioned.

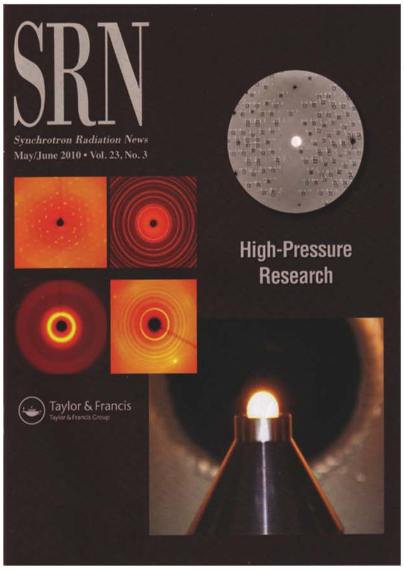
Main SRF linac

The ERL requires a main linac section (as opposed to the injector linac) to be capable of CW operations at high current with 2 ps short bunch lengths while preserving emittance and dealing effectively with higher order modes. The main linac of the Cornell ERL would be composed of 64 cryomodules, each containing 6 superconducting cavities of seven niobium cells in a row and one superferric quadrupole and steering corrector package per cryomodule.

A full 9.8-m-long linac cryomodule prototype is currently under design (see Figure 4) and will be fabricated and tested at Cornell during the next few years. The program includes development of requisite cavities, higher order mode absorbers, beam position monitors, in-vacuum cryomagnets, RF amplifiers and power couplers, and cool-down procedures.

Cryomodule component development and testing is being done collaboratively with the Helmholtz Zentrum Berlin and STFC's Daresbury Laboratory to demonstrate highly stable operation of the





cavities while requiring only minimal RF power to maintain the RF field in the cavities. A major focus of the R&D activity will be on reliability and the efficient operation of the SRF cavities in the ERL main linac.

X-ray undulators

X-ray undulators are needed to produce ultra-high spectral brightness, coherent X-ray beams from an ERL. The small round ERL electron beam makes it possible to design very small, compact, symmetric undulators whose magnetic field strengths are only limited by the maximum magnetization strength of available materials. Being compact and 4-fold symmetric with magnetic arrays at 90 degree intervals around the beam axis, the amount of magnetic material required and the associated physical supports can be dramatically reduced relative to devices built for storage rings, resulting in simpler, lower cost insertion devices.

The Delta undulator [20,21] is a pure permanent magnet (PPM) undulator that can operate as a helical or planar undulator. In the helical mode, only first harmonic radiation exists on-axis, opening up the possibility of optics-free monochromatic beamlines. This will revolutionize certain types of experiments such as coherent X-ray imaging. With no optics in the X-ray beam, the X-ray source and beamline components can be designed so that nearly every photon produced in the forward cone of the ID hits the specimen and is useful for data collection. Wave front degradation can be completely avoided by bypassing conventional front-end and X-ray optics components such as windows, mirrors, and monochromators.

Circularly polarized radiation behaves like unpolarized radiation in conventional scattering experiments (and those not utilizing magnetic materials or chiral molecules), removing constraints imposed by horizontal polarization normally assumed at storage rings. Analysis of experiments that involve scattering in an arbitrary plane (e.g., crystallography) should be simplified with circularly polarized radiation.

In the Delta design, the undulator gap is not changed; rather, the field is adjusted by sliding the magnetic arrays relative to one another along the electron beam direction. The range of motion required to change the polarization of the X-ray beam from circular to linear is only one quarter of the undulator period. In linear mode (when vertical and horizontal fields are in phase), the field strength on the beam axis is $\sim\sqrt{2}$ larger [22] than for a conventional planar undulator with the same gap of 5 mm.

The goals of the pure permanent magnet development program include: 1) build and test a 30 cm prototype ID; 2) based on this experience, build a full-scale 2-meter-long prototype and test its performance at a high energy linac. A prototype 30-cm-long Delta undulator has been completed (Figure 5), and recently successfully tested at the Brookhaven National Lab Accelerator Test Facility [23]. Design work is now proceeding on the 2-meter-long version. For the full-fledged ERL facility 5 m and 25 m long undulators are anticipated. Due to the low energy spread in the ERL electron beam, radiation from many undulator poles can add coherently so that 25m undulators of 20mm period become useful. Due to ultra-small emittances the forward cone is diffraction limited, even for first harmonics of up to 10keV.

Summary

Energy Recovery Linacs are in development in a number of laboratories across the world for applications ranging from accelerator beam cooling and electron-ion colliders to soft free electron lasers and hard coherent X-ray sources. Cornell University is focused on R&D for a transversely coherent, hard X-ray source. R&D is proceeding on critical parts of the technology (e.g., the injector, main linac, and undulators). A many hundred page Project Definition Design Report has nearly been completed for a 5 GeV, 100 mA large-scale facility to replace the existing storage ring source, CESR. We anticipate that this report will be submitted to the National Science Foundation in 2011. Given adequate support, it would be possible to start construction of the full-scale facility within a few years.

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