

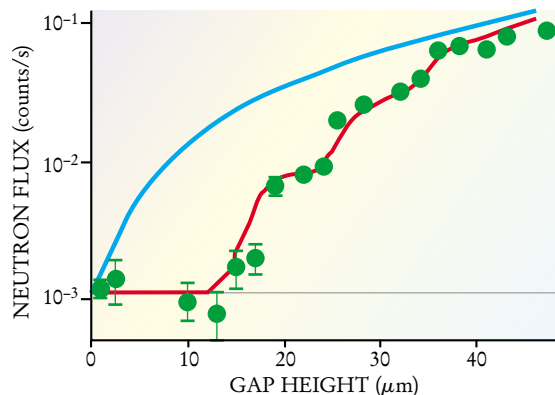


FIGURE 3. TRANSMITTED NEUTRON FLUX as a function of gap height in the Laue-Langevin experiment shows a clear threshold near 15 μm and indications of steps at larger gap heights, consistent with the quantum-mechanical prediction (red curve). The blue curve is what one expects simply from the increasing phase-space acceptance of the gap. The horizontal line indicates the detector's background level. (Adapted from ref. 1.)

any quantum effects. The data clearly favor the quantum-mechanical prediction, though the extremely limited statistics can only hint at quantum steps beyond the first. “Our experiment had to select only one in a billion incoming reactor neutrons,” Nesvizhevsky told us.

The experiment's energy resolution is not limited only by statistics. The quantum-mechanical uncertainty relation

$$\Delta E \Delta t \gtrsim \hbar$$

also comes into play. The 0.01 s it takes a neutron to traverse the 10-cm-

long gap in this experiment limits the energy resolution of the quantum-well eigenstates to 0.07 peV. One could, of course, do a hundred thousand times better if one could keep the neutron trapped in the well for its full lifetime—about 15 minutes.

If the horizontal and vertical neutron motions are sufficiently decoupled, the transmission curve in figure 3 should be independent of the neutron beam velocity. And that is indeed what the experimenters find. Furthermore, the fact that the gap, even when it's less than 10 μm high, has no difficulty transmitting visible light is evidence that its opacity to neutrons at that height is really due to the neutron ground-state energy in the gravitational well. The width of the ground-

state wavefunction is, roughly speaking, the de Broglie wavelength corresponding to the vertical momentum component of that state. The much smaller de Broglie wavelength corresponding to the horizontal beam momentum, on the other hand, plays no role at the threshold in figure 3.

“For precision experiments in search of new, unpredicted effects,” says Nesvizhevsky, “we will have to find ways of making the neutrons spend more time in the gravitationally bound states. And, of course, we'll need a significant increase in the available density of ultracold neutrons.”

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An Energy Recovery Linac Is Seen as a Bright Idea

The popularity of synchrotron radiation facilities continues to grow, spurred by their usefulness for studying the structure and dynamics of materials ranging from membrane proteins to nanocomposites. In response to the growing demand, the newest synchrotron storage rings provide more brilliant radiation beams—that is, beams having greater fluxes of photons per unit area and solid angle—and they allow more room for arrays of magnets that wiggle the electrons, causing them to generate highly collimated beams of radiation.

So where to go from here? Many types of experiments require shorter, more flexible pulses and greater brilliance. For example, pulses as short as 100 femtoseconds would enable studies of structural dynamics, and brighter, better collimated beams would allow the use of smaller samples.

To move forward, researchers at a number of accelerator centers are eyeing an x-ray light source in which electrons are accelerated by what's known as an energy-recovery linear accelerator (ERL) rather than by a synchrotron.¹ Perhaps, they hope, an ERL can produce electron beams with shorter

Will some future light sources be based on linear accelerators rather than synchrotron storage rings?

pulses and smaller angular spread—that is, lower emittance—than is possible in a synchrotron (emittance is the product of the beam width and its divergence). Smaller emittance contributes to greater brilliance, both in the electron beam and in the radiation it produces.

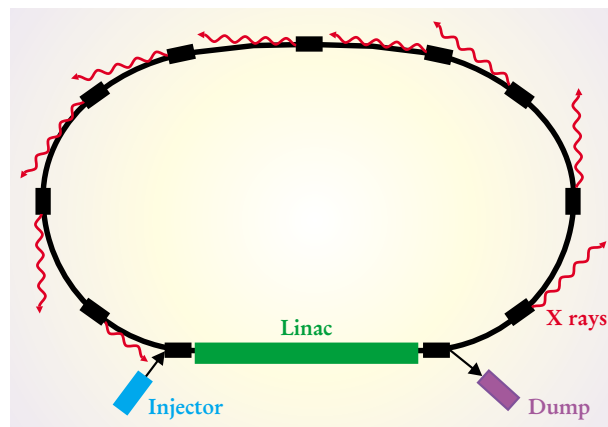
Proponents of ERL light sources have been buoyed by the successful performance of an ERL-based, infrared free-electron laser (FEL) with high average current,² which has been operating at the Thomas Jefferson National Accelerator Facility since 1999. Researchers face considerable challenges to scale up to the much higher electron energies and currents envisioned for x-ray ERL light sources. But, as Sol Gruner, director of the Cornell High-Energy Synchrotron Source, put it, the Jefferson Lab FEL has at least shown that the concept is not a “pie in the sky” idea.

In today's synchrotron radiation

facilities, bunches of electrons race around a storage ring, emitting radiation each time the electrons are bent by a dipole magnet or subjected to the oscillating magnetic field of devices known as wigglers and undulators. Once the electron beam is brought up to the target energy and stored, only a small amount of energy from a radio-frequency (RF) field is required to replace what's lost through the emission of synchrotron radiation.

Recycling energy, not electrons

Whereas a storage ring continually recycles the electron beam, an ERL recycles the energy but not the electrons. As shown in the figure on page 24, an electron bunch is injected from a photocathode gun into a linear accelerator (linac). If the bunch enters at just the right phase, it gains energy from the resonant electromagnetic field in the linac. The electron bunch is then looped back through a path whose length is adjusted so that the bunch re-enters the linac out of phase with the accelerating field and is slowed. Energy is thus given back to the electromagnetic field, and the spent electrons are dumped. One can make a light source from this design



AN ENERGY-RECOVERY LINAC light source is shown schematically. Electron bunches from the injector are accelerated in the linac and guided by magnets around the arc. As they pass through the undulators (black boxes), the electrons generate x rays, shown in red. Electron bunches return to the linac out of phase with the resonant field and give energy back. The spent electrons then go to the beam dump.

by inserting dipoles, wigglers, and undulators in the looping beam path.

In a storage ring, the beam characteristics are those reached at equilibrium, after the electron bunches have circled the ring thousands of times. By limiting electrons to one pass (or perhaps just a few passes) through a linac, machine designers hope to provide electron pulses whose properties are limited only by the quality of the photocathode gun and linac. It should be possible to have much lower emittance and beam pulses as short as 100 fs, compared to the 20- to 500-picosecond lengths found in storage rings. The ERL design also allows much greater flexibility in tailoring the pulse. As electron guns improve, it should be easy to upgrade the ERL.

An old idea

Maury Tigner (Cornell University) suggested the ERL concept³ for a particle collider in 1965. In the past decade, Gennady Kulipanov and his colleagues at the Budker Institute for Nuclear Physics in Novosibirsk, Russia, have been championing ERLs as x-ray sources.⁴ The possibility of energy recovery is more feasible today because of the steady development since the 1970s of superconducting linacs, which are greatly preferred for energy recovery schemes because of their low losses.

Several groups have undertaken some low-level demonstrations of the ERL concept over the years, but Jefferson Lab's FEL has taken the ERL concept farther down the feasibility path by combining a superconducting linac with an undulator in the recycling loop and by showing that nearly all the energy put

into beam acceleration can be recovered. The linac for the FEL imparts an energy of 48 MeV to the electrons, and produces up to 5 mA of current. Frederick Dylla, head of the FEL, said that the machine is now being upgraded to 160 MeV and 10 mA.

The challenges ahead

Some of the ERL-based light sources now being proposed would feature GeV-scale linacs, capable of producing low-emittance currents of 100 mA. Scaling up to these energies and currents will require great strides in the design of the electron guns, or photoinjectors, that provide the electrons and in the superconducting linacs that accelerate them. The payoffs are sufficiently promising, however, to have elicited considerable interest from groups around the world.

The research efforts will focus on the critical areas of photoinjectors and linacs. Researchers are working on two possible approaches to the design of the gun: one using a DC electric field and the other, an RF field. They are also trying to perfect linacs that have very low energy losses and that are able to operate continuously rather than in a pulsed mode. The ERL designs to date have focused on the RF cavities being developed for the TESLA test facility at the German Electron Synchrotron Facility (DESY) in Hamburg.

One of the three US groups with ERL proposals is a collaboration of researchers at Cornell and at Jefferson Lab.⁵ Their long-term goal is a high-energy (5–7 GeV), 100-mA ERL light source. However, the collaborators think the technology must be explored on a prototype before anyone commits to a specific design. This group has proposed to build, over the next five years, a prototype with a DC electron gun capable of providing the full 100 mA but with a 100-MeV linac.

A second US proposal, dubbed the Photoinjected Energy Recovery Linac

(PERL), comes from Ilan Ben-Zvi, James B. Murphy, and coworkers at the National Synchrotron Light Source at Brookhaven National Laboratory.⁶ They plan to develop an RF photoinjector that can run continuously, and are aiming at energies of 3 GeV and currents of 100–200 mA. The Brookhaven team sees a synergistic role for PERL in connection with Brookhaven's existing accelerators. For example, PERL might supply charges for high-energy electron cooling of the ion beam in the Relativistic Heavy Ion Collider; or electrons from PERL might be made to collide with the ions from RHIC.

The third US group studying ERLs is at the Lawrence Berkeley National Laboratory. There, John Corlett and his colleagues have been interested in using femtosecond-scale pulses to study ultrafast molecular dynamics. They are proposing a facility based on existing technologies that can produce high fluxes of femtosecond x-ray pulses, but not necessarily at high repetition rates. To get the very short radiation pulses, they will use a specialized technique developed by team member Alexander Zohlents. The Berkeley plans call for a 600-MeV linac, with electrons passing through it four times to get up to a final energy of 2.4 GeV before the recycling stage.

In the UK, researchers at the Daresbury Laboratory are working on an ERL facility dubbed 4GLS, for Fourth Generation Light Source. It will feature a lower-energy (600 MeV) linac than proposed by two of the US groups.⁷ The electrons would pass through FELs as well as undulators to provide multiple photon sources ranging from the far-infrared to the extreme ultraviolet and soft x-ray regions. According to Daresbury's Elaine Seddon, the project occupies an intermediate position between the existing radiation facilities and the GeV-scale x-ray FELs, which require a giant leap in technology.

Kulipanov and his Budker colleagues are working on a machine they call a multiturn accelerator-recuperator source (MARS), which, they hope, can be more compact and less expensive than other proposed ERL projects. In Germany, Andreas Magerl of the University of Erlangen is leading an initiative involving several universities to build a 3.5-GeV, 200-mA state-of-the-art synchrotron light source; in a second phase, they will incorporate an energy-recovery injector to gain the beam characteristics of a next-generation light source.

Alternative approaches

An ERL is not the only idea for new light sources. Researchers at the European Synchrotron Radiation Facility in Grenoble, France, for example, are studying a plan they call the "ultimate" storage-ring-based light source. The machine would be built using proven technology, but the ring would be far larger than existing storage rings, to reduce the transverse beam emittance, allow for higher brilliance, and make room for an increased number of beamlines. Annick Ropert of ESRF thinks that this plan will fulfill the needs of the majority of users, offering them a large, constant, and stable flux of high-energy photons in the 5–50 keV range, although with no specific capabilities for producing very short pulse lengths.

A very different kind of light source under development is an x-ray FEL, which is based on self-amplified spontaneous emission and which would produce highly coherent radiation in very intense, femtosecond-scale pulses. DESY has a prototype x-ray FEL that's part of the test facility for its proposed 30-km TESLA collider, and SLAC has proposed the Linac Coherent Light Source. (See the article on FELs by William B. Colson, Erik D. Johnson, Michael J. Kelley, and H. Alan Schwettman in *PHYSICS TODAY*, January 2002, page 35). These proposed x-ray FELs could open the door for totally new applications. By contrast, the ERL light source and the ESRF's ultimate storage ring are expected to enhance many of the same kinds of experiments that are going on at synchrotron radiation facilities today. Proponents of an ERL-based light source see an x-ray FEL as complementing rather than competing with ERLs.

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