FUTURE SRF-LINAC BASED LIGHT SOURCES: INITIATIVES AND ISSUES*

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Abstract

The light source communities have become more and more aware of the substantial advantages of superconducting linear accelerators for the production of the brightest and most intense electromagnetic radiation. The basic needs of these researchers are reviewed. Currently contemplated light sources driven by SRF linacs are presented together with their unique features and the issues that must be addressed to bring them to fruition.

WHAT DO USERS WANT?

The history of accelerator-based light has seen ever increasing demands on the brightness and intensity of the photon sources. The driving desire is to probe matter at substantially finer length and time resolutions, and the next scientific frontier is where physical, chemical, and biological systems can be viewed on their characteristic temporal, spatial, and energy scales—femtoseconds, nanometers, and millivolts. Dynamics will be the key theme of the future, supplanting the studies of static systems that have been the bread and butter of today's light sources. The science enabled includes, for example, delineating the elementary steps of catalysis and chemical transformations, understanding how correlations of electrons and spins create high T_c superconductors, and elucidation of the remarkable functionality of complex biological systems [1]. In addition, high average photon flux density is often required, whether to perform photon-in/photon-out experiments on condensed matter systems or to study multi-photon atomic physics or to develop speed-of-light weaponry for missile defense [2, 3].

These user requirements translate into accelerator beam specifications, and these specifications are well matched to the capabilities of superconducting linacs. Short pulses (subpicosecond) are central to many of the next generation light source initiatives. While this parameter range is difficult, if not impossible, for storage rings, it is typical of linear accelerators. With their weaker wakefields from relatively larger apertures, SRF linacs can maintain low energy spread at high bunch charge more easily than room temperature linacs. The superb emittances generated by state-of-the-art electron guns, much less than what is possible in reasonably sized storage rings, can be preserved in SRF linacs. For FELs, a linear accelerator is preferred over a storage ring because the FEL interaction is disruptive of the beam quality and fresh beam is continuously needed; for ERLs, energy recovery is most effective in a superconducting structure with its low losses. CW operation allows for the required high average beam power demanded by many applications. In addition, a typical light source user is part of a small research team, and there is a premium on high repetition rates to allow many simultaneous experiments to keep the cost/experiment-hour comparable to that of today's storage rings.

SOFT X-RAY FELS

SASE and Seeded FELs

First generation FELs such as LCLS and FLASH are based on the principle of Self Amplified Spontaneous Emission (SASE) which produces only transversely coherent radiation. Since the start-up radiation is generated from shot noise on the particle beam, the output radiation is noisy and temporally incoherent. Shot to shot reproducibility is poor. A key goal for future X-ray FEL light sources is to generate fully coherent radiation, both transversely and longitudinally (temporally). For soft X-rays several seeding approaches are available. As developed at BNL [4], seeding with a conventional (typically IR) laser starts the FEL process by modulating the energy of the electron beam on passage through an undulator tuned to the laser wavelength. After passing through a buncher, higher harmonics in density are generated which are amplified and radiate in a following undulator tuned to a harmonic. The resulting radiation is temporally coherent, mimicking the coherence of the conventional laser seed. Furthermore, this process can be cascaded to offer several stages of up conversion in photon energy. Since these original experiments, the process of high harmonic generation (HHG) [5] using IR laser ionization of a noble gas can produce sufficient power to seed at much shorter wavelengths, ~ 40 nm. An additional advantage of seeding is that the FEL can be turned down in intensity, since it need not be driven into saturation to generate reproducible radiation.

Early designs called for a so-called "fresh bunch" technique, where substantial beam degradation develops as the FEL reaches saturation in a cascade stage. To continue cascading, the timing of the longer electron bunch is slipped relative to the photon pulse to offer previously unperturbed electrons for continued FEL amplification. Since the overall peak current must be high (~1 kA), nanocoulomb bunch charge was required. More recently, approaches utilizing low gain sections and HHG have shown that keV photons can be generated with lower bunch charge [2]. See Fig. 1. This enables, for a given average current (typically of the order of a milliampere), more simultaneous users to be supported.

Another method, echo enhancement [6], utilizes two stages of laser seeding to develop filamentation of the electron bunch. This process generates very high

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harmonic content and enables production of keV photons with few if any cascades. See Fig. 2.

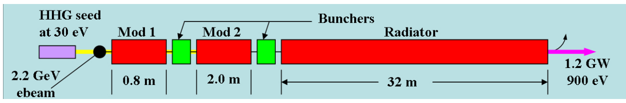

Figure 1: Cascading in WiFEL with 200 pC bunch charge.

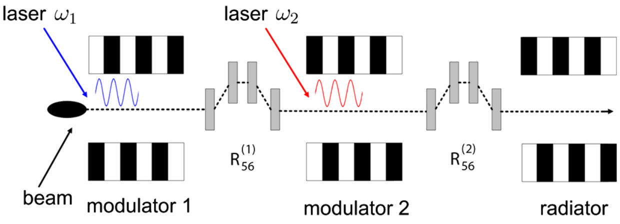

Figure 2: Echo enhancement configuration [6].

Soft X-ray FEL Initiatives

There are three major projects on the drawing boards for soft X-ray FELs using SRF linacs: the Wisconsin FEL (WiFEL), the UK New Light Source Project (NLS), and the future light source at Berkeley Lab [2, 7, 8]. Given that all projects aim at ~1 keV photons in first harmonic and serving multiple users, the linac energies (2.2-2.4 GeV) and layouts are similar. For example, see Fig. 3. Differences can be found in assumed repetition rates, cascading schemes, undulator gap/period assumptions, and auxiliary capabilities.

The common specifications are:

1. High brightness (> 10^{11} photons/pulse)
2. Transform limited output--both transverse and longitudinal
3. Short pulses, tens of femtoseconds, with potential upgrades to subfemtosecond performance
4. Energy resolution of meV or less
5. Tunability in photon energy and polarization
6. Synchronization with short pulsed lasers

Pulse repetition rates for these projects vary from kilohertz to several megahertz. Rates of a kilohertz represent present technology, whereas megahertz rates depend on the success of R&D programs on CW electron guns and high power seed and photocathode lasers. Both low frequency room temperature and high and low frequency SRF guns are under consideration. Ancillary devices may include terahertz sources based on coherent synchrotron radiation from short bunches.

Cascading schemes for the NLS and WiFEL use the low gain approach of Fig. 1, with typical bunch charges of 200 pC. The LBNL design may invoke the enhanced SASE scheme (ESASE) [9], with laser induced bunch compression to generate spikes with high harmonic content, or the echo scheme discussed earlier.

Recirculation has been considered to reduce costs, but beam quality preservation may be marginal in the recirculation arcs because of CSR and wakefield degradation. Further modelling and experimental work needs to be done to make a convincing case for this approach.

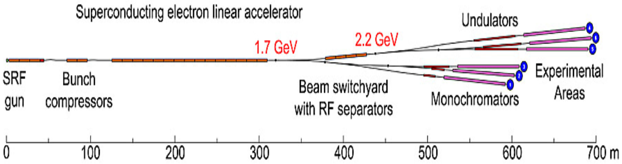

Figure 3: WiFEL layout

The beam currents envisioned for these light sources, of the order of one milliampere, are well within the range of current technology. RF phase and amplitude stability are tight but feasible (typical numbers are 0.02% and 0.03°). The baseline approaches do not require recirculation, so high order mode damping is much less stringent than in energy recovery linacs (ERLs), which also must accelerate substantially higher average currents. The designs invoke existing L-band technologies, either variations on the Jefferson Lab/Cornell cavities or CW versions of the DESY cavities. This choice has been made for the practical reason of likely availability. However, since bunch repetition rates are megahertz, not gigahertz, other frequency choices could be considered. A full study of the optimal frequency, both for cost and beam dynamics considerations, has not yet been performed.

TOWARD TEMPORALLY COHERENT HARD X-RAY FELS

For harder X-rays (> 1keV), the seeding approaches discussed above become inefficient because of the many stages of up conversion required. Current projects, including the European XFEL [10], utilize SASE. For temporal coherence one might consider simply using a soft X-ray seeded FEL in saturation as the seed for a hard X-ray FEL, but this requires real estate and fresh bunches. Two other approaches, self-seeding [11] and X-ray oscillators based on crystal cavities [12] are other avenues for better temporal coherence and spectral purity

Self seeding consists of two undulators separated by a magnetic chicane and a monochromator. See Fig. 4.

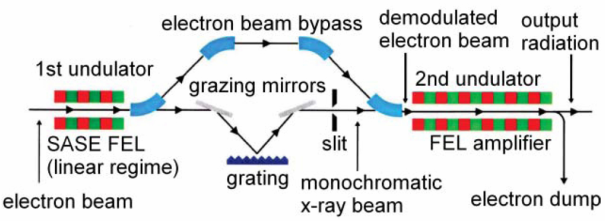

Figure 4: Self seeding configuration from [11].

In the self seeding approach, SASE radiation not in saturation is filtered by a monochromator and used to seed a subsequent FEL. The bypass removes the beam modulation generated in the first undulator and equalizes the time delay of the monochromator. Spectral brightness can be increased by a factor of 100 over straight SASE.

In an X-ray Oscillator FEL (XFELO), Figure 5, a low-loss Bragg crystal cavity and low charge bunches at megahertz repetition rates with very low emittance are used.

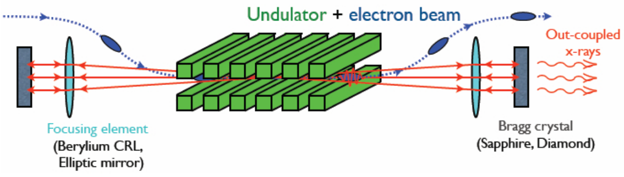

Figure 5: XFELO configuration [12].

Beam energies of ~7 GeV are required for 1Å output. The pulses are temporarily and transversely coherent, with an rms bandwidth of about 2 meV and rms pulselength of about 1 ps. Compared to SASE from a high-gain FEL, the pulse intensity of an XFELO is lower, but the XFEL spectrum is narrower by a larger factor, giving an overall brighter photon beam.

The bunch charge is ~20 pC with a normalized emittance of ~ 0.1 mm-mrad. The optical cavity length requires the bunch repetition frequency of order one megahertz. In combination, this would allow many such oscillators to be driven by a one milliampere average current linac. Energy recovery is not required, although recirculation may reduce costs significantly if emittance degradation of these high quality but low charge bunches can be minimized. One possible layout is shown in Fig. 6.

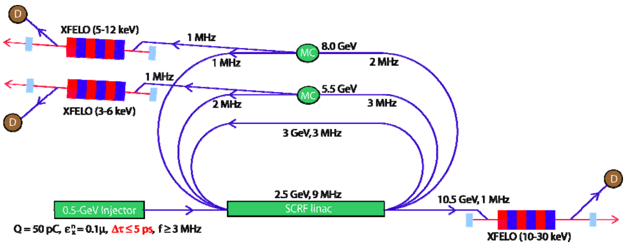

Figure 6: A multi-XFELO facility with recirculation [12].

SPONTANEOUS EMISSION ERLS

The emittance of electron storage rings results from an equilibrium reached between the damping and the quantum fluctuations induced by the synchrotron radiation process. Achieving sub-nanometer geometric emittances, especially at higher energies, is difficult. Superconducting linacs driven by photocathode sources appear to be able to better this performance [13]. To achieve significant flux requires acceleration of currents of order 100 mA, which requires energy recovery for reasonable power costs. A 5 to 7 GeV, 10 to 200 mA ERL machine could produce electron beams of a few microns diameter with very low emittances (8 to 100 pm) in both the horizontal and the vertical planes, if in practice source performance meets theoretical estimates. With a lower beam energy spread than found in storage rings, longer undulators (possibly 25 meters in length) can be considered to produce ultra-high transverse brightness X-ray beams by spontaneous emission. The most mature design is that of the Cornell ERL. See Fig.7.

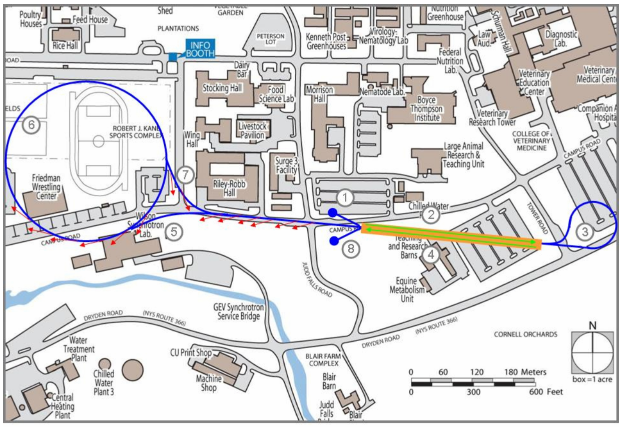

Figure 7: Cornell ERL. [14].

ERLs have also been considered for an upgrade of the Advanced Photon Source and for construction in Japan in collaboration between KEK, JAEA, ISSP, and other synchrotron radiation institutes. The peak and average transverse brightness of these sources do not match those of ultimate CW FEL sources, but offer the advantage of closely spaced, lower peak intensity pulses that more closely mimic storage rings.

As with CW FELs, the electron gun technology for ERLs has yet to be demonstrated. Average currents are at the 100 mA level rather than the milliampere level for FEL drivers. With recirculation at these currents, higher order mode damping becomes critical both for beam breakup and for ensuring dissipation of higher order mode losses outside the cryogenic environment. Halo, gas scattering, and ion trapping limits are being investigated.

ERLS FOR FELS ET AL.

Energy recovery linacs have been utilized successfully as drivers for FEL oscillators at longer wavelengths (IR), where beam parameters for lasing are relaxed and do not preclude recirculation and clean beam transport. The Jefferson Laboratory IR FEL is a prime example of this approach [15], achieving 14 kW average power at 1.6 microns. Other similarly sized demonstration projects (ALICE, BerlinPro, US Naval Postgraduate School, and Japan Compact ERL) are at various stages of construction. The Jefferson FEL is a prototype of a weapons system with the goal of a megawatt CW FEL to defend naval ships from missile attack [3]. The Navy is supporting design of a 100 kW palletized system for deliver in FY 2014-2015, with initial awards made to Boeing and Raytheon.

At Jefferson Lab a major upgrade is being proposed—JLAMP, a 4th generation FEL light source covering the range 10 eV–200 eV in the fundamental mode with harmonics to 1 keV [16], Fig. 8. For the highest energies, an amplifier FEL would be used at repetition rates of a few megahertz. This light source is based on an energy upgrade to the existing energy recovery linac at Jefferson Lab, using technology developed for the CEBAF 12 GeV upgrade. Specifically, gradients of 20 MV/m and re-circulation allow electron beam energies of greater than 600 MeV to be achieved with bunch charge of ~200 pC. Preliminary studies indicate that emittance degradation in the arcs can be controlled, and the facility offers the ability to more fully characterize degradation processes such as coherent synchrotron radiation (CSR).

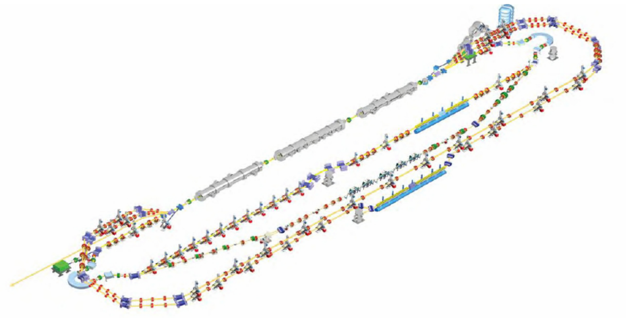

Figure 8: JLAMP, using new recirculation arcs and upgraded SRF added to the JLab IR FEL prototype [16].

The US National High Magnetic Field Laboratory is pursuing an initiative named BigLight [17], whose layout is shown in Fig. 9. It is to provide photons commensurate with the energy- and time-scales typically encountered in materials research at high magnetic fields. The BigLight design offers unique measurement capabilities: three co-located narrow-band tuneable sources with overlapping frequency ranges spanning the full terahertz-to-infrared (THIR) regime.

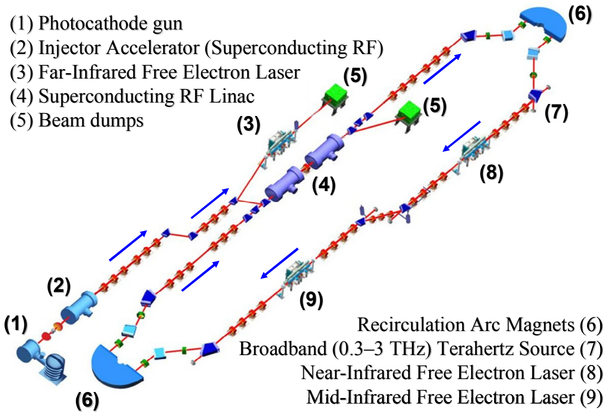

Figure 9: BigLight [17].

The BigLight design builds on the concept of the JLab IR prototype, and it uses a photo-injected electron accelerator with beam energy of 60 MeV, an average current of 3 mA, an SRF linac, and undulators within optical cavities to generate light. It uses energy recovery to minimize capital and operating costs, as well as to minimize radiation hazards.

The ARC-EN-CIEL [18] concept brings together both spontaneous sources, oscillators FELs, and HGHG seeded FELs into one project, with both straight linac and ERL operation. See Fig. 10. Installation will be phased, first with a single-pass linac up to 1 GeV for seeded FELs followed by construction of recirculation loops, either for energy recovery or multipass operation. Spontaneous hard X-ray undulators, VUV oscillators, and extraction at 3 GeV for a HGHG X-ray FEL will then be possible. Terahertz CSR can also be produced. Recirculated beam currents may be as high as 100 mA.

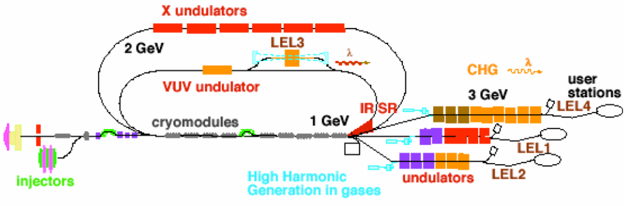

Figure 10: ARC-EN-CIEL [18].

REVERSE COMPTON SOURCES

The limited availability of high quality, hard X-ray beams for academic research and commercial applications has driven interest in developing small, high performance sources to supplement synchrotron radiation facilities. One promising approach is inverse Compton scattering, using an electron beam interacting with an intense laser beam. Ruth et al. [19] are pursuing a small synchrotron as the electron source, where a relatively high current beam (60 mA) is stored. Since a small ERL can achieve similar currents with smaller transverse emittances, one can construct a Compton source using one of the low energy superconducting ERLs that exist or are currently under construction. For example, such a source is being developed at Daresbury's ALICE facility [20], driven by a multi-terawatt laser. Hard X-rays, ranging from 15 keV to 30 keV, depending on the backscattering geometry, will be generated through the interaction of the laser pulse and an electron bunch delivered by ALICE. The X-rays created contain 15×10^6 photons per pulse from head-on collisions, with pulse duration comparable to that of the incoming electron bunch, and 5×10^6 photons per pulse from side-on collisions, where the laser pulse defines the pulse width. The peak spectral brightness is about 10^{20} photons/s/mm^2/mrad^2/0.1% $\Delta\lambda/\lambda$.

However, the cost of such high current ERLs for commercial and academic applications may still be prohibitively expensive. An alternate design, CUBIX, has been proposed by an MIT group using a short superconducting linac [21], Fig. 11. Although the time-average current is low in the linac (1 mA), a much smaller interaction volume is generated using the lower emittance from a low charge bunch from a photocathode electron gun. The electron–photon interaction is additionally improved with a laser enhancement cavity that stores 1 MW pumped from a 1 kW CW laser.

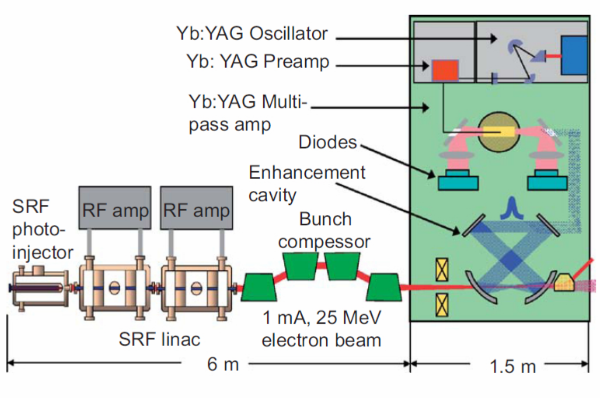

Figure 11: Layout for MIT Reverse Compton Source [21].

The facility can operate in two modes: at high (megahertz) repetition rates with flux and brightness similar to that of a beamline at a large 2nd generation synchrotron, but with short ~1 ps pulses, or as a 10 Hz high flux-per-pulse single-shot machine. The high brightness electron beam is to be produced by a superconducting RF photoinjector. The photocathode laser will produce electron pulses at either many megahertz with 10 pC per bunch or at 10 Hz with 1 nC per bunch. At low charge, emittance of 0.1 mm-mrad, energy spread of 10 keV, and rms bunch lengths as short as 100 fs are expected. Cost control is necessary to make such a source commercially viable. One approach may be to use lower frequency cavities to allow operation at 4K.

CONCLUSION

Superconducting RF has become the key ingredient in many, if not most, of future light source projects, from terahertz to hard X-rays.

ACKNOWLEDGMENT

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