OVERVIEW OF HIGH-BRIGHTNESS ELECTRON GUNS*

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Abstract

In most electron linear accelerators, the beam brightness is set by the beam source. It is very difficult to improve the overall beam brightness after it has been produced; on the other hand, providing a brighter beam source can provide an "instant upgrade" to the performance of a brightness-limited electron-linac-based facility. The development and routine operation of high-brightness guns, therefore, is critical to the success of next-generation linac-based light sources. This includes sources already under construction, as well as proposed and as-yet completely theoretical machines.

In recent years, other potential applications of high-brightness electron beams have been identified, including high-average-power IR and UV free-electron lasers, and (relatively) high-energy electron microscopes.

The source requirements are discussed for these application areas, along with a description of some sources currently under development to meet those requirements.

AREAS OF INTEREST

High-brightness electron gun development can be broadly categorized into four distinct categories. Injectors for national facility-scale linac-based light sources represent one broad category. This includes both x-ray free-electron lasers and energy-recovery linacs; the main differences lie in the required beam repetition rates, as the desirable single-bunch characteristics are quite similar.

Second, there is presently strong interest in the use of small energy-recovery linacs to provide beams for high-power IR and UV free-electron lasers. The injectors for this category of device generally have (relatively) relaxed transverse emittance requirements, strong longitudinal emittance requirements, and very high (~ 1 A) average beam current requirements.

Third, a tantalizing possibility is the use of high-brightness injectors for use as electron microscope beam sources. Typical electron microscope beams have excellent emittance but very low (tens of keV) beam energies; among other things, this limits the depth of the sample that can be studied in transmission electron microscopes (TEMs). A high-energy (500 kV–5 MeV) electron gun, if transverse emittance and energy spread requirements can be met, represents a very interesting possible path towards dramatically expanding existing capabilities.

Finally, electron beam sources for next-generation linear colliders represent a combination of several fascinating challenges. The ability to produce a "flat" beam with a high transverse emittance ratio could at worst reduce the requirements on the e^- linac damping ring, and at best eliminate the need for one altogether. There is also a strong interest in developing photoinjectors capable of producing beams of polarized electrons.

* This work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.
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LINAC-BASED LIGHT SOURCES

The next generation of x-ray user facilities are widely seen as being driven by electron linacs, rather than storage rings. Thus, the electron beam source will be of critical importance to the performance of the facility.

In general, one can consider improving an x-ray source by increasing the flux (photons/s), the average or peak brightness, the coherence, or the temporal structure of the radiation pulse.

Linac-based light sources will probably offer the greatest potential enhancements in peak (and, to an extent, average) brightness, coherence, and temporal structure. They can be roughly categorized depending on whether the source provides spontaneous undulator radiation at a large number of photon beamlines, or uses a gain mechanism to provide coherent radiation at a relatively few number of photon beamlines. The former will be referred to as storage-ring replacements (SRRs), while the latter are known as x-ray free-electron lasers (X-FELs).

Although most future facilities will probably encompass combinations of these two basic categories of machines, the injector requirements can be derived separately. This is done more thoroughly in [1]; a synopsis is presented here.

For X-FEL injectors, we require the LCLS wavelength performance at the minimum practical electron beam energy, given present undulator technology. For storage-ring replacement injectors, we require a factor of at least 100 times peak brightness increase over existing third-generation storage rings such as the APS or ESRF.

X-ray Free-Electron Lasers

The equation relating the operational wavelength of a free-electron laser (FEL) to the electron beam energy and undulator parameters is

$$\lambda = \lambda_u \frac{1 + ½K^2}{2\gamma^2}, \qquad (1)$$

where λ is the photon wavelength generated, λ_u is the undulator period, γ is the electron beam Lorentz factor, and K is the normalized undulator magnetic field strength. K scales with λ_u as well as the on-axis undulator field.

To minimize the overall length of the accelerator Eq. (1) implies that one should minimize λ_u and K; this results in the smallest possible electron Lorentz factor for a given wavelength. Given practical limits on undulator technology [2], setting λ_u to 1.25 cm and K to 1 yields the smallest beam energy to obtain a given wavelength.

The Linac Coherent Light Source (LCLS), presently under construction at the Stanford Linear Accelerator Center (SLAC) is a prototypical SASE-based linac-based light source [3]. The LCLS will use a 14.35-GeV electron beam to generate 1.5-Å photons. The undulator will be approximately 90 m in length, with a K parameter of 3.7 and a period of 3.0 cm.

The LCLS is, in effect, emittance-limited. It requires large values for K and λ_u, along with strong bunch compression, to reduce the gain length to practical values given the design emittance of 1.2 μm (normalized). The LCLS saturation length as a function of emittance is shown in Figure 1, along with the relative importance of the emittance in determining the saturation length.

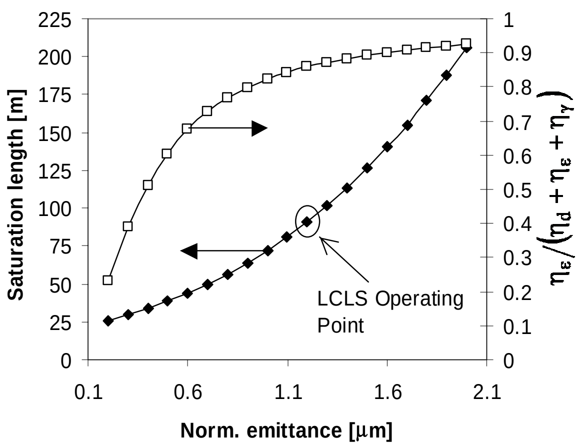

Figure 1: Saturation length (black dots) and the relative influence of emittance on saturation length (white squares) for the LCLS "High-Energy" case.

In order to reproduce the LCLS wavelength performance with a 4-GeV linac, a transverse emittance of about 0.1 μm and a peak current of 1 kA is required.

Storage Ring Replacements

Electron storage rings are typically very flexible in terms of the charge per bunch and bunch spacing within the ring, which allows the facility operator to make trade-offs between peak x-ray beam brightness, average brightness, and flux, depending on the needs of the local user community. For comparison purposes, "typical" operating figures from the Advanced Photon Source* (APS) will be used [4].

The spectral brightness of an x-ray beam from an undulator can be written as

$$B_{\Delta\omega/\omega} \propto \frac{\gamma^2 N^2 I}{\sigma_x \sigma_y \sqrt{\left(1+\frac{\sigma'^2_x}{\theta^2_{cen}}\right)\left(1+\frac{\sigma'^2_y}{\theta^2_{cen}}\right)}}, \qquad (2)$$

where γ is the electron beam Lorentz factor, N is the number of undulator periods, I is the beam current, $\sigma_{x(y)}$ is the horizontal (vertical) spot size of the electron beam, $\sigma'_{x(y)}$ is the horizontal (vertical) divergence of the electron beam, and θ_{cen} is the angular width of the radiation cone from a single electron. If $I = I_{peak}$, the peak electron beam current, Eq. (2) yields the peak photon beam brightness; if the average electron beam current is used instead, Eq. (2) provides the average x-ray beam brightness.

Of significant interest is the case of a small transverse emittance at modest charge and at a reduced repetition rate. Running in this fashion could theoretically improve the peak brightness significantly, without incurring a significant performance penalty on average brightness. (The flux, however, would of course be lowered considerably due to the lower beam current.) Several possible scenarios are given in Table 1.

There are two items of note regarding this table. First, there is an implicit assumption that the injectors can meet not only the single-bunch requirements but also the repetition rate and average current requirements. Second, unlike the X-FEL, which will either lase (e.g., saturate) or not, there is no single cutoff point at which an SRR can be said to either start or stop working. The desire for at least 100x brightness enhancement is fairly arbitrary, but is useful for showing the direction in which one might wish to proceed.

Common Considerations

It is interesting to note that X-FELs and SRRs have, at least in principle, similar single-bunch parameter requirements, in terms of emittance, bunch length, and charge. This strongly suggests that one driver linac could provide beam for both a storage ring replacement and an X-ray free-electron laser facility. Indeed, many proposed linac-based light source designs, such as LUX [5] and 4GLS [6], take just such an approach.

IR AND UV FREE-ELECTRON LASERS

In general, FELs are cost effective for applications only where conventional laser technology cannot be used due to wavelength or average power output considerations. This is the case in the hard x-ray regime, which was discussed in the previous section. It is also the case when average laser powers in the kW range and above are desired. At these power levels, removing heat from the optical medium can become problematic, and conventional lasers tend to grow large and expensive.

The Jefferson Laboratory FEL program, for instance, has proven to be a very impressive demonstration of a high-average-power FEL operating in the IR [7], with ongoing programs to increase the output power and to operate in the UV.

* Although some parameters are available on the Web, the APS has an ongoing program of storage ring performance improvements. The best way to obtain the most recent performance figures is to contact either the Accelerator Physics or Operations Analysis groups at APS.

Table 1: Brightness enhancement factors for several possible beam sources. The net brightness enhancement is normalized to the APS case, at 100-mA average beam current.

	Nominal parameters		Peak brightness enhancement factor		Net brightness enhancement	
Beam Source	Norm. emittance (hor. x vert.)	Peak current (assumed charge)	from ε_n decrease	from I_{peak} increase	peak	average
APS	$40\ \mu m \times 0.5\ \mu m$	300 A	(n/a)	(n/a)	1	1
S-band gun	$1\ \mu m \times 1\ \mu m$	3 kA (1 nC)	$\sqrt{20} \approx 4.5$	10	45	45(1)
new gun design	$0.1\ \mu m \times 0.1\ \mu m$	1 kA (0.1 nC)	$\sqrt{400} \cdot \sqrt{5} \approx 45$	3	135	13.5(2)

(1) assumes 1 nC at 100 MHz for 100 mA average beam current
(2) assumes 0.1 nC at 100 MHz for 10 mA average beam current

In an FEL, the gain medium is the electron beam, and waste heat exits the cavity at just under the speed of light. Theoretically, the optical power output is limited only by the ability to extract energy from the electron beam and the ability of the mirrors to withstand the optical power.

The basic design of such a source is an energy-recovery linac, operating CW at high average beam currents with peak beam energies in the 100- to 500-MeV range. The emittance requirements are not particularly stringent compared to X-FELs, due both to the longer operating wavelengths and to the use of an optical cavity. Typical specifications would be 1-A average beam current, 5-µm (normalized) transverse emittance, and 100-keV·ps longitudinal emittance. Lower linac frequencies are preferred; the larger cavities allow for more stored energy, smaller wakefields, and lower cavity losses.

There are several complications to these designs not generally found in existing injector designs, centering around the high average currents. Beam breakup and transverse wakes are likely to be important in the injector. Further, a 1-A beam at 5 MeV delivers 5-MW beam power; limits on the ability to couple power into the cavities will thus limit available field gradients. An optimistic estimate is 2-MW power gain per cavity at 1-A average currents [8]. This will hold true whether the basic configuration is a dc gun "head" with rf booster cavities or a purely rf-based design.

Beam halo also becomes a significant concern, especially if the rf system is either partly or entirely superconducting. Consider that at 5 MeV, having 0.01% of a 1-A beam as halo corresponds to 500-W halo power. In an SRF system, this could exceed heat-leak and rf loss powers by an order of magnitude. Recent work on the subject implies that halo formation may be unavoidable [9]; further work is clearly needed on the subject.

ELECTRON MICROSCOPES

Electron microscopes are highly refined scientific instruments based around low-energy electron beam accelerator technology. To date, there has been remarkably (and depressingly) little information exchange and cross-fertilization between microscope designers and injector designers, perhaps due to the very different final goals for the electron beams.

This is unfortunate for both sides. From the injector side, the microscope designs present truly impressive electron beam transport optics, in terms of aberration corrections and beam control. On the other hand, the average currents are low, the beam is at extremely low energy (10–100 kV), and it is not bunched at all.

From the microscope side, injectors represent huge increases in beam voltage and, possibly, average power. The beam emittance, however, is about 10^3 greater than the best e-microscope beams, and the energy spread, at a few tenths of a percent, is huge.

A starting set of parameters for a "high-energy" electron microscope (from a high-brightness gun designer's standpoint) might be: average beam current, 0.1 mA; beam energy, 1-2 MeV (kinetic); normalized transverse emittance, 5 nm; rms energy spread, 10^{-5} or less. Clearly, these will be difficult parameters to meet; however, some initial work on the subject [10] is quite promising.

It is important to note that, with the exception of the beam energy, all of these parameters are mediocre at best from the electron microscope's perspective; they represent a starting point only. It is equally important to note, however, that the electron microscope community has spent the better part of a century refining their techniques and designs. An injector designer should not expect to meet all aspects of current microscope performance on the very first try, any more than an e-microscope designer should expect to be able to design the perfect 100-kW UV FEL injector on the first attempt.

It seems apparent that the electron microscope and high-brightness injector communities have much to offer each other in principle. The main hurdle, from the author's experience, appears to be a lack of willingness to consider accepting some sub-state-of-the-art parameters for the sake of initial investigations.

LINEAR COLLIDERS

The overall requirements for a linear collider gun are fairly similar to those of linac-based light sources, with two exceptions. First, the injector should be capable of producing a beam of polarized electrons. Second, the injector should be capable of producing a "flat" beam so as to relax the requirements for, or ideally eliminate, the electron beam damping ring. These are, in effect, separable concerns. Most of the present development work in these areas focuses on rf photoinjector guns.

Polarized electron beams have been produced for some time using dc guns with strained GaAs cathodes [11]. The challenge in applying these techniques to rf photoinjectors lies in both the vacuum environment (generally worse in rf guns than in dc guns, all else being equal) and in the higher gradients typically found in rf guns. Initial attempts were interesting but inconclusive; additional work is ongoing at a number of places, including SLAC [12].

Flat-beam production from an rf gun is based around the transformation of a magnetized, symmetric electron beam [13]. Results to date [14] are quite promising, compared to the desired 100:1 aspect ratio.

The idea of a positron gun is interesting to contemplate. Typical positron-generation schemes, such as running a 200-MeV electron beam into a tungsten converter target, result in positron beams with large energy spreads and emittances. By using the target as a positron "cathode" one could consider designing a positron "gun" to effectively capture and damp the positron beam. Some initial studies on the idea apparently were not fruitful [15], and it appears from the dearth of publications on the subject that the idea has not been pursued further. More recent design tools, codes, and concepts, however, might permit both a more thorough and more successful exploration of the concept.

COMMON ELEMENTS

Electron injector design is in the process of branching out into several different areas, with applications ranging from the sole accelerator in an individual laboratory instrument (i.e., an electron microscope) to the beam source for a national facility (i.e., a linac-based light source or linear collider). There are elements common to most of these areas of application, however, which must be addressed regardless of the final application. These include:

- Increasing the duty factor, for higher average-performance figures;
- Improving the beam quality, for higher single-bunch performance figures;
- Improving the techniques used to build the guns, e.g., for improved symmetrization, cooling (for NC guns), or power-feed capabilities (for SRF guns);
- Increasing the operational reliability of the entire injector system, including drive laser and rf systems;
- Improving the fundamental electron source, e.g., cathodes and cathode research; and
- Improving the basic tools (theory and simulation) used to understand and design injectors.

Of these, perhaps the cathode research and development is the most critical common element. All of the injector categories require high-performance cathodes in one sense or another. Order-of-magnitude improvements in lifetime, robustness, quantum efficiency, and thermal emittance are known requirements. Electron beam emission uniformity is known to be a critical factor in determining final beam quality [16]; this is a topic that requires considerable further attention, both in terms of the type of cathode (especially high-quantum-efficiency materials) and in terms of uniformity evolution over time in an operational environment.

ONGOING INJECTOR DEVELOPMENT

There are several injector development projects worldwide that are addressing some or all of the performance aspects for these next-generation injector applications; most of the work, however, has tended to focus more on light source (including high-power FELs) and collider injectors.

Dr. Sinclair's group at Cornell has obtained good results with dc injectors; in particular, their simulations are predicting 0.7-µm emittances at 0.8 nC and 0.1-µm emittances at 0.08 nC, not including thermal emittance [17]. These results have been obtained in part through the use of large concurrent simulation runs for parameter optimization, a technique the author has long believed is underutilized in the high-brightness injector community.

In the past, rf guns for long-wavelength FELs have operated at up to 25% duty factor [18]. At present there is a development effort underway at Los Alamos National Laboratory (LANL) and Advanced Energy Systems, Inc. (AES) to develop a normal-conducting rf gun capable of true CW operation at high gradients [19].

The Drossel collaboration, centered at Rossendorf University, has made excellent progress in the construction and operation of a fully-superconducting rf gun [20]. Brookhaven National Laboratory (BNL), in collaboration with AES, has made significant progress in this area as well [19]. Recently, AES and BNL have begun working with Rossendorf on an improved overall design for high-power FEL applications.

The injector design for TESLA and the TESLA X-FEL, as well as for LUX, have taken somewhat different approaches. The LUX injector, a normal-conducting rf gun, is intended to produce single electron bunches per rf macropulse, at repetition rates at 1 kHz. The TESLA injector prototype, under study at the PITZ test facility at DESY-Zeuthen, has achieved a 1% rf duty factor operation at 1.3 GHz, producing ms-duration electron beam bunch trains at 10 Hz.

Linear collider injector development is also proceeding well. Flat-beam production tests at Fermi National Accelerator Laboratory (FNAL) have proven very successful to date and appear to be maturing. Development of rf gun cathodes for polarized beam production is an ongoing effort. The SLAC effort is considering the use of a plane-wave transformer (PWT) injector design [21] in order to improve vacuum pressure and pumping speed, and another effort at AES will be comparing several different injector types in the light of cathode bombardment from both ions and field-emitted electrons.

There is also interesting work going on that is not as neatly categorized into one or more of the roles presented here, yet represents interesting developments in the field. This work includes the harmonic bandgap structures, x-band and higher frequency guns, on-axis coupling schemes, and multifrequency fields.

CONCLUSIONS

High-brightness electron beam source development will be critical to the success of upcoming projects, such as linac-based light sources and industrial-scale UV lasers, and offers the promise of extending capabilities of instruments such as electron microscopes.

Disparate needs are driving injector design in several different directions; for instance, high beam powers for IR and UV FELs, low transverse emittances for linac-based x-ray light sources, and emittance aspect-ratio control for linear colliders.

A number of common elements are identifiable, however. Almost all of these applications would benefit from higher duty-factor operation. Improvements to the cathode, encompassing uniformity, lifetime, and quantum efficiency, are likewise universally desirable.

Improvements to the software used to model injectors are also required. The specific needs vary widely depending on the application; however, common themes include multibunch effects, cavity-beam interactions (i.e., transverse and longitudinal wakefields), fine-structure resolution within the electron bunch, beam halo formation and evolution, and realistic cathode emission models.

High-energy, low-emittance electron guns are also being considered for use in novel (to the injector development community) applications such as electron microscopes. Doing so will require adaptation to a very different set of operational performance requirements and conditions; however, the potential benefits appear to be worth the effort.

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