ACCELERATOR CHALLENGES BEYOND LCLS: DEVELOPMENT OF ULTRA-HIGH-BRIGHTNESS GUN*

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Abstract

Cost and complexities of next-generation light sources based on high-gain x-ray free-electron lasers (FELs) can be reduced significantly if the beam brightness can be increased by an order of magnitude than what is feasible today. We discuss the benefits of such ultra-high-brightness beams and possible R&D paths towards producing them.

INTRODUCTION

With the promise of a ten-orders-of-magnitude increase in the peak brightness over that available from third-generation synchrotron radiation facilities, several x-ray FEL projects are proposed to start operation around the end of this decade, prominent among them being LCLS [1] and TESLA FEL [2]. Table 1 shows the major parameters of these projects. These devices are designed to reach the limits of performances in x-ray wavelengths with currently known accelerator technology. Based on the experience of these projects, one can expect that higher-performance facilities tailored to user specifications will be constructed sometime in the future [3]. A general layout of such a facility is shown in Fig. 1, in which electron beams are generated from a high-brightness gun, compressed to subpicosecond pulses, accelerated by a 10-20 GeV superconducting linear accelerator, and delivered to a complement of high-gain FELs for self-amplified spontaneous emission (SASE) or seeded high-gain harmonic generation (HGHG) of intense x-ray beams.

As the design of the future, x-ray-FEL-based light sources will take advantage of the advances in accelerator science and technology during the intervening period. In particular, advances in the technique producing beams of ultra-high brightness would have a large impact in enhancing the performance and reducing the cost of the future light source facility. In this paper we discuss the benefits of ultra-high-brightness beams and possible approaches to produce such beams. These issues were discussed extensively at the ANL Theory Institute on Production of Bright Electron Beams [4].

OPTIMUM PARAMETERS FOR A HIGH-GAIN X-RAY FEL

The condition that the transverse phase space of the electron beam matches that of the optical mode requires that the normalized rms electron beam emittance ε_n satisfy

$$\varepsilon_n \le \gamma\lambda/4\pi, \qquad (1)$$

where γ is the electron energy in units of its rest energy and λ is the x-ray wavelength. For λ = 1 Å and $\gamma = 10^4$, we have ε_n = 0.1 mm-mrad, which is lower by an order of magnitude than the current state of the art. A lower emittance at a fixed current implies higher brightness. Thus we see that the optimal e-beam brightness of an x-ray-FEL-based future light source is an order of magnitude higher than currently feasible.

The limitation due to large normalized emittance can be partially avoided by employing a higher-energy electron beam. However, higher energy at a fixed wavelength implies a higher deflection parameter K, and hence a higher magnetic field. This is the approach adopted by the current x-ray FEL projects such as the LCLS and the TESLA FEL. Even with the higher electron energy, the electron beam phase-space area in these FELs is several times larger than that of the optimal emittance given by the RHS of Eq. (1). In any case, the strategy of employing large electron energy and large K to compensate for the large normalized emittance cannot continue indefinitely, since the spontaneous emission background as well as electron beam energy spread due to quantum fluctuation become too large.

Table 1: LCLS and TESLA FEL Project Parameters

	LCLS (upgrade)	TESLA (upgrade)
Operation start	2009(2013)	2012(?)
# endstations/ FEL	6	5
# FEL undulators	1(8)	3(5)
Spectral coverage (1ω)	≤ 8 keV (<12.4 keV)	≤ 12.4 keV
$\Delta\omega/\omega$	10^{-3} (10^{-6})	10^{-3} (10^{-6})
$\Delta\tau$	100 fs (10 fs)	100 fs (10 fs)
Peak spectral brightness	10^{33} (10^{36})	10^{33} (10^{36})
Linac	S-band RT	L-band SCRF
Electron energy	15 GeV (15-45 GeV)	20 GeV
Pulse format (linac)	1(<32) pulses per 1μs burst×120 Hz	4000 pulses per 1 ms×10 Hz
Burst format (@endstation, per undulator)	120 Hz to one (40 Hz to three)	5 Hz to three (2.5 Hz to five)
I_p ($Q/\Delta t_{FWHM}$)	4.3 kA	5 kA
Emittance	1.2 mm-mrad(?)	1.4 mm-mrad(?)
λ_u minimum	3 cm(?)	3.8 cm
K	3.7	3.8
Undulator length	115 m	145 m

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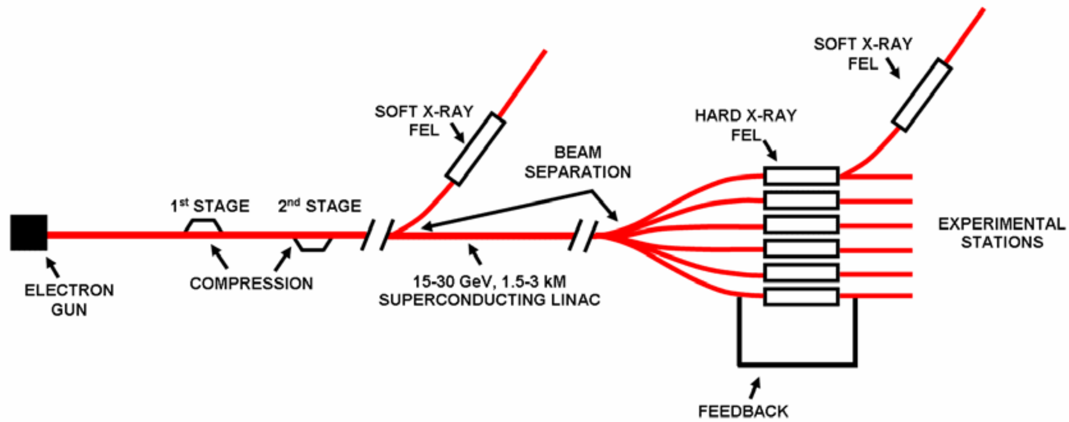

Figure 1: Layout of a future FEL.

If the electron emittance were matched, i.e., satisfies Eq. (1), the optimum value of K turns out to be about 1.4. Assuming that the undulator period is 1 cm, the electron beam energy determined by the resonance condition is 5 GeV, much less than the 14 GeV in the LCLS.

Table 2 illustrates the advantage of low emittance by comparing several different design parameters for λ = 1.5 Å. The electron current of 3.5 kA, undulator period of 3 cm, and beam envelope function β_x = 18 m are taken from the LCLS design and kept fixed throughout this table. The first row corresponds to the LCLS case with the saturation length = 84 m. The second and third rows show that by reducing the emittance to ε_n = 0.5 mm-mrad and ε_n = 0.1 mm-mrad, respectively, the saturation length is reduced to 50 m and 29 m, respectively. The last row shows that, for ε_n = 0.1 mm-mrad, the saturation length remains practically the same as the case in the third row when the deflection parameter and thus the electron energy are reduced to K = 1.4 and E = 7 GeV, respectively.

Similarly, Table 3 compares different designs for λ = 0.4 Å. Again, the undulator period and the electron currents are fixed at 3 cm and 3.5 kA, respectively. The first row shows that the saturation length of the FEL is 300 m if the electron beam and the undulator parameter are the same as in the LCLS except that the electron energy is increased to 30 GeV for resonance at 0.4 Å. The next two rows show that the saturation length is dramatically reduced to 130 m if the electron emittance could be reduced to 0.5 mm-mrad and to 40 m for 0.1 mm-mrad. The last row demonstrates that a high-performance FEL can be designed with a 14-GeV linac with a significantly weaker magnetic field in which K=1.4 if an electron gun producing an order of magnitude smaller emittance were available.

The advantages of ultra-low emittance for high-gain FELs are clear from these examples. However, the current x-ray FEL projects cannot take advantage of these examples since electron guns producing such low emittances are not available at the present time.

Table 2: Improvement of the 1.5-Å FEL with Low-Normalized Emittance Electron Beams for I_p = 3.5 kA, λ_u = 3 cm, β_x = 18 m

Electron energy E (GeV)	**Normalized emittance ε_n (mm-mrad)**	**Deflection parameter K**	**Saturation length L (m)**
14	1.2	3.7	84
14	0.5	3.7	50
14	0.1	3.7	29
7	0.1	1.4	30

Table 3: Improvement of a 0.4-Å FEL with Low-Emittance Electron Beams

Electron energy E (GeV)	**Normalized emittance ε_n (mm-mrad)**	**Deflection parameter K**	**Saturation length L (m)**
30	1.2	3.7	300
30	0.5	3.7	130
30	0.1	3.7	40
14	0.1	1.4	60

ULTRA-LOW-EMITTANCE BEAM GENERATION

Improving the electron beam brightness by an order of magnitude is a challenging task that would require intense R&D efforts in several areas: developing low intrinsic emittance cathodes, suppressing the space-charge effects, and beam bunching and transport with minimum emittance degradation. Different gun types can be envisaged with different solutions.

Developing cathode materials with ultra-low intrinsic emittance for rf photocathode guns will involve basic study of the electron emission process with theoretical analysis and experimental measurements to confirm and exploit advantages of material types, such as negative electron affinity [5]. The tolerance in the transverse and temporal profiles of the drive-laser pulse would be much tighter than is the case at present. The accelerating gradient in the gun cavity may need to be several times larger than the current state of the art, 100 MV/m. An important issue is whether the cavity surface can withstand such a high field. Table 4 shows parameters of a possible ultra-low-emittance gun compared with currently available guns.

Table 4: High-Brightness Electron Injectors (courtesy of Xijie Wang)

Type	DC gun [6]	RF gun	Ultra-bright gun
E [MeV]	0.5	5	50
G [MV/m]	10	100	500
τ [ps]	500	10	<1
I_p [A]	10	100	500
Q [nC]	0.5	1	<0.5
ε_n [μm]	1	1	0.1

A speculative design of an ultra-low-emittance gun based on an entirely different concept is shown in Fig. 2. A DC beam is generated from a microtip. The beam is low current (10 mA) and low energy (100 keV), but with very high beam quality, with ε_n = 0.1 mm-mrad and relative energy spread of 10^{-5}. Such beams are currently employed in scanning electron microscopes. The beam is then chopped into 100-ns pulses with 10-kHz repetition rate, accelerated and chirped in an induction linac, and compressed by a factor of one million to pulses of 100 fs, which can be further accelerated if necessary. Assuming phase-space conservation, the final beam parameters at 10 GeV are ε_n = 0.1 mm-mrad, peak current = 10 kA, relative energy spread = 10^{-4}, and pulse length = 100 fs. Such a beam would be a very efficient driver for high-gain FELs.

Ultra-low-emittance guns will not be ready for the LCLS project due to the time scale involved. However, they could have very significant impact on future FELs if the relevant R&D can be launched now, and they could, of course, be of great benefit to LCLS and TESLA in future years.

OTHER ADVANCED METHODS

Rather than reducing the emittance, it is also possible to modify the beam properties to improve the FEL performance. An interesting possibility is "beam conditioning," in which a suitable correlation is introduced between the electron energy and the amplitude of the betatron oscillation so that the errors in the forward velocity of the electrons caused by these two effects are cancelled [7]. A simple scheme for beam conditioning is schematically shown in Fig. 3 [8,9]. Here the first rf cavity generates time-energy correlation, the focusing channel introduces energy-betatron amplitude correlation, and the second rf cavity cancels the time-energy correlation of the first cavity. The net result is that the energy and betatron amplitude become correlated as desired. Improved FEL performance by conditioning is demonstrated in Fig. 4 in the case of a future FEL for 30-keV x-ray generation [10], which shows that the conditioning improves the FEL performance significantly, in particular if combined with strong focusing.

Due to the nonlinear nature of the conditioning [9], however, the conditioning needs to be gentle; the system for full conditioning will therefore become excessively long. An effort is underway to find a practical implementation [10].

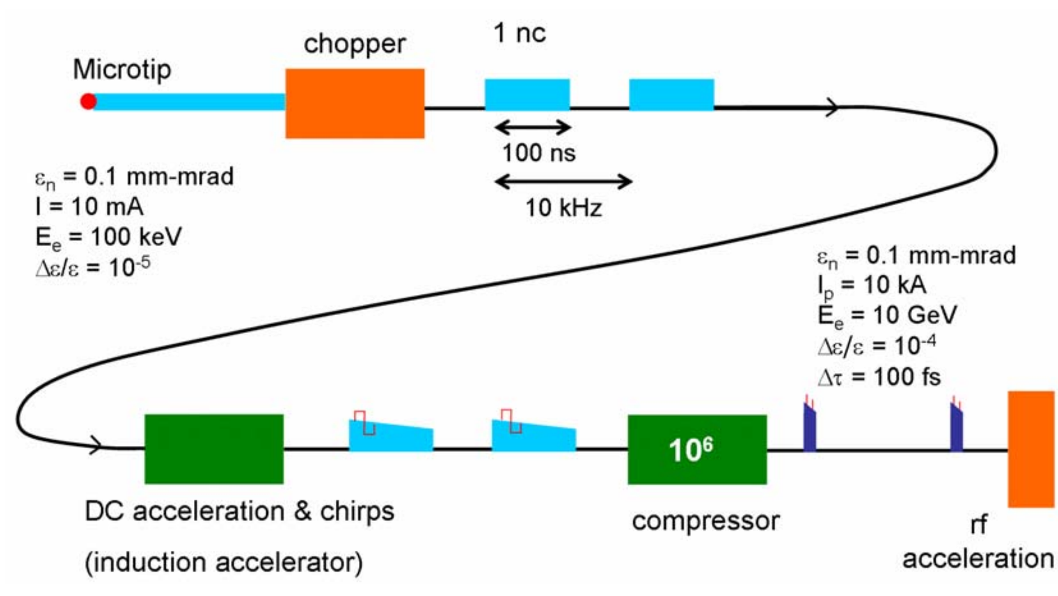

Figure 2: A speculative scheme for producing high-brightness electron beams.

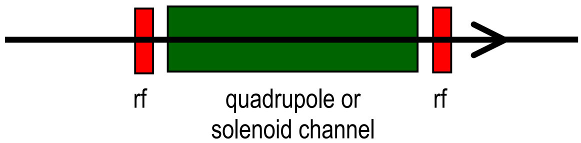

Figure 3: A beam-conditioning scheme.

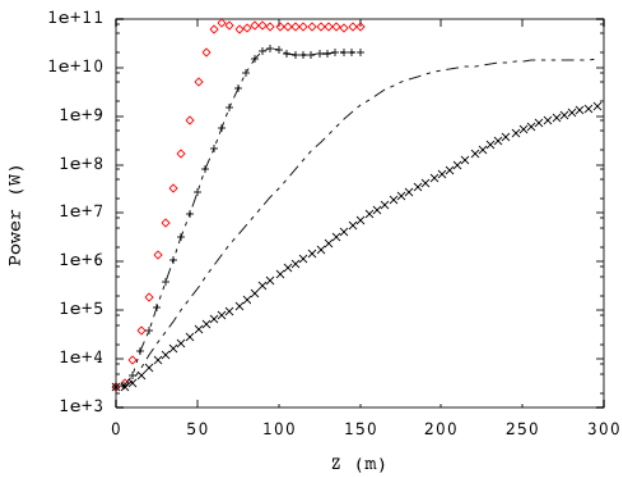

Figure 4: Effect of conditioning on the performance of an FEL. Curve (A) is for unconditioned beams with ε_n =1.2 mm-mrad, corresponding to the first row in Table 3. Curve (B) shows the improvement of the FEL gain when the beam is conditioned. Curve (C) shows that improvement is more dramatic when the beam conditioning is combined with a stronger focusing, β_x=4.4 m. Finally, curve (D) is for an unconditioned beam but with ε_n =0.1 mm-mrad [10].

The FEL performance can also be improved if a portion of the transverse emittance can be traded with the longitudinal emittance. For the current FEL proposal, this is due to the fact that the electron energy spread at the entrance of the undulator is $\Delta E/E < 10^{-5}$, which is two orders of magnitude smaller than the requirement for the high-gain FEL, $\Delta E/E < 10^{-3}$. Thus we have the situation that the transverse phase-space area is too large while the longitudinal phase-space area is too small for an optimal FEL operation for sub-Angstrom wavelengths. The mismatch may be corrected if a volume-preserving transformation in phase-space can be made from $\varepsilon_{nx}\ \varepsilon_{ny}\ \Delta E/E$ = (1 mm-mrad)^2 10^{-5} to $\varepsilon_{nx}\ \varepsilon_{ny}\ \Delta E/E$ = (0.1 mm-mrad)^2 10^{-3}. Such a transformation will also help to alleviate the harmful effects of small energy spread for accelerator operation, such as the coherent synchrotron radiation instability in the bunch-compression chicanes [11]. Unfortunately, it is known that such a transformation is not possible in a symplectic Hamiltonian system [12]. It would be interesting to study whether a non-Hamiltonian process involving, for example, radiation damping can be exploited to effect the desired transformation.

APPLICATION TO A LINEAR COLLIDER

A linear collider with center-of-mass energy of 500 GeV or greater has been endorsed by the U.S. high energy physics community as the highest priority after the Large Hadron Collider construction. Electron guns producing ultra-low emittance may obviate the damping rings in future linear colliders. The normalized emittances in the two transverse dimensions for the case of the Next Linear Collider are: ε_{nx} = 3.6 mm-mrad and ε_{ny} = 0.04 mm-mrad, with the product $\varepsilon_{nx}\ \varepsilon_{ny}$ = 0.14 (mm-mrad)^2 [13]. Such a beam may be created by an rf photocathode gun with ε_n = 0.37 mm-mrad combined with the flat-beam generation technique [14,15]. Of course there are issues associated with the polarization and positrons.

CONCLUSIONS

The R&D for ultra-low-emittance electron sources will require substantial resources. Technical infrastructures for accelerator R&D should be constructed, maintained, and operated as user facilities in national laboratories open to university groups and others through competitive grants. A decade of sustained effort will be required to achieve the ambitious goal for an order-of-magnitude improvement in electron source brightness. Research disciplines required include surface chemistry and physics, laser techniques, nanoscale structures, and solid-state physics, in addition to accelerator physics and engineering. The R&D will be expensive. However, the expenditure is well worthwhile in view of the tremendous benefits the higher-brightness gun will bring in future accelerator development, in particular a fourth-generation light source based on x-ray free-electron laser technology and a future linear collider.

Facilities capable of general accelerator-based R&D have been and are constructed as a part of larger accelerator complexes for research in various scientific disciplines, generally without provisions for their use for research in advancing accelerator science. Sophistication in accelerator devices has become such that it is now necessary to promote accelerator research in its own right, to be pursued with strong participation by university groups.

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