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HIGH-BRIGHTNESS PHOTOEMITTER INJECTOR FOR ELECTRON ACCELERATORS*

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Summary

A free-electron laser (FEL) oscillator, driven by an rf linac, requires a train of electron bunches delivered to an undulator. The electron-beam brightness requirement exceeds that available from a conventional buncher. The demonstrated high peak brightness of laser-illuminated photoemitters indicates that the conventional buncher system might be eliminated entirely without the usual large loss in beam brightness that occurs in bunchers. A photoemitter with a current density of about 200 A/cm^2 is located on an end wall of an rf cavity to accelerate a 60-ps bunch of electrons to 1 MeV as rapidly as possible. Preliminary experimental work and simulation calculations are presented.

Introduction

A free-electron laser oscillator builds up the intensity in a photon packet by interaction between a train of electron bunches passing through an undulator in the middle of an optical resonator. The time interval between electron bunches must be a multiple of the round-trip time in the optical resonator cavity. Losses caused by mirror absorption, diffraction, and vignetting are minimized if the electron bunch interval is equal to the photon round-trip time. Multiple photon bunches will be produced if the electron bunch interval is a submultiple of the photon round-trip time.

A high single-pass gain in an FEL requires a high electron density in the bunches. A high electron density implies not only a high peak current (typically >100 A), but also a low transverse beam emittance. If high peak-current bunches were placed in every rf bucket, excessively high beam powers would result. Therefore, a subharmonic bunching (SHB) scheme is usually employed.

In rf-linac-driven FELs, conventional subharmonic bunchers are currently used, but the resulting dilution of phase space is not acceptable for advanced high-power and/or short-wavelength FELs. Recent developments in photoemitter technology suggest that high-brightness electron bunches produced at a subharmonic of the linac frequency can be produced while eliminating the conventional bunching process entirely.

Brightness of Electron Sources

The normalized peak brightness of a beam is defined as

$$B_n = I/(E_x E_y) \quad A/(m^2 \cdot rad^2) \quad ,$$

where I is the peak current and E_x and E_y are the normalized transverse emittances of the beam.[1] The lower limit of the normalized rms phase-space area of a beam from a thermionic emitter of radius r_c at uniform temperature T is[2]

$$E_n = 4 \pi [\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2]^{1/2}$$

$$= 2 \pi r_c [kT/m_0 c^2]^{1/2} \text{ m·rad}$$

because $\langle xx' \rangle = 0$ at the cathode. For a typical thermionic emitter at 1160 K, the average transverse energy of the emitted electrons is 0.1 eV. For a uniform current density J, the total current is $I = \pi r_c^2 J$ and the lower limit on the rms emittance is

$$E_n = 5.0 \times 10^{-6} \pi (I/J)^{1/2} \text{ m·rad with J in A/cm}^2 \quad .$$

The current density from a dispenser cathode generally is less than 10 A/cm^2; therefore, for an emitting area of 1 cm^2, the ratio I/J is of order unity. The corresponding normalized peak brightness is limited to

$$B_n = I/E_n^2 = 4.1 \times 10^9 \text{ J A/(m}^2 \cdot \text{rad}^2) \quad .$$

The bunching and initial acceleration process typically results in high peak currents, but a price is paid in the dilution of phase space. Typical results for single-bunch accelerators are shown in Fig. 1 as well as results for two pulse-comb accelerators. The line at the bottom of the graph represents the thermal limit of the emittance at the electron source for emitters characterized by I/J = 1. A photoemitter with a 1 cm^2 area and J = 200 A/cm^2 would produce a peak current of 200 A with an emittance of $5 \times 10^{-6} \pi$·m·rad if no perturbing processes occurred to raise the emittance.

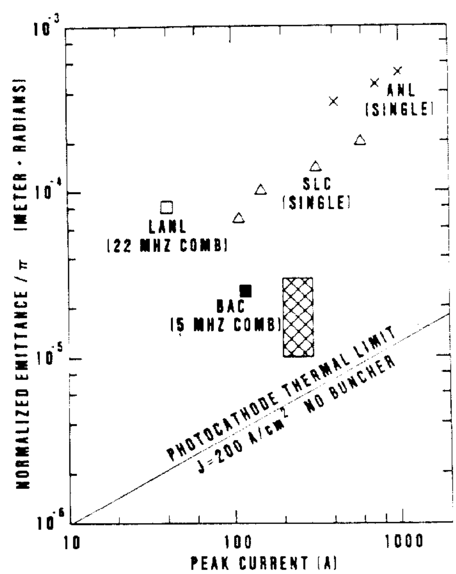

Fig. 1. Normalized emittance for several typical subharmonic buncher systems in single-bunch accelerators (Argonne National Laboratory,[3] Stanford Linear Collider)[4] and pulse-comb accelerators (Boeing Aerospace Co.,[5] Los Alamos National Laboratory).[6] The straight line represents the theoretical thermal limit for a photocathode with J = 200 A/cm^2. The objective for a photoemitter injector for FELs is shown in the cross-hatched box.

The electron beam emittance desired in the undulator of an FEL can be derived from the requirement that the electron beam overlap the strong central optical field, assumed to be a Gaussian, $E = E_0 \exp[-(r/w_0)^2]$

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(Ref. 7). The half-width parameter w_0 is related to the FEL wavelength and the Rayleigh range, Z_0, (distance to double the beam area) by $Z_0 \lambda = \pi w_0^2$ (Ref. 8). Because Z_0 typically is about one-half the undulator length, L_u, $2\pi w_0^2 = L_u\lambda$.

For an electron beam phase-space density function of two-dimensional Gaussian form

$$\rho(x, x') = \rho_0 \exp [-1/2(x^2/\sigma^2 + x'^2/\sigma'^2)] \quad ,$$

86% of the intensity is contained in an rms ellipse of area $E = 4\pi \sigma\sigma'$ m•rad (Ref. 9). For an effective overlap of the electron and photon beams, the electron beam area is about one-half the photon beam area at the 1/e level; the electron beam half-width $2\sigma = 2 w_0$. For the divergences of the electron and photon beams to be equal, we have $2\sigma' = w_0/Z_0 = \lambda/\pi w_0$. The desired electron beam emittance is then $E = 2 \lambda$, and the normalized emittance is $E_n = 2\beta\gamma\lambda = 2\gamma\lambda$. For an FEL to operate in the ultraviolet, with $\lambda = 10^{-7}$ m, for example, and using a 200-MeV ($\gamma = 392$) electron-bunch comb, the normalized emittance required is $E_n = 25 \pi \times 10^{-6}$ m•rad. The required normalized brightness with 200-A peak current is then $B_n = 3.2 \times 10^{10}$ A/(m^2•rad^2). Figure 2 displays the theoretical brightness available from a photoemitter injector, the required brightness for an ultraviolet FEL, and the brightness of the conventional bunched-beam linacs plotted in Fig. 1. The goal of the present development is shown as the cross-hatched box.

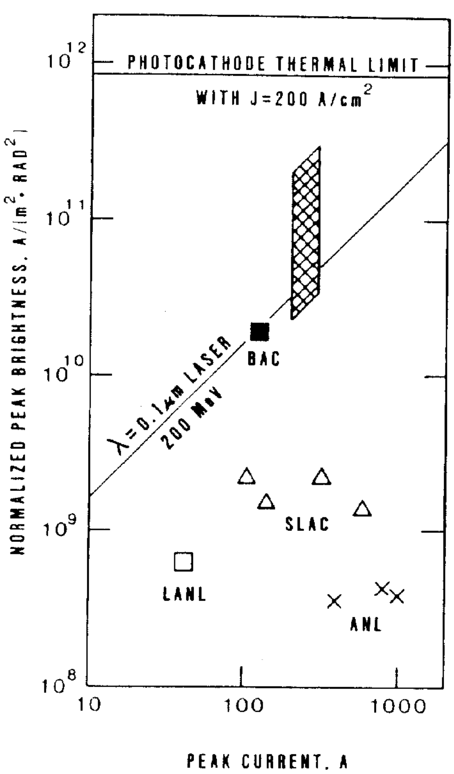

Fig. 2. The data of Fig. 1 replotted as normalized brightness. The required brightness for an ultraviolet FEL is shown for an electron beam energy of 200 MeV.

Electron Bunch Formation by Optical Chopping

The high current density available from semiconductor photoemitters makes feasible the formation of high peak-current bunches without the loss of beam quality that accompanies the conventional bunching process. Current densities of about 200 A/cm^2 have been reported[10,11] from laser-illuminated GaAs and Cs_3Sb. Furthermore, the average electron energy has been shown to be ~0.1 eV for low current densities.[12] If the average transverse energy of the emitted electrons does not rise rapidly with current density, then the possibility of producing bunches of high peak brightness is indeed attractive.

The temporal profile of the bunches can be controlled to the same extent that the incident laser pulse can be tailored. The operation of streak cameras with picosecond time resolution indicates that no statistical delays occur in electron emission of sufficient magnitude to increase the electron pulse width significantly.

The radial profile of the electron current density also can be controlled through the laser pulse. Studies of the influence of nonlinear space-charge forces on emittance growth[13,14] lead to the conclusion that a uniform current density (and therefore a uniform light intensity) is desirable.

Phase-Space Dilution in Short Electron Bunches

The thermal energy of the electrons as they leave the surface of the photoemitter is low. However, the transient forces to which an intense bunch is subjected as it emerges into a strong accelerating field are very large, comparable to the space-charge force. In a continuous beam with space-charge-limited flow, the optimum geometry to minimize emittance growth is one that ensures that the electric field at the boundary of the beam[15] is purely radial. For the short, high-intensity bunches under consideration in this paper, three time-dependent effects are important. (1) In the leading portion of a column of current, the potential at the cathode is not as depressed as in a dc beam, implying that higher currents can be obtained than those in a dc beam having the same external field. (2) The Pierce-geometry design for a dc beam will overfocus the short bunch. (3) Large longitudinal forces are exerted on the leading and trailing ends of the bunch, resulting in a reduction of the energy spread produced by the space-charge forces. The inward-directed forces are the result of the large time derivatives of the longitudinal vector-potential components caused by the rapidly changing current emerging from the photocathode.

Detailed simulation studies are in progress,[16] directed towards an understanding of the perturbations that cause emittance growth in the formation and acceleration of intense, short bunches of electrons in a strong accelerating field. Preliminary results suggest that a steeply rising and falling laser pulse is desirable and that the maximum acceleration rate short of the sparking limit is advantageous.

Design of a Photoemitter Injector

To accelerate the optically chopped electron bunches as rapidly as possible, the photoemitter is placed on the flat end wall of the first rf cavity in an injector linac. The profile of the opposite wall, corresponding to the anode of a dc diode, is shaped to minimize the emittance growth of the bunch as it is accelerated and passes through the drift tube to the second accelerating cell. The minimum-emittance growth criterion used here is in contrast to the more usual criterion of maximum shunt impedance. Superior beam quality is more important than efficiency in this experiment. A material with rf conductivity lower than that of OFHC copper, such as nonmagnetic stainless steel, may be used if it can be shown to support a higher rf field.

Following the initial acceleration in the rf-gun cavity, the beam enters a second cavity that is separately powered and phased. Figure 3 is a schematic of a proposed photoemitter injector. The septum separating the two cavities is made as thin as possible so that the overall accelerating gradient is maximized. The energy gain in the first two cavities could be as large as 2-3 MeV. Following the first two cavities, a more conventional series of coupled cavities will boost the beam energy to about 10 MeV.

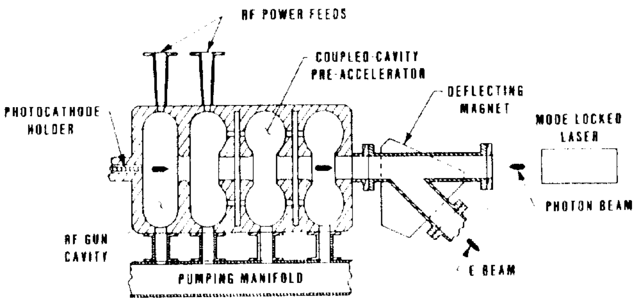

Fig. 3. Schematic diagram of a proposed photoemitter injector.

The entire preaccelerator assembly is part of an ultra-high vacuum system with a base pressure of 10^{-9} torr or lower. It will, therefore, have pumping connections from each cavity to a manifold, can be baked to 300° C or higher, and can be connected to the main accelerator though a differentially pumped transport line that can sustain a pressure ratio from end-to-end of at least 1000.

Immediately following the last accelerating cavity of the preaccelerator, a dipole magnet deflects the beam into the transport line so the laser beam can be directed through a window along the preaccelerator axis to the photocathode.

The laser in the initial experiments is a mode-locked Nd:YAG laser with the frequency doubled to yield a wavelength of 532 nm, a value within the broad maximum of the quantum efficiency curve for GaAs and Cs_3Sb. The acoustooptical mode locker is driven by a power amplifier at a subharmonic of the preaccelerator frequency, 108.3 and 1300 MHz, respectively, in the present experiments. The jitter in the laser pulse must be less than 5 ps for effective operation of an FEL.

Conclusion

The prospects for producing an improved electron-bunch comb injector for an FEL rf linac are good. Important processes involved, such as the production of high peak currents and temporal profiling, have been demonstrated in single-bunch experiments. Further experiments to verify the low emittance and long lifetime of photoemitters in the environment of an rf cavity are needed.

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