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HIGH-BRIGHTNESS ELECTRON INJECTORS*

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SUMMARY

Free-electron laser (FEL) oscillators and synchrotron light sources require pulse trains of high peak brightness and, in some applications, high-average power. Recent developments in the technology of photoemissive and thermionic electron sources in rf cavities for electron-linac injector applications offer promising advances over conventional electron injectors. Reduced emittance growth in high peak-current electron injectors may be achieved by using high field strengths and by linearizing the radial component of the cavity electric field at the expense of lower shunt impedance.

INTRODUCTION

FEL oscillators and synchrotron sources require linac injectors capable of delivering pulse trains of electron bunches with high brightness. A high electron brightness implies not only a high peak current (typically more than 100 A) but also a low transverse beam emittance. For high single-pass gain, a good overlap is required of the electron bunches with the light-wave field in the optical resonator, which, in turn, implies an upper limit to the transverse emittance of the electron beam. If high peak-current bunches were placed in every rf bucket, excessively high beam powers would result. Therefore, the electron pulses are typically at a subharmonic of the accelerator.

In rf-driven FELs, conventional subharmonic bunchers are currently used, but the resulting degradation of beam brightness 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. However, emittance growth is excessive if the beam is too tightly bunched at a low energy.[1] Therefore, the trend in improved injector-linac design is toward initial acceleration of a partly bunched beam. Because electrons rapidly become relativistic in a typical linac, further bunching at moderate energies can only be done with the magnetic bunching method.[2]

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ELECTRON-SOURCE BRIGHTNESS

The normalized peak brightness is defined as

$$B_n = I/(\varepsilon_x \varepsilon_y) \qquad [\text{units: } A/(m^2 \cdot rad^2)] \; ,$$

where I is the peak current and ε_x and ε_y are the normalized transverse emittances of the beam.[3] In accelerator discussions, it is constructive to use the rms emittance formulation, defined as

$$\varepsilon_x = 4\,\pi[<x^2><x'^2> - <xx'>^2]^{1/2} \; ,$$

where x and x' are the particle's transverse coordinate and angle of divergence from the optic axis, respectively, and $< >$ means an average over the electron distribution. In this formulation, the rms emittance is equal to the total phase-space area for a Kapchinskii-Vladimirskii distribution.[4] The normalized emittance is then

$$\varepsilon_n = \gamma\beta\varepsilon \; ,$$

where for an azimuthally symmetric beam $\varepsilon = \varepsilon_x = \varepsilon_y$.

The lower limit of the beam's normalized emittance from a thermionic electron source is governed by the emitter size and by the transverse component of the thermal motion of the electrons. The thermal limit of the normalized rms emittance of a beam from a thermionic emitter of radius r_c at a uniform absolute temperature T is[5]

$$\varepsilon_n = 2\,\pi\, r_c[kT/m_0c^2]^{1/2} \qquad (\text{units: } m \cdot rad)$$

because $<xx'> = 0$ at the cathode. For a typical thermionic emitter at 1160 K, the average transverse energy of 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

$$\varepsilon_n = 5.0 \times 10^{-6}\,\pi(I/J)^{1/2} \quad \text{with J in } A/cm^2 \; .$$

The corresponding normalized peak brightness is limited to

$$B_n = I/\varepsilon_n^2 = 4.1 \times 10^9 J \; .$$

The current density from a dispenser cathode is typically not more than 10 A/cm^2; therefore, for an emitting area of 1 cm^2, the ratio I/J is of the order unity. Semiconductor photoemitters, on the other hand, are capable of delivering[6] over 500 A/cm^2, and their effective temperature[7] is low enough to produce beams an order of magnitude brighter than those from thermionic cathodes.

REDUCTION OF EMITTANCE GROWTH IN INJECTOR LINACS

In an rf accelerating cavity of frequency ω, the rf radial force on a particle crossing the gap depends on both the rf phase angle and the radial position of the particle. Using a thin-lens approximation for an rf gap, Weiss[8] has shown that the increase in rms emittance, when a particle bunch of finite size crosses an rf gap, is $\Delta\varepsilon_{rms} \propto (r_{rms}^2\omega)^2$. Clearly, rms emittance growth in an rf gap is minimized with a small beam radius as well as with a low-frequency cavity.

It is evident from simulation studies[9] of the acceleration of short bunches in an rf cavity that (a) dense space charge and (b) the external rf field lead to a degradation of beam quality and, therefore, to a loss of brightness. Although pulses of only a few picoseconds can be produced in a photocathode, it now seems advisable to generate pulses that are initially around 100 ps, then, after acceleration to about 10 MeV, to bunch them magnetically.[2] The acceleration of the longer bunches is best done in a low-frequency linac at a subharmonic of the main linac frequency.[10] Nevertheless, there is a strong incentive to accelerate the bunches as rapidly as possible, a condition that can only be met with high-frequency rf fields. A study of the envelope equation (Ref. 5, p 134) reveals that, for continuous beams, the dominance of space charge over emittance is adiabatically damped as $\gamma^{-1/2}$. Jones and Carlsten[1] have shown that, for bunched beams, the damping dependence on energy is much stronger, namely γ^{-2}. Therefore, the requirement of maximum acceleration gradient (hence a high frequency) to minimize the influence of space charge has to be balanced against a conflicting need to accept long pulses (hence a low frequency) to reduce the emittance growth associated with rf fields.

ADVANCED INJECTOR DESIGN

In 1985, the achievement of high-peak currents from a Cs_3Sb photocathode was reported.[6] More recently, it has been shown that the laser-driven photocathode produces an intrinsically bright beam.[7] It remains to be demonstrated that short bunches can be accelerated to relativistic energies without loss of brightness. With suitably short laser pulses incident on a photocathode that has a high quantum efficiency, it would appear to be a straightforward matter to create a high-brightness, optically chopped beam, accelerate it in several rf cavities, and then deliver it to the main rf linac.

A laser-illuminated photocathode can readily produce the electron-bunch train that is required by rf linac-driven FEL oscillators. The emittance-growth problem associated with high space-charge density in short bunches can be alleviated by choosing an injector design that retains the requisite high-average current but accelerates, initially, a relatively long bunch. The longer bunch is best accelerated in a lower-frequency linac operated at a subharmonic of the main linac frequency. After acceleration to several million electron volts, a magnetic phase compressor shortens the bunch.

A laser-illuminated photocathode can be used in a dc-gun configuration in much the same way that it is employed in the laser-klystron[11] or lasertron.[12] In an rf cavity, on the other hand, a more rapid acceleration rate can be achieved than in a dc gun. The rf gun forms the heart of an experimental program[13] at the Los Alamos National Laboratory to develop an intrinsically bright electron source for linacs. A similar program based on a dc gun is under way at Stanford University.[14]

MAGNETIC PHASE COMPRESSION

Relativistic particles can be bunched by utilizing the path-length differences in a system of bending magnets for particles of different momenta. The longitudinal phase space occupied by an ensemble of particles must be elongated and rotated so that a correlation exists between energy and phase. In this respect, the magnetic phase-compressor system is similar to the energy-compressor systems used with some intermediate-energy electron linacs to reduce the energy spread of the beam.[15-16] A magnetic phase compressor differs from an energy compressor only in the sense of rotation of the longitudinal phase space of the bunch to produce a narrow phase spread rather than a narrow energy spread. Figure 1(a) is a longitudinal phase-space diagram such as would be produced by an rf cavity operated as a buncher to put an energy ramp on the bunch but with the centroid unchanged in energy. In a system of dipole magnets, the path-length difference produced for particles with different momenta is represented in TRANSPORT notation by the R_{56} matrix element. For a positive R_{56} element, bunching will occur if the phase-energy diagram is as shown in Fig. 1(a); for a negative R_{56}, the slope of the scatter plot of Fig. 1(a) must be reversed. Figure 1(b) shows the bunching effect of a set of magnets whose matrix element R_{56} is 0.24 cm/%.

The energy spread that makes the magnetic compression possible can be reduced if the bunching is left incomplete, as it is in Fig. 1(b). Segall[19] has proposed the use of a second rf cavity to compress the energy spread impressed on the bunch by the first cavity. Figure 2 shows the result of a final set of cavities, which put a reversed energy ramp on the bunch to reduce the energy spread.

THE LOS ALAMOS PHOTOINJECTOR PROGRAM

The Los Alamos program is based on an rf cavity with a photocathode electron source. The reasons for this approach were described earlier in the Advanced Injector Design section and in Ref. 10. The initial rf gun experiments are being carried out at a frequency of 1300 MHz because a powerful klystron was available. A schematic diagram of the Los Alamos injector experiment is shown in Fig. 3 (Fig. 1 of Ref. 14).

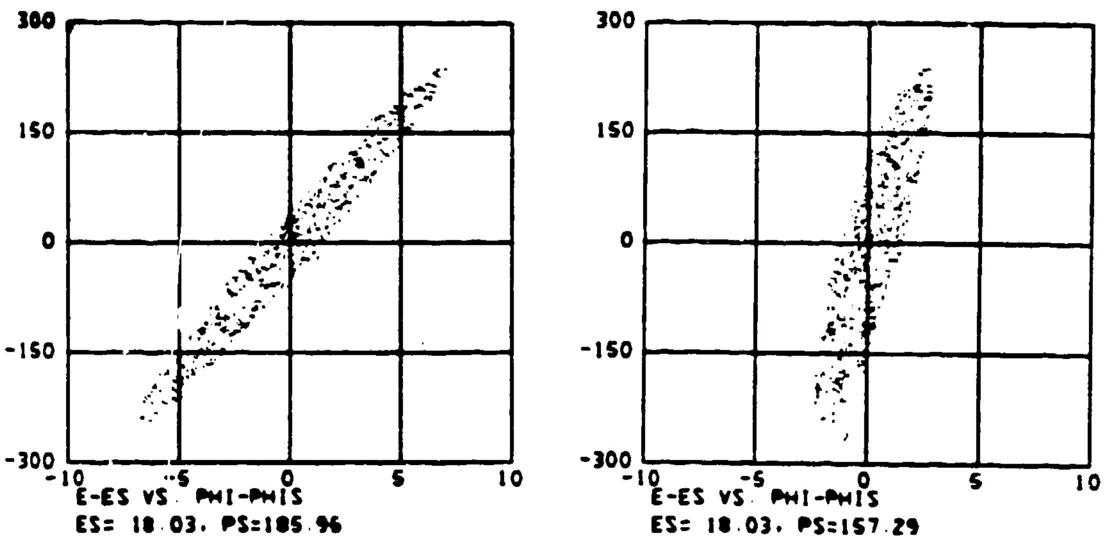

Fig. 1. (a) Energy ramp impressed on the bunch by an rf cavity and (b) partial phase compression after passing through a set of magnets with R_{56} = 0.24 cm/%.

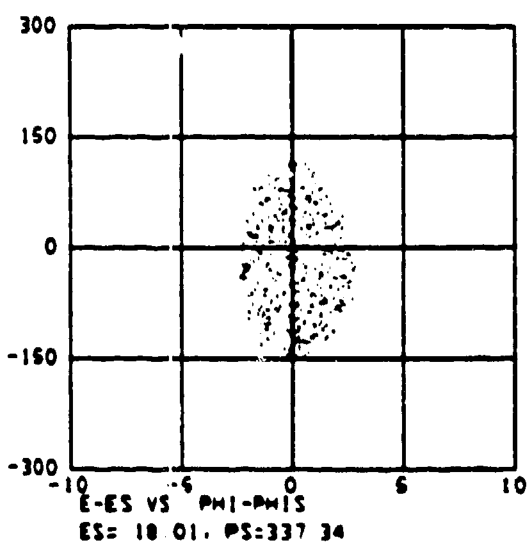

Fig. 2. Energy spread reduced from that of Fig. 1(b) by an energy ramp of reversed slope to that of Fig. 1(a).

Photocathode Design

In recent years, photocathodes for polarized electron sources have been made from wafers of GaAs.[20,21] Current densities as high as 180 A/cm^2 have been reported.[21] Photoemitters of Cs_3Sb are less demanding of system cleanliness[22] than are those of GaAs. An additional advantage of a positive electron affinity semiconductor like Cs_3Sb lies in the rapid emission of the photoelectrons.[23] By

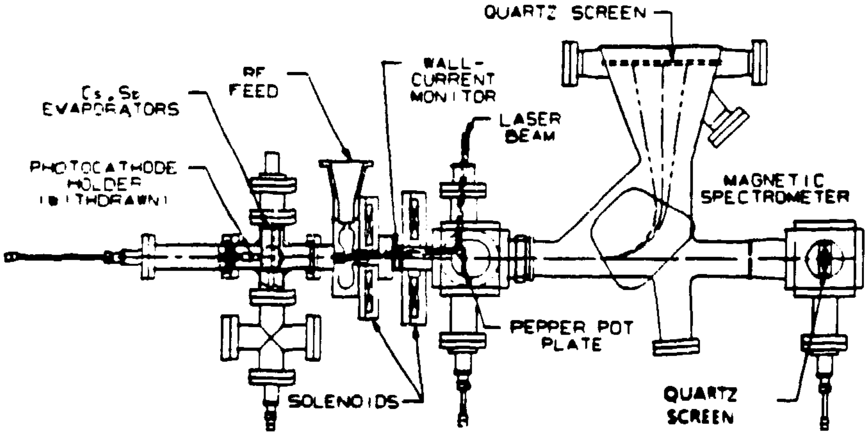

Fig. 3. Plan view of the photoinjector experiment.

contrast, the intrinsic emission-time uncertainty of GaAs has been measured in the range from 8 to 71 ps for active layers between 50 nm and 2 µm in thickness.[23]

A Cs_3Sb photocathode was chosen for its ease of preparation within the vacuum environment of the linac and for its relative tolerance of vacuum conditions in the injector linac.[22] A photoinjector linac must be bakeable in its entirety to about 200°C and be capable of maintaining a pressure below 10^{-9} torr, preferably 10^{-10} torr. If a Cs_3Sb photocathode is damaged in use, the damage can be erased by heating to 400°C, then a new one prepared *in situ*.

The spectral response[24] of Cs_3Sb extends from a quantum energy of 1.8 eV (λ = 690 nm) to energies greater than 3.8 eV (λ < 320 nm). Therefore, a Cs_3Sb photocathode can be used with a Nd:YAG laser with frequency doubled (λ = 532 nm) or tripled (λ = 355 nm). A Nd:YAG laser can readily be mode-locked to deliver trains of 60-ps pulses at a microscopic repetition rate in a range from 50 to 120 MHz.

RF Gun Design

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 large and are comparable to the space-charge force.

Jones and Peter[25] have shown the importance of nonlinear forces in detailed simulation calculations of the transport of very short electron bunches in dc and rf fields. Emittance growth is minimized if at least two conditions are met: (1) the current density in the bunch is uniform and therefore the space-charge force is linear in the radial direction, and (2) the cavity field (in the absence of space charge) is radially linear. The latter condition is satisfied if the cavity wall shape is given by

$$\rho^2 = 2[(\psi - \zeta)(1 - 2\mu) + \zeta^3/3 - \mu\zeta^2]/(\zeta - \mu) \ ,$$

where $\rho = r/z_0$, $\zeta = z/z_0$ $\psi = -\phi/E_0 z_0$, and ϕ is the electric potential; E_0 is the (axial) electric field at the origin ($r = 0, z = 0$). The radial electric field is given by $E_\rho = \rho(\zeta - \mu)$. The position at which the axial electric field vanishes for $r = 0$ is denoted by z_0, and μ is an arbitrary focusing parameter. For $0 < \mu < 0.5$, the radial electric field exerts a focusing force in the region $0 < z < \mu z_0$.

In a bunch of finite length, the electrons in the leading- and trailing-edge regions are acted upon by the large, nonlinear, transient, longitudinal forces arising from the large, rate of change in the total current. These forces lead to emittance growth that is reduced by using long pulses in which the hot end regions form a smaller fraction of the whole. The cavity walls near the beam axis are shaped according to the above equation for ρ^2. The focusing parameter μ was chosen to be 0.15, a value that gives minimum emittance growth,[9] and the scaling parameter $z_0 = 4.0$ cm was used. The outer part of the rf gun cavity was shaped to maximize the cavity quality factor Q. Figure 4 shows the rf gun cavity designed for an operating

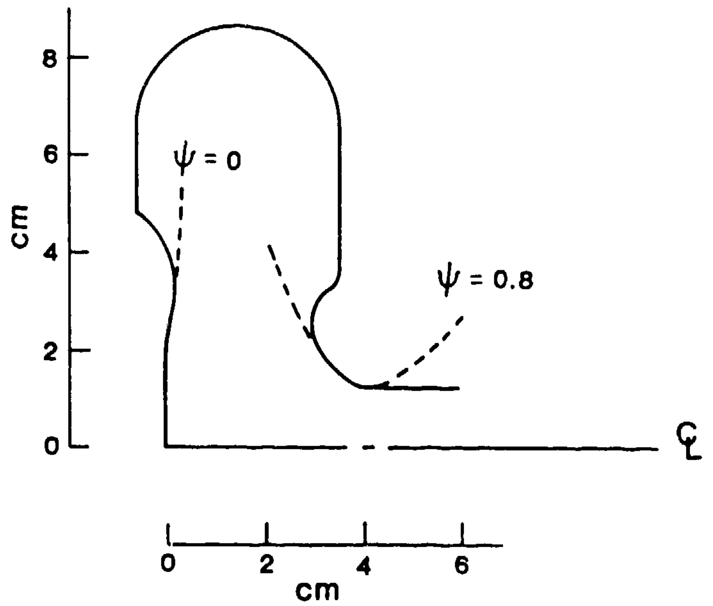

Fig. 4. Profile of the linear-field rf gun cavity. The inner walls of the cavity (radius < 2 cm) are given by the equation above with $\psi = 0$ to 0.8, shown by dashed lines at large radii. The bore radius is 1.7 cm.

frequency of 1300 MHz. Plots of the radial electric field for different Z values obtained from the code SUPERFISH for a conventional high Q cavity and linear field cavity are shown in Fig. 5 and Fig. 6, respectively. The specially designed cavity is much more linear than the corresponding fields in a more conventional rf cavity optimized for high shunt impedance.

Experimental Results

Initial observation of the accelerated electron beam from the rf gun was obtained with the wall-current monitor shown in Fig. 3. With a fast oscilloscope, the largest pulse trains repeatedly observed had peak amplitudes of 4.4 V with 40 dB of

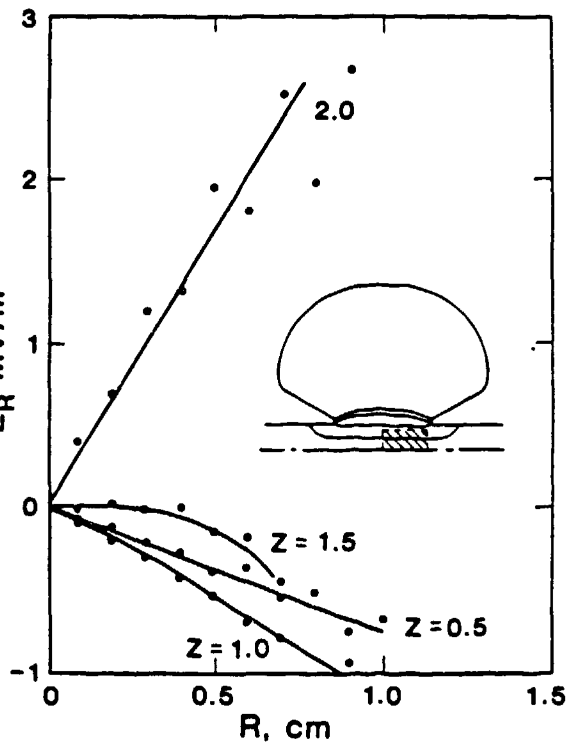

Fig 5. The radial electric fields near the axis of a conventional rf accelerator cavity optimized for high shunt impedance (within the cross-hatched area of the insert).

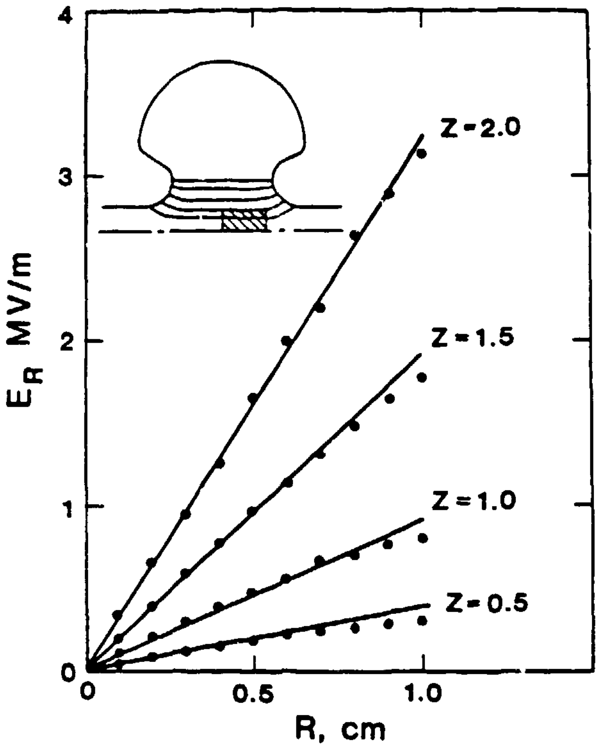

Fig. 6. The radial fields near the axis of the rf gun cavity (within the cross-hatched area in the insert). The bore radius is 1.3 cm.

attenuation in place. The measured bunch charge, obtained from the integrated pulse profiles, was 27 nC, giving an average current in the pulse train of 2.9 A. Assuming that the temporal profile was Gaussian (see below), the peak current was 390 A. The probable error in these measurements is ±20%.

The minimum laser pulse width observed was 53 ± 1 ps FWHM; on the same streak-camera sweep, the electron bunch widths were the same to within the experimental error when allowance was made for the observed 6% energy spread. We conclude, therefore, that for the present experimental conditions, the pulse broadening introduced by the Cs_3Sb photoemission is less than 2 ps.

The emittance of space-charge-dominated beams was measured with peak currents ranging from 100 to 150 A. Three measurement sets were made under various combinations of peak current and focusing strength in the first solenoid (Table I). The normalized emittance for 130 A peak was 20 π·mm·mrad. The corresponding normalized peak brightness was ~4 × 10^{10} A/(m^2·rad^2), and the average macropulse current was ~1.0 A. The estimated probable error on all these measurements is ±20%. No corrections have been made for space-charge effects.

TABLE 1
EMITTANCE MEASUREMENTS

Set	Peak Current (A)	Lens 1 Current (A)	Bunch Charge (nC)	X_m (mm)	X'_{int} (mrad)	Normalized Emittance ($\beta\gamma = 3.0$) (π·mm·mrad)	Normalized Brightness ($A/(m^2 \cdot rad^2)$)
1	100	235	8	3.9	1.7	20	2.5×10^{10}
2	150	310	12	7.5	1.4	32	1.4×10^{10}
3	130	314	10	3.9	1.5	18	4×10^{10}

The beam energy measured on the double-focusing spectrometer agreed within 10% of the predicted value, 1.1 MeV. The measured energy spread was ±3%.

CONCLUSIONS

An advanced electron injector design concept, based on the photoinjector, has been demonstrated. The acceleration of the bright beam from the photoinjector may best be carried out in a staged, subharmonic- or fundamental-frequency linac combined with magnetic compression at relativistic energies.

ACKNOWLEDGMENTS

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REFERENCES

1 M. E. Jones and B. E. Carlsten, "Space-Charge-Induced Emittance Growth in the Transport of High-Brightness Electron Beams," Proc. 1987 Particle Accelerator Conference, Washington, D. C., March 16-19, 1987, to be published.

2. M. James, J. Clendenin, S. Ecklund, R. Miller, J. Sheppard, C. Sinclair, and J. Sodja, "Update on the High-Current Injector for the Stanford Linear Collider," IEEE Trans. Nucl. Sci. 30 (4), 2992-2994 (1983).

3. C. LeJeune and J. Aubert, "Emittance and Brightness: Definitions and Measurements," Applied Charge Particle Optics, A. Septier, Ed., Advances in Electronics and Electron Physics, Supp. 13A, 159-259 (1980).

4. P. Lapostolle, "Possible Emittance Increase Through Filamentation Due to Space Charge In Continuous Beams," IEEE Trans. Nucl. Sci. 18 (3), 1101-1104 (1971).

5. J. D. Lawson, *The Physics of Charged Particle Beams*, (Oxford University Press, 1977), p. 199.

6. C. H. Lee, P. E. Oettinger, E. R. Pugh, R. Klinkowstein, J. H. Jacob, J. S. Fraser, and R. L. Sheffield, "Electron Emission of Over 200 A/cm^2 from a Pulsed-Laser Irradiated Photocathode," IEEE Trans. Nucl. Sci. 32 (5), 3045-3047 (1985).

7. P. Oettinger, I. Bursuc, R. Shefer, and E. Pugh, "Brightness of an Intense Electron Beam Generated by a Pulse-Laser Irradiated Photocathode," Proc. 1987 Particle Accelerator Conf., Washington, D.C., March 16-19, 1987, to be published.

8. M. Weiss, "Bunching of Intense Proton Beams with Six-Dimensional Matching to the Linac Acceptance," unpublished CERN report CERN/MPS/LIN 73-2, February 1973.

9. M. E. Jones and W. K. Peter, "Particle-in-Cell Simulations of the Lasertron," IEEE Trans. Nucl. Sci. 32 (5), 1794-1796 (1985).

10. J. S. Fraser, "Electron Linac Injector Developments," Proc. 1986 Linear Accelerator Conf., Stanford Linear Accelerator Center report SLAC-303, 411-415 (1986).

11. G. A. Loew, "The SLAC Linear Collider and a Few Ideas on Future Linear Colliders," Proc. 1984 Linac Conf., Gesellschaft für Schwerionenforschung, Darmstadt report GSI-84-11, 282-287 (September 1984).

12. M. Yoshioka, M. Mutuo, Y. Fukushima, T. Kamei, H. Matsumoto, H. Mizuno, S. Noguchi, I. Sato, T. Shidara, T. Shintake, K. Takata, H. Kuroda, N. Nakano, H. Nishimura, K. Soda, M. Miyao, Y. Kato, T. Kanabe, and S. Takeda, "Lasertron: Laser Triggered RF-Source for Linacs in TeV Region," Proc. 1984 Linac Conf., Gesellschaft für Schwerionenforschung, Darmstadt report GSI-84-11, 469-471 (September 1984).

13. J. S. Fraser, R. L. Sheffield, E. R. Gray, P. M. Giles, R. W. Springer, and V. A. Loebs, "Photocathodes in Accelerator Applications," Proc. 1987 Particle Accelerator Conf., Washington, D.C., March 16-19, 1987, to be published.

14. T. I. Smith, "Intense Low Emittance Linac Beams for Free Electron Lasers," 1986 Linear Conf. Proc., Stanford Linear Accelerator Center report, SLAC-303, 421-425 (1986).

15. M. C. Crowley-Milling, "Linear Accelerators as Injectors for Cyclic Machines," in *Linear Accelerators*, P. M. Lapostolle and A. L. Septier, Eds., (North-Holland Publishing Co., Amsterdam, 1970), p. 495-522.

16. H. Herminghaus and K. H. Kaiser, "Design, Construction and Performance of the Energy Compressing System of the Mainz 300 MeV Electron Linac," Nucl. Instrum. & Methods **113**, 189 (1973).

17. W. A. Gillespie and M. G. Kelliher, "The Energy Compressor at the Glasgow 170 MeV Electron Linac," Nucl. Instrum. & Methods **184**, (2,3) 285-292 (1981).

18. N. Afanas'ev, A. Buki, Yu. Vladimirov, A. Dovbnya, G. Ivanov, G. Kramskoi, L. Makhneneko, V. Polishchuk, S. Ryadnykh, N. Schevchenko, and V. Shendrik, "Energy Compressor for a 300 MeV Electron Linac," Sov. Phys. Tech. Phys. **29** (31), 308 (1984).

19. S. B. Segall, "Hybrid Accelerator Design for a Free Electron Laser," IEEE Trans. Nucl. Sci. **32** (5), 3380-3382 (1985).

20. D. T. Pierce, R. J. Celotta, G. C. Wang, W. N. Unertl, A. Galens, C. E. Kuyatt, and S. R. Mielczarek, "GaAs Spin Polarized Electron Source," Rev. Sci. Instrum. **51**, 478-499 (1980).

21. C. K. Sinclair and R. H. Miller, "A High Current, Short Pulse, RF Synchronized Electron Source for the Stanford Linear Collider," IEEE Trans. Nucl. Sci. **28** (3), 2649-2651 (1981).

22. C. H. Lee, P. E. Oettinger, A. Sliski, and M. Fishbein, "Practical Laser Activated Photo-emissive Electron Source," Rev. Sci. Instrum. **56**, (4) 560-562 (1985).

23. C. C. Phillips, A. E. Hughes, and W. Sibbett, "Photochron Streak Camera with GaAs Photo-Cathode," in *Ultrafast Phenomena IV*, D. H. Auston and K.W.B. Eisenthal, Eds., Springer-Verlag, Berlin, 1984, p. 420-422.

24. W. E. Spicer, "Photoemissive, Photoconductive, and Optical Absorption Studies of Alkali-Antimonide Compounds," Phys. Rev. 112, 114-122 (1958).

25. M. E. Jones and W. K. Peter, "Theory and Simulation of High-Brightness Electron Beam Production From Laser-Irradiated Photocathodes in the Presence of DC and RF Electric Fields," Proc. 6th Int. Conf. on High-Power Particle Beams, Kobe, Japan, 1986, to be published.