High-Brightness Electron Injectors: A Review*

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Abstract

The last decade has seen increased emphasis on the development of high-brightness electron beams because of rigorous requirements of the new generation of colliders and the advent of free-electron lasers. This talk describes the approaches now being explored for attaining intense, bright electron beams. The methods for producing bright electron beams include photocathode-based, short-pulse injectors; dc electrostatic accelerator sources; long-pulse beams, which are then compressed in time using subharmonic bunching; combining first and third harmonics in an accelerator to attain the equivalent of high-gradient dc fields; and LaB_6 rf guns. For several of the approaches, the temporal length of the electron pulse is decreased after acceleration to relativistic energies by impressing an energy spread on the electron bunch and using a nonisochronous beam-transport system to increase the peak current.

Introduction

Free-electron oscillators require electron accelerators capable of delivering pulse trains of electron bunches of high brightness to a wiggler or undulator.[1] A high brightness implies a high peak current (10 A to 2000 A) and a low transverse beam emittance (2 to 80 π·mm·mrad, determined by matching the transverse size of the electron beam to the optical beam in the wiggler). Electron-beam collider machines also require high peak currents (>2 nC in picoseconds) with extremely small emittances (<10 π·mm·mrad).[2]

Several approaches have been proposed to attain such performance.[3-6] The technology for the production of bright electron beams can be divided into two distinct catagories: long pulse (>1 ns) or dc electron sources and short pulse (<100 ps) electron sources.

In the first catagory, electron guns using a long pulse or a dc beam rely on a well-designed gun producing a beam that has a beam temperature near the thermal limit of the electron source. The beamline design after the gun depends on if the application ultimitely requires a dc beam or a short pulse. For a dc beam (or pulsed beams where the pulse end effects are negligible), very good quality beams can be produced if care is taken in the beam transport design. If the application requires a short pulse, then a bunching system must be designed that preserves the beam quality throughout the bunching and acceleration process. Preserving beam quality is difficult because of the effects of nonlinear rf fields in the bunching cavities and the space-charge forces present at subrelativistic energies.

The second catagory uses a light-activated photoemissive electron source placed directly in the first accelerating cavity (Fig. 1). This design has the advantage of rapidly accelerating the electrons to relativistic energies before substantial degradation in the beam quality caused by space charge can occur. The idea of using photocathodes as high-current electron sources started with lasertrons[7-9] and the production of spin-polarized electrons.[10,11] A light-activated electron source gives unprecedented control over all aspects of the electron distribution: peak current, spatial profile, and temporal profile. This control is possible because the electron distribution is not determined by grids or a cathode, but rather by an incident laser pulse on the photocathode, and lasers have a wide range of variability in pulse format. Pulse lengths can range from femtoseconds to continuous and, for pulses greater than several picoseconds, can have almost any conceivable temporal profile.[12-14]

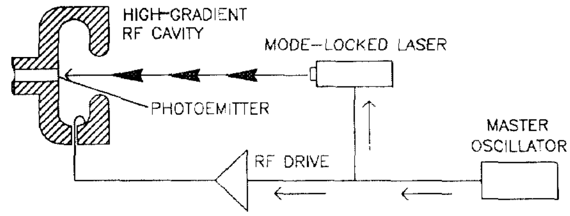

Fig. 1. Schematic of a photoinjector.

Intrinsic Source Brightness

The normalized peak brightness is defined as

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

where I is the peak current and ε_x and ε_y are the normalized transverse emittances of the beam.[15] For a thermal distribution or a distribution that does not have recoverable correlations in phase space, it is constructive to use the rms emittance formulation, defined to be the area in phase space, which is

$$\varepsilon_x = 4\pi(\langle x^2\rangle \cdot \langle x'^2\rangle - \langle x \cdot x'\rangle^2)^{1/2} \ ,$$

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 f(x,y,z):

$$\langle x^2\rangle = \frac{\int\int\int f(x,y,z)\, x^2\, dx\, dy\, dz}{\int\int\int f(x,y,z)\, dx\, dy\, dz} \ .$$

Another common definition of emittance is as the area in phase space divided by π, with the π included in the units.

Using the above formulation, the rms emittance is equal to the total phase-space area for a Kapchinskii-Vladimirskii distribution.[16] 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

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

because $\langle x \cdot x'\rangle = 0$ at the cathode.[17] 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

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is

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

The corresponding normalized peak brightness is limited to

$B_n = 2 I/\varepsilon_n^2 = 8.2 \times 10^9$ J [units: A/(m $\cdot$ rad)^2].

The current density from a dispenser cathode is typically not more than 20 A/cm^2; therefore, the maximum achievable brightness is 1.6×10^{11}.

Semiconductor photoemitters have an effective temperature of 0.2 eV (Ref. 18). The electron thermal temperature is not simply the difference between the incident photon energy and the semiconductor band gap (a difference of 0.7 eV) because of phonon scattering in the semiconductor crystal lattice. Semiconductor cathodes are capable of delivering[19] over 600 A/cm^2, giving a brightness of 2.5×10^{12} A/(m $\cdot$ rad)^2.

The brightness of the source normally does not limit the final brightness of the beam. Instead, the acceleration process and transport through a beamline can decrease the beam brightness by several orders of magnitude.

DC Injectors

The following information on very long pulse (>> 1 ns) and dc injectors is a summary of a paper[6] by W. Herrmannsfeldt. These types of guns are well suited for two applications: first, for electron cooling of ion beams and, second, for electrostatic free electron lasers (FEL).

The design of a dc gun must include the effects of space charge. In the gun, the space-charge self-force in the beam must be cancelled out with a carefully designed focusing electrode (at the Pierce angle[20]), thus maintaining a uniform current density. Also, the exit energy of the beam from the gun should be as high as possible to minimize further space charge defocusing downstream from the gun. If the beam maintains a uniform profile up to relativistic energies, then the beam emittance can be near the thermal temperature of the beam as it was emitted from the cathode. The emittance of the beam caused by thermal effects is discussed in the preceding section.

A gun designed by Herrmannsfeldt for the UCSB FEL and described in a paper[21] by Elias and Ramian is shown in Fig. 2.

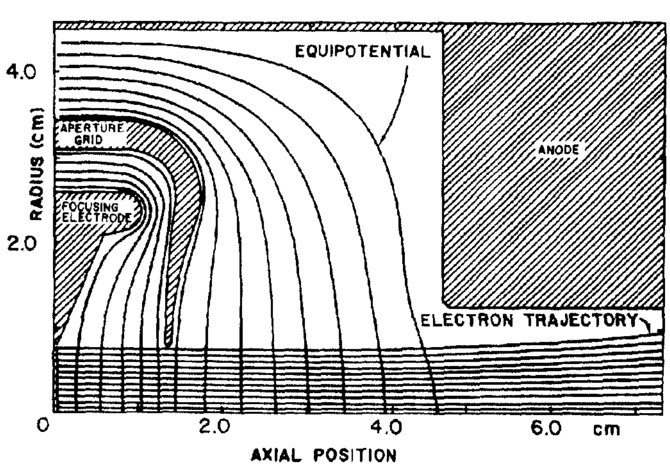
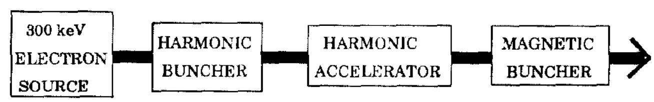


Fig. 2. A dc gun designed for UCSB's electrostatic accelerator.

Injectors Using Third Harmonic Cavities

Bunches accelerated with a dc field do not suffer the emittance growth that is due to time-varying effects typically found in rf accelerators. Harmonics can be used to eliminate this source of emittance growth. A design[4,22] that corrects for the time-varying fields in a radio-frequency (rf) accelerator uses cavities that operate at the third harmonic of the main linac frequency. Two conditions must be met to approximate a dc accelerating field during pulse transit. First, the amplitude of the third harmonic is set to nine times the fundamental frequency's amplitude. Second, the phase of the third harmonic is chosen to decelerate the bunch at the peak acceleration of the fundamental. The amplitude is flat to within 0.1% over 37° of the rf. However, the resulting two-frequency cavity will have increased phase and amplitude control complexity.

For relativistic beams, the harmonic component may be added with separate cavities, considerably reducing cavity design and control complexity. Improved accelerator performance using separated cavities for the first and third harmonic has been verified using PARMELA by Todd Smith.[4] After initial acceleration to several MeV with a long pulse (to minimize space-charge effects), the peak current is then increased using magnetic compression. A schematic of the design is given in Fig. 3.



ENERGY:	300 keV	300 keV	2.5 MeV	2.5 MeV
BUNCH LENGTH:	333 ps	100 ps	100 ps	5 ps
PEAK CURRENT:	3 A	10 A	10 A	200 A

Fig. 3. Injector designed by T. Smith for the Stanford High-Energy Physics Laboratory's Superconducting Accelerator. Calculated emittance using PARMELA is 20 $\pi$$\cdot$mm$\cdot$mrad.

Photoinjectors

A photoinjector is a photoemissive electron source placed directly in an rf cavity. The photoinjector design depends on the electron bunch produced from a photocathode being rapidly accelerated to relativistic energies in a single rf cavity, hence eliminating the conventional bunching process entirely. The emittance growth of the electron beam is reduced because electron-beam transport at low energies has been significantly reduced.

Los Alamos Experiment

Experiment Design. The Los Alamos experiment uses a laser-driven photocathode electron source situated on-axis in the first rf cavity. The electron-pulse shape is easily tailored in both time and space by appropriately shaping the incident laser pulse. The configuration of the experiment is shown in Fig. 4. The linac has two 1300-MHz rf cavities with independent amplitude and phase controls. Both rf cavities have loops to measure the phase and amplitude of the rf fields present in the cavities. Following the second cell are the diagnostics for bunch charge, beam energy, emittance, and temporal profile. The details of the rf cavity design are presented elsewhere.[23]

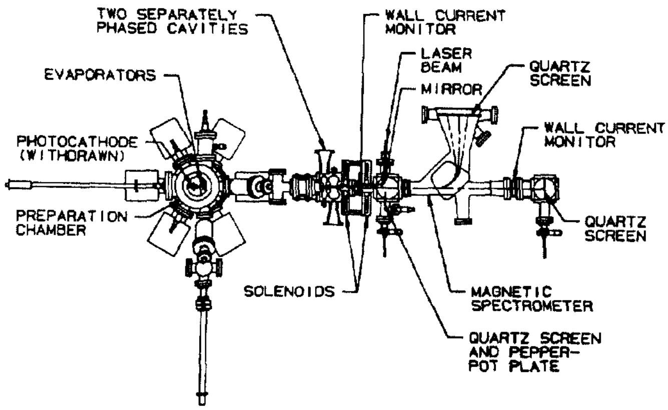


Fig. 4. Two-cavity experiment showing gun, beam transport, and diagnostics.

The photocathodes are fabricated in a preparation chamber vacuum coupled to the rf linac. Following fabrication in the preparation chamber, the photocathode is inserted into the rf cavity. When the quantum efficiency of the photocathode decreases below some arbitrary minimum value, the substrate is pulled back and heat cleaned at 400°C. A new photocathode is then fabricated over the existing substrate without opening the UHV system.

The photocathode is illuminated with a frequency-doubled Nd:YAG laser. The laser is mode locked at the twelfth subharmonic of 1300 MHz, 108.33 MHz. The mode-locking crystal is driven by the same master oscillator that drives the 1300-MHz rf klystron and is phase locked to the rf. The laser generates 100-ps pulses at 1.06 µm that, after frequency doubling to 532 nm, become 70-ps-long pulses. A Spectra-physics pulse compressor was added to the optical train for generation of 4- to 20-ps pulses. The power available at 532 nm is approximately an average of 250 kW over 10 µs.

Experiment Results. The electron energy gain for typical operation was 0.9 MeV in the first cavity and 1.8 MeV in the second cavity. This corresponds to operating both cavities at approximately 2 Kilpatrick (58 MeV/m peak surface field).

The laser pulse length was limited by the gain bandwidth of the Nd:YAG amplifiers to approximately 16 ps. The maximum charge extracted for this pulse was 13.2 nC from 1 cm^2 of photocathode surface. This gives 820 A/cm^2 of current density at the cathode. However, PARMELA simulations predict that a 16-ps electron pulse increases to 22 ps on passage through the first cavity, giving a peak current after the first cavity of 600 A.

The emittance measurements were performed on an earlier experiment that used only a single rf cavity. The experimental parameters were 11 nC (200-A peak), 70-ps Gaussian temporal width, <0.4-cm beam radius at the cathode (was not accurately measured at the time of the experiment and only the upper bound is known), 1.0-MeV beam energy, and a solenoid field of 1.8 kg. The measured emittance was 40 π·mm·mrad. The measured emittance did not agree with a PIC simulation (which gave greater than 150 π·mm·mrad) of the experiment. This disagreement led to a detailed examination of the gun, beamline, and the pepper-pot emittance diagnostic using PARMELA, MASK,[24] and ISIS[25] simulations.

The experimental and simulated electron-beam diameter at the pepper pot and the diameters of the beamlets produced by the pepper pot at the second quartz screen are in close agreement, confirming the accuracy of the simulations. The emittance of the electron beam for that experiment, with 10 nC per bunch, was calculated from the simulations to be 120 π·mm·mrad for 100% of the beam. Simulations[24] show that, if the beam is clipped in time and left with 75% of the original charge, then the emittance of the remaining beam was calculated to be 40 π·mm·mrad in agreement with the experimental results. The results of the MASK calculations are shown in Fig. 5 (Ref. 5). The large decrease in beam emittance with a small decrease in the charge is due to the temporal tails of the long Gaussian pulse used in the previous experiment. Because the focusing solenoid downstream of the cavities can only be properly matched for one space-charge density, the beam is matched only for the peak of the Gaussian pulse, and the head and tail of the electron bunch are overfocused. The low-intensity tails from all the beamlets overlap on the pepper-pot screen; therefore, an individual beamlet's spatial distribution cannot be resolved unambiguously. Hence, an experimental emittance value was obtained for only the temporal core of the electron bunch.

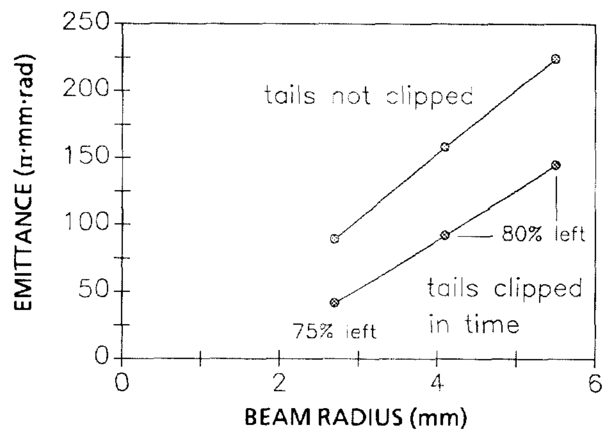


Fig. 5. The beam emittance from MASK simulations (performed by Bill Herrmannsfeldt of SLAC) are within the experimental error in beam radius if the temporal tails of the Gaussian pulse are not included. The two curves show the difference in emittance gained by excluding a small fraction of the charge at the front and tail of the pulse.

Although neglecting the temporal tails of the distribution consequently gives low emittances, most applications of bright electron beams depend upon only the bright central core of the electron bunch. More importantly, the accuracy of the simulation codes have been verified for future linac design.

Duke-Rocketdyne Experiment

The construction of the Mark III accelerator has been described in detail elsewhere.[3] The layout of the experiment is shown in Fig. 6. The machine parameters are as follows: macropulse length of 2 to 5 µs, micropulse length of 2.2 ps, gun energy of 1 MeV, and a magnetic compression of 10 from the alpha magnet. The alpha magnet is a momentum filter and is able to limit the electron energy spread to less than 0.5%.

The electron source in the Mark III is a LaB_6 cathode. Originally the cathode produced electrons by pure thermal emission. However, because the electrons are emitted at all phases of the rf, many of the electrons are accelerated at the wrong phases for matching into the main linac.

The current emission from the cathode is limited by average-power heating; therefore, using the laser to limit the emission to the correct rf phase, higher peak currents can be

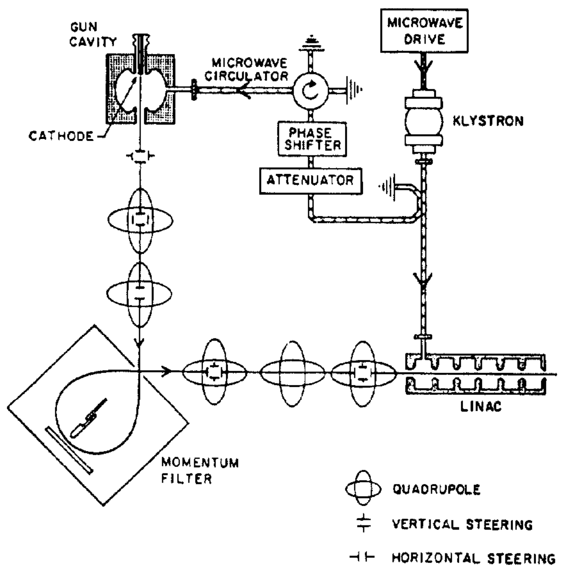


Fig. 6. Schematic of the experiment showing microwave feed system and the path of the electrons from the laser-switched thermionic gun to the Mark III accelerator.

obtained.[26] In this mode, the LaB_6 cathode was operated just below its normal emission temperature, and a laser was used to pulse the cathode. Operation with the laser resulted in an increase in peak current from 33 to 75 A with no observable loss in beam emittance. The gun brightness was approximately 5×10^{12} A/(m-rad)^2.

During operation, the gun pressure was about 5×10^{9}. Not enough operation time has been available to study the cathode lifetime; but based on previous performance, the expected lifetime should be much greater than 1000 hours.

Present Photoinjector Designs

Los Alamos National Laboratory

Two separate initiatives are now underway at Los Alamos based on photoinjector technology.

Design of a Compact Linac. Design of a 20-MeV compact linac based on the photoinjector has been completed. The linac is approximately 1.2 m long and will be operated with a 10-µs macropulse at up to 15 Hz with a 0.5-A average during the macropulse. The design of the linac is based on emittance reduction by reversing the effects of space charge after the photoinjector gun.[27-29] The final electron-beam characteristics from PARMELA simulations are a beam emittance of less than 20 π·mm·mrad and peak currents in excess of 350 A. Magnetic compression of the 16-ps electron pulse can increase the peak current to greater than 500 A. The limit in peak current depends on the application. For instance, a free-electron laser oscillator is very sensitive to the jitter in the arrival time of the electron bunches in the wiggler. Because variations in the electron bunch charge cause variations in the final electron-beam energy, the amplitude stability of the photocathode laser system, which produces the electron bunches, will determine the maximum amount of pulse compression allowed (a change in the electron-beam energy maps into a change in time in the magnetic compressor).

Upgrade of Los Alamos FEL Accelerator. The Los Alamos FEL is now being upgraded to provide electron beams of the quality and intensity required by advanced FELs. The improved electron beam is primarily the result of adding a photoinjector to the accelerator. However, the entire device is being modified to demonstrate that the beam quality can be transported to the FEL without degradation. The facility should provide initial data by summer, 1989. This facility will provide a good benchmark for the computational models used to design advanced FELs because the same models will design the photoinjector, beam transport, oscillator, and amplifier. The design goals of the accelerator are 40 MeV of electron energy, peak currents of 400 A, and a normalized emittance less than 50 π·mm·mrad (90%). An experiment layout is given in Fig. 7.

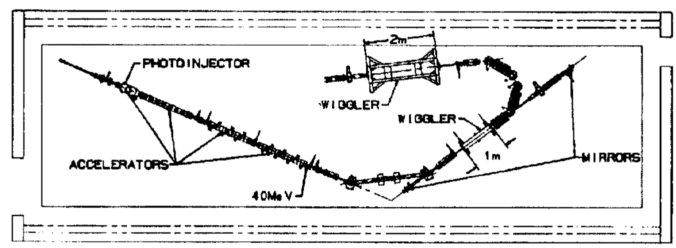


Fig. 7. Upgrade of the Los Alamos FEL with photoinjector.

Brookhaven National Laboratory

The Accelerator Test Facility at Brookhaven National Laboratory (BNL) is being developed into a research facility for laser acceleration and FELs. The design goal for the accelerator is 50 MeV at an emittance of 15 π·mm·mrad. The research team at BNL are building (scheduled for operation in spring of 1989) a 2.856-GHz photoinjector to drive the linac.[30] The S-band, standing wave, disk-loaded structure will operate in the short rf pulse regime (6 µs). The gun is designed for a maximum surface field of 120 MV/m and a pulse repetition rate of 5 Hz.

The surface field at the cathode is 102 MV/m. The energy gain in the 1 1/2-cell structure is 4.9 MeV. The disk-loaded structure was designed to minimize the ratio of the peak surface field to the field at the cathode surface and is not optimized for maximum shunt impedance. To match to the π-mode in the cells, a side-wall coupling scheme is used. In this configuration, the TE_{10} waveguide mode couples strongly to the π-mode and does not, to first order, couple to the zero mode. The π-mode operation was chosen to minimize emittance growth caused by rf defocusing fields in the accelerating gaps.[31]

Lawrence Berkeley Laboratory

A photoinjector design[32] at Lawrence Berkeley Laboratory (LBL) to produce bright beams for linear colliders, compact FELs, propagation of intense bright beams, and coherent x-ray holography has been completed. The rf cavity design is a 1.269-GHz rf cavity consisting of 2 1/2 cells with a peak surface field of 60 MV/m and a cathode field of 30 MV/m. The design goals are to obtain a 3- to 5-ps pulse length and a 1-nC charge at a gun exit energy of 5 MeV.

The photoinjector parameters were obtained by extensive PARMELA simulations[33] and theoretical analysis.[34] The exiting pulse from the gun has an rms length of 6 ps and a 0.6% energy spread. The calculated emittance is 8 to 15 π·mm·mrad.

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This design for a photoinjector is unique in that the rf gun cavity is superconducting.[35] The design parameters are

1.3 MeV, 5 to 70 ps, and pulse charge of 0.15 to 14 nC. Peak currents range from 2.3 to 200 A. This program will be studying the performance of high QE photocathodes on a niobium surface. A significant advantage to operating a photocathode in a superconducting cavity is that the possiblity of contamination of the photocathode by water or CO_2 will be greatly reduced.

LEL-HF in Bruyères-le-Chatel

This photoinjector design[36,37] has a much lower cavity frequency, 144 MHz, than the previous designs. A lower frequency can reduce the rf effects because the cavity apertures are larger and the fields approximate dc conditions during the electron transit. The design parameters are a beam with 10 to 20 nC, a 1- to 1.5-MeV exit energy from the first cavity, bunch lengths of 50 to 100 ps, an accelerator gap of 7 cm, and a surface field at the cathode of 15 to 20 MV/m.

The design was developed using ATHOS, PARMELA, and OAK. The expected emittance is approximately 20 π·mm·mrad. After initial acceleration to greater than 4 MeV, magnetic compression would be used to increase the peak current.

Summary

The production of high-current high-brightness electron beams has enjoyed considerable progress over the last several years, mainly because of changes in the requirements imposed by free electron lasers. Several approaches show considerable potential for producing very bright electron beams. The concept of placing a photoemissive source in an accelerating structure has been demonstrated. The basic physics of photoinjectors is understood and the technology is now in the initial engineering phases. Several groups around the world are designing bright beams based on this technology and continued improvement in photoinjector design is expected.

Acknowledgments

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References

[1] J. M. Watson, *IEEE Trans. Nucl. Sci.* **32** (5), 3363 (1985).

[2] R. B. Palmer, SLAC-PUB-4295, April (1987).

[3] S. V. Benson, J. Schultz, B. A. Hooper, R. Crane, and J. M. J. Madey, *Nucl. Instr. and Meth.*, **A272**, 22-28 (1988).

[4] T. I. Smith, *1986 Linear Conf. Proc.*, Stanford Linear Accelerator Center report, SLAC-303, 421-425 (1986).

[5] J. S. Fraser and R. L. Sheffield, *IEEE J. Quant. Electron.* **23** (9), 1489 (1987).

[6] W. B. Herrmannsfeldt, SLAC-PUB-4843, January (1989).

[7] 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, *Proc. 1984 Linac Conf.*, Gesellschaft fur Schwerionenforschung, Darmstadt report GSI-84-11,469-471 (1984).

[8] C. K. Sinclair, *AIP Proc. on Advanced Accel. Concepts*, Madison, WI, 156 (1986).

[9] P. J. Tallerico, R. L. Sheffield, W. D. Cornelius, E. R. Gray, M. T. Wilson, D. C. Nguyen, K. L. Meier, and R. L. Stockley, *1988 Linear Accel. Conf.*, Williamsburg, VA, October 2-7 (1988), to be published.

[10] D. T. Pierce, R. J. Celotta, G. C.Wang, W. N. Unertl, A. Galens, C. E. Kuyatt, and S. R. Mielczarek, *Rev. Sci. Instrum.* **51**, 478-499 (1980).

[11] C. K. Sinclair and R. H. Miller, *IEEE Trans. Nucl. Sci.* **28** (3), 2649-2651 (1981).

[12] A. M. Weiner, J. P. Heritage, and R. N. Thurston, *Opt. Lett* **11**(3), 153 (1986).

[13] M. Haner and W. S. Warren, *Opt. Lett.* **12** (6), 398 (1987).

[14] D. C. Nguyen, D. E. Watkins, and M. E. Weber, *SPIE Proc.*, January 11-16, Los Angeles, CA (1988).

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

[16] P. Lapostolle, *IEEE Trans. Nucl. Sci* **18** (3), 1101-1104 (1971).

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

[18] P. Oettinger, I. Bursuc, R. Shefer, and E. Pugh, *Proc. 1987 Part. Accel. Conf.*, IEEE Catalog No. 87CH2387-9, **1**, 288 (1987).

[19] 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 Part. Accel. Conf., IEEE Catalog No. 87CH2387-9, **3** 1705 (1987).

[20] J. R. Pierce, *Theory and Design of Electron Beams* (van Nostrand, 1949).

[21] L. R. Elias and G. Ramian, *Phys. Quant. Elect.* **9**, 577 (1982).

[22] T. Energa, L. Durieu, D. Michelson, and R. Worsham, *IEEE Trans. Nucl. Sci.* **32** (5), 2936 (1985)

[23] E. R. Gray and J. S. Fraser, *Proc. 1988 Linear Accel. Conf.*, Williamsburg, VA, October 3-7, 1988, to be published.

[24] W. Herrmannsfeldt, R. Miller, and H. Hanerfeld, SLAC-PUB-4663, June (1988).

[25] M. E. Jones and W. K. Peter, *Proc. 6th Int. Conf. High-Power Particle Beams*, Kobe, Japan (1986).

[26] S. V. Benson et al., Lasers 88, to be published (1988).

[27] B. E. Carlsten and R. L. Sheffield, *1988 Linear Accel. Conf.*, Williamsburg, VA, October 2-7, 1988, to be published.

[28] B. E. Carlsten, "Photoelectric Injector Design Code," these proceedings.

[29] B. E. Carlsten, 10th Int. FEL Conf., Jerusalem, Israel, August 29-September 2, (1988).

[30] K. Batchelor, J. Sheehan, and M. Woodle, Brookhaven Internal Report, BNL-41766 (1988).

[31] K. T. McDonald, Princeton University Report DOE/ER/3072-43, March (1988).

[32] S. Chattopadhyay, Y. J. Chen, D. Hopkins, K. J. Kim, A. Kung, R. Miller, A. Sessler, and T. Young, *Proc. 1988 Linear Accel. Conf.*, Williamsburg, VA, October 2-7, 1988, to be published.

[33] Y.-J. Chen, LBL internal notes, BES 4, ESG Tech Note-74.

[34] K.-J. Kim and Y.-J. Chen, *Proc. 1988 Linear Accel. Conf.*, Williamsburg, VA, October 2-7, 1988, to be published.

[35] H. Chaloupka, H. Heinrichs, H. Piel, C. K. Sinclair, F. Ebeling, T. Weiland, U. Klein, and H. P. Vogel, *Proc. Euro. Part. Accel. Conf.*, Rome, June 7-11 (1988).

[36] S. Joly, R. Dei-Cas, C. Bonetti, F. Cocu, J. P. De Brion, J. Frehaut, G. Haouat, A. Herscovici, H. Leboutet, and J. Siguad, *Proc. Euro. Accel. Conf.*, Rome, June 7-11, 1988, to be published.

[37] R. Dei-Cas et al., 10th Int. FEL Conf., Jerusalem, Israel, August 29-September 2, (1988).