RF PHOTOELECTRON GUN EXPERIMENTAL PERFORMANCE*

R. L. Sheffield, W. D. Cornelius, D. C. Nguyen, R. W. Springer, B. C. Lamartine, E. R. Gray, J. M. Watson, and J. S. Fraser**

MS H825, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract

Free-electron lasers require electron beams of high peak brightness. In this paper, we describe the performance of a compact high-brightness electron source for driving short-wavelength free-electron lasers. The experiment uses a laser-illuminated photoemitter located in the first rf cavity of a two-cavity linac. The photocathode source and associated hardware are described. The doubled ND:YAG laser (532 nm), which is used to drive the photocathode, produces 75-ps micropulses at a 108-MHz repetition rate and peak powers of approximately 300 kW. Diagnostics include a pepper-pot emittance analyzer, a magnetic spectrometer, and a <4-ps resolution streak camera. Present experiments give the following results: micropulse current amplitudes of 10 mA to 400 A, 75% beam emittances ranging from 10 π·mm·mrad to 40 π·mm·mrad and peak current densities of >600 A/cm^2. Results on photocathode lifetime will be presented. Future plans for applications of the photoinjector at Los Alamos National Laboratory are discussed.

Introduction

Free-electron laser (FEL) oscillators require electron bunches of high charge density and low emittance. Recent developments in photoemitter technology have demonstrated that high currents can be extracted from photoemitters.[1,2] 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.

Experimental 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. 1. The linac has two 1300-MHz rf cavities with independent amplitude and phase controls. The first cell of the linac has an on-axis photocathode incorporated directly into the back wall of the cavity. Both rf cavities have loops for measurement of phase and amplitudes of the rf fields present in the cavities. Following the second cell are diagnostics for bunch charge, beam energy, emittance, and temporal profile. The details of the rf cavity design and electron-beam diagnostics are presented at this conference.[3]

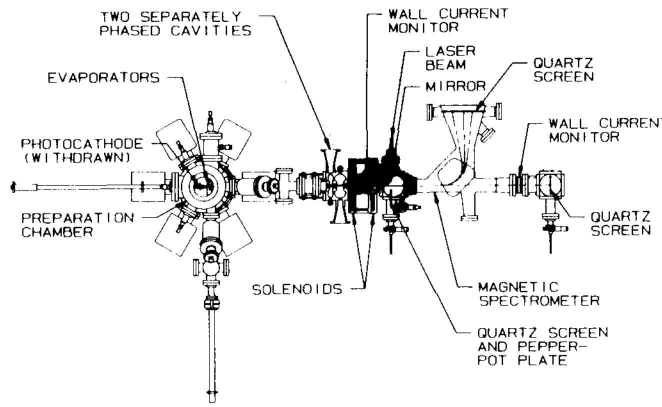

Fig. 1. Photoinjector, two-cavity experiment.

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 first experiments used Cs_3Sb as the photocathode material because of ease of fabrication. However, Cs_3Sb is not stable at room temperature and is therefore not useful for experiments of long duration. A different photocathode material (CsK_2Sb) is thermally stable up to 100° C and not only lasts significantly longer in the experiment, but also has a long shelf life.

The photocathode is illuminated with a frequency-doubled Nd:YAG laser (Fig. 2). The laser is mode-locked at the 12th 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

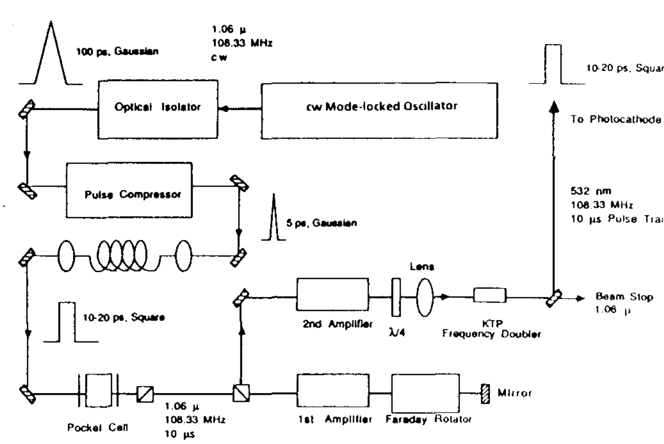

Fig. 2. Block diagram of the photocathode illuminator consisting of a cw mode-locked Nd:YAG oscillator and pulsed amplifiers.

*Work supported and funded by the US Department of Defense, Army Strategic Defense Command, under the auspices of the US Department of Energy.

**P. O. Box 1341 Ganges, British Columbia, VOS 1 EO, Canada

70 ps long. 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 250 kW average over 10 μs.

Experiment Results

The electron energy distribution for a 10-μs train of 28-ps pulses is shown in Fig. 3. 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 MV/m) peak surface field.

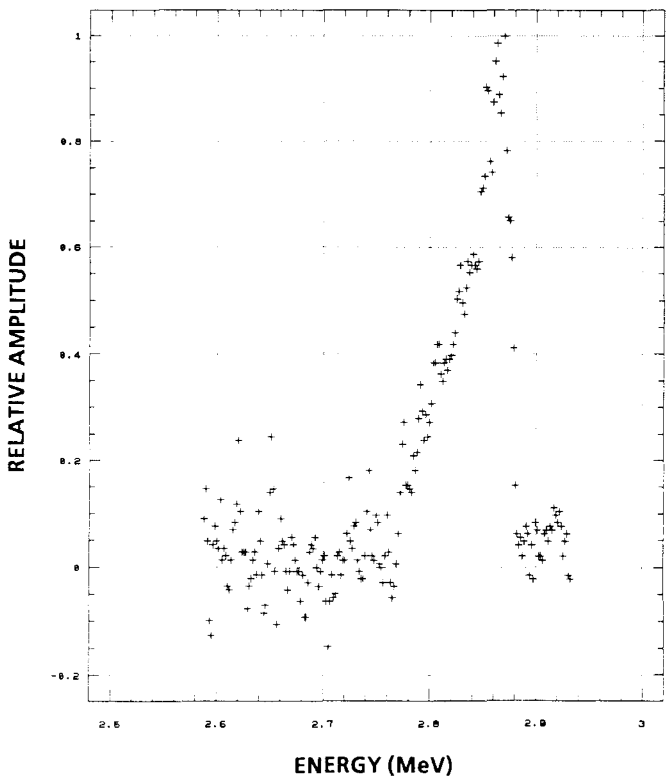

Fig. 3. Energy spectrum for 28-ps pulse.

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 lifetime of the photocathode electron source has improved markedly since the initial measurements two years ago. The measurements are presented in Table I.

Table I. Lifetime Measurements on Photoinjector Experiment

Photocathode	Rep rate (Hz)	Pulse length (μs)	Average Current Macropulse (A)	1/e life (h)
Cs_3Sb (9/87)	1	5	1	0.5
CsK_2Sb (2/88)	10	10	1	2.0
CsK_2Sb (8/88)	10	10	0.5	17.5

The first major improvement in cathode lifetime (9/87 to 2/88) occurred because of the switch from Cs_3Sb to CsK_2Sb photocathodes. After the switch of photocathode materials, we noticed that the photocathode response (current extracted versus laser power input) would be nearly constant for the first hour and then begin to degrade at a much faster rate. From this we determined that the electron spectrometer quartz screen (used as the beam dump for the lifetime experiments) was getting excessively hot (see Fig. 1). The temperature rise increased the outgassing rate of the beam dump to the point where the photocathode performance was affected. This problem was eliminated by using a water-cooled copper beam stop beginning in August 1988. We believe that the final lifetime value (8/88) in Table I is limited primarily by the outer fringe of the beam hitting the downstream beam-transport tubes because of nonuniform beam space charge and the long drift.

In separate experiments, photocathode lifetimes were measured in low current dc operation. Over 400 coulombs have been extracted from a CsK_2Sb photocathode over 2 days of operation. In a third apparatus for shelf-life testing, another photocathode was fabricated with an initial quantum efficiency of 7.5% and did not have any observable degradation over 2 months.

The beam emittance cannot be directly measured in this experiment because of the space-charge-induced emittance growth in the long drift between the second cavity and the pepper-pot plate. However, an emittance measurement of the beam was carried out in the previous single-cavity experiment, and this result was compared with the PARMELA, MASK,[4] and ISIS[5] simulations. The results are shown in Fig. 4. 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 theelectron 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 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,[4] in agreement with

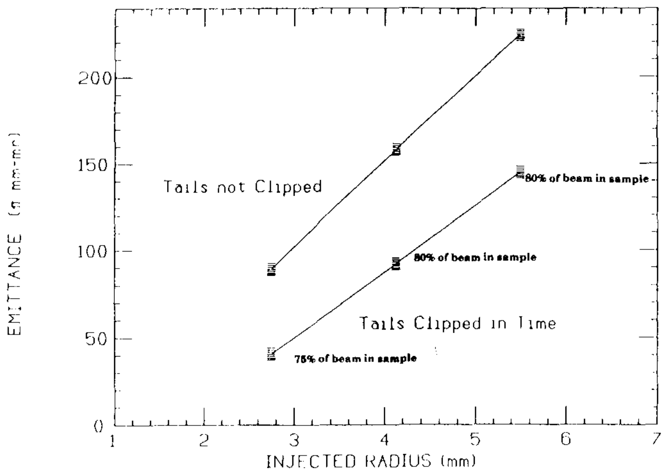

Fig. 4. Emittance vs injected pulse radius.

the experimental results. 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 only matched for the peak of the Gaussian pulse, and the head and tail of the electron bunch are overfocused. The low intensity tails from all of the beamlets overlap on the pepper-pot viewing screen and so an individual beamlet's spatial distribution cannot be unambiguously resolved. Hence an experimental emittance value was obtained only for the temporal core of the electron bunch.

This analysis gives the following results:

Table II. Experimental Measurements of Beam Emittance

DATA SET	Actual Current (A)	Actual Bunch Charge (nC)	Derated Charge (nC)	Normalized Emittance ($\beta\gamma = 3.0$) (π·mm·mrad)	Norm. Brightness $1/\gamma^2$ (A/m^2·rad^2)
1	50	4	3	10	5×10^{10}
2	100	8	6	24	2×10^{10}
3	150	11	8	39	1×10^{10}
4	200	15	11	40	1.3×10^{10}

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

The theoretical simulations[6] show that for a properly tailored light pulse (square in time and in spatial extent), 90% of the beam will have the emittances shown in Table II. However, because a drifting electron beam experiences emittance growth over tens of centimeters even at a relativistic gamma factor of 5, the only way to accurately determine the electron beam emittance from an rf photocathode gun is to measure the beam quality after acceleration greater than 15 MeV.

Future Research

Design of a 15-MeV compact linac based on the photoinjector has been started. The linac will be approximately 1.2 m long and operated with a 10-μs macropulse at up to 15 Hz with 0.5 A average during the macropulse. The final electron beam characteristics from PARMELA simulations are a beam emittance of less than 35 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 temporal 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 that 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).

Conclusions

The photoinjector experiment has now been completed. The performance of the device has been fully characterized and is well understood. Present photocathode performance meets the requirements of most research programs requiring high-brightness beams (1-4 weeks of operation depending on duty factor). Further experiments on improving photocathode lifetime will be carried out during the lasertron experiments,[7] which, were started this September.

Acknowledgments

The authors are grateful to Robert Hoeberling, John Kinross-Wright, Donald Greenwood, Noel Okay, Louis Rivera, Jake Salazar, Boyd Sherwood, Floyd Sigler, Scott Volz, and Reine Mussett for assistance in the design, construction, and operation of the experiment.

References

[1] J. S. Fraser and R. L. Sheffield, IEEE J. Quan. Elec. QE-23 (9), 1489 (1987).

[2] C. H. Lee, P. E. Oettinger, E. R. Pugh, R. Klinkowstein, J. H. Jacob, J. S. Fraser, and R. L. Sheffield, IEEE Trans. Nucl. Sci. 32 (5), 3045 (1985).

[3] E. R. Gray and J. S. Fraser, these proceedings.

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

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

[6] Bruce Carlsten and R. L. Sheffield, these proceedings.

[7] P. J. Tallerico, R. L. Sheffield, and W. D. Cornelius, these proceedings.