IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

ELECTRON EMISSION OF OVER 200 A/CM^2 FROM A PULSED-LASER IRRADIATED PHOTOCATHODE*

C. H. Lee and P. E. Oettinger, Thermo Electron Corporation, Waltham, MA 02254
E. R. Pugh, Physical Sciences Incorporated, Andover, MA 01810
R. Klinkowstein and J. H. Jacob, Science Research Corporation, Cambridge, MA 02138
J. S. Fraser and R. L. Sheffield, Los Alamos National Laboratory, Los Alamos, NM 87545 USA

Summary

High-current-density, bunched electron beams with low emittance are required for efficient operation of rf-linac-driven free-electron lasers (FELs). Laser-irradiated, photoemissive electron sources are suitable for this application. Currents of over 200 A have been generated in an ultrahigh vacuum chamber from a 1-cm^2 Cs_3Sb photocathode irradiated by a frequency-doubled, Q-switched pulse from a Nd:glass laser. These currents are over two times larger than previously reported from any photocathode. The duration of the electron pulse was 50 ns (FWHM), corresponding to the width of the 532-nm laser pulse.

Introduction

The rf linacs used to drive FELs traditionally operate at low average currents. Conventional dispenser cathodes can provide these currents. For efficient FEL operation, the thermionically emitted electrons are prebunched by rf fields before being injected into the accelerator. Peak currents of several hundred amperes in these bunches can be achieved. However, both the thermal spread of the emitted electrons and the process of bunching these electrons in the rf cavities contribute to an undesirably large emittance of the beam.

The prospect of a different electron source with reduced energy spread and one that has, in addition, the capability of emitting the electrons in high-density pulses is very attractive, because it eliminates the bunching cavities. Laser-driven photoemitters appear to meet these specifications. In fact, the use of semiconducting photoemissive cathodes as stable high-current-density electron sources already is becoming a reality.

Traditionally, photocathodes are used as detectors to measure extremely low levels of light. The photosensitive surfaces are enclosed in tube structures containing nonpoisoning vapors at moderate vacuums (10^{-6} torr). Small current densities of nanoamperes-to-microamperes per centimeter can be emitted stably. Operating such photocathodes at better vacuum levels and illuminating them with higher-power laser radiation, spectrally matched to the surface's photoemissive response, can provide high-brightness electron beams.

Prototypes of laser-driven photocathodes have been developed already. Continuous emission of over 3 A/cm^2 was achieved from a 37-μm-square, semitransparent Cs_3Sb photocathode, back illuminated by an argon ion laser.[1] Energy spreads below 0.3 eV were recorded for laser wavelengths between 458 and 515 nm, and these spreads decreased to 0.1 eV with He-Ne laser irradiation at 633 nm.[2] The brightness of the beam activated at 488 nm substantially exceeded that observed for LaB_6 thermionic sources.[3] In pulsed emission, a 20-ns KrF excimer laser beam, operating at 249 nm, extracted a current of 1 A from a 2-cm^2 aluminum surface.[4] A much larger emission of 60 A in a 1-ns burst was obtained from GaAs (Cs,O) activated bv a frequency-doubled Nd:YAG laser.[5] Recently, a group of investigators at the University of Tokyo has irradiated a 1.33-cm^2 bialkali antimonide photoemissive surface at 532-nm wavelength and generated a train of picosecond pulses with peak current densities of 75 A/cm^2.[6] Each pulse in the train was ~35 ps long, with a pulse repetition frequency of 2884 MHz (etalon up-converted from the mode-locked, Nd:YAG laser-pulse frequency of 169.6 MHz).

In this paper, we report on the emission of electron pulses, with peak current densities of over 200 A, from a Cs_3Sb photocathode irradiated by a 50-ns (FWHM) frequency-doubled, Nd:glass laser beam.

Experiment

The experiment was performed in a vacuum chamber pumped to 10^{-9} torr (Fig. 1). A Cs_3Sb photo-cathode was fabricated in situ in the following manner: A nickel-plated copper substrate was retracted from its normal operating position in contact with the cathode plate shown in the figure. The substrate was first thermally cleaned by resistance heating to 450°C. Next, a thin film of antimony was deposited on the surface from a resistance-heated antimony bead. The thickness of this film was monitored by simultaneously depositing antimony on an adjacent glass slide and monitoring the optical transmittance of a He-Ne laser beam. Finally, with the photocathode substrate maintained at 130°C, a metallic channel, containing cesium chromate, was heated to supply cesium to the antimony layer. Optimized deposition was achieved by irradiating the surface with a low-intensity white-light source and monitoring the photoemission continuously during this procedure. Upon reaching the maximum photocurrent, the cesium supply was shut off. The completed photocathode was then pushed forward from its retracted position until it made contact with the area around a 1-cm^2 hole in the 0.075-cm-thick stainless steel corona shield. The edges of this hole were beveled at the appropriate 22° Pierce angle to minimize beam expansion at a total current of 200 A.

With ceramic stand-offs in the support structure, both the corona shield and the cathode were electrically isolated from ground. A current lead from the cathode fixture passed through an insulated feedthrough in the vacuum chamber to externally connect the cathode to ground. A Pearson current transformer surrounded this lead outside the chamber and measured the photocurrent emitted by the cathode.

The anode of the diode was a stainless steel torus with a major diameter of 7.0 cm and a minor diameter of 2.5 cm. The torus was turned on edge with its closest point located ~4.6 mm from the photocathode surface. The frequency-doubled beam from the Nd:glass laser was transmitted through a window in the vacuum chamber, irradiating the photocathode at an angle of about 65° to the normal.

The electron-beam accelerating field was provided by a 200-kV dc power supply that charged a 500-pF capacitor outside the vacuum chamber connected directly to the high-voltage feedthrough to the anode. At applied voltages above 50 kV, a four-stage Marx generator, with an erected capacitance of 1350 pF, supplied the field. Each stage could be charged to a maximum of 30 kV. Large overvoltages at the diode, which led to undesirable premature breakdown, were limited by damping resistors located in the Marx

*Work performed under the auspices of the Dept. of Energy and supported by the Dept. of Defense Ballistic Missile Defense Advanced Technology Center.

0018-9499/85/1000-3045$01.00© 1985 IEEE

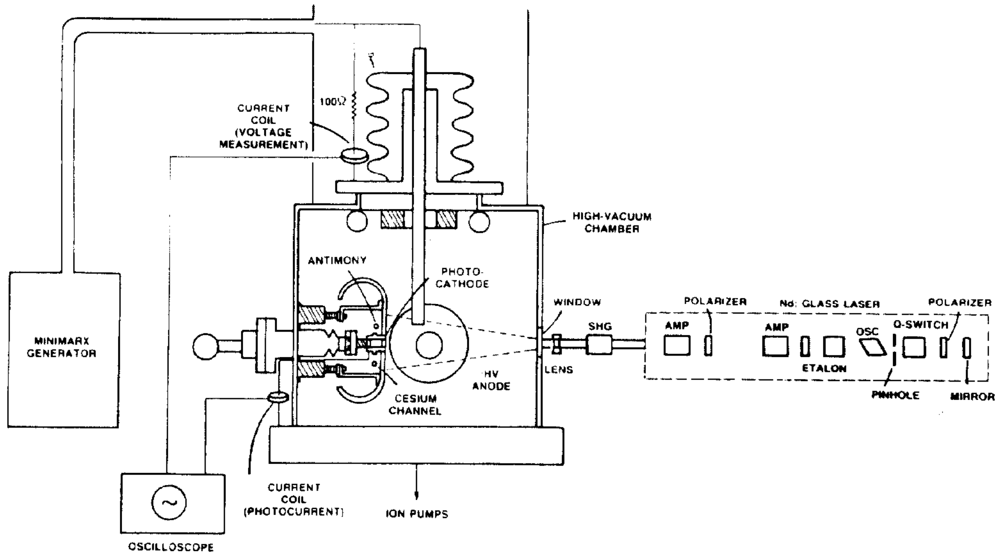

Fig. 1. Experimental apparatus. A toroidal anode is suspended on a high-voltage feedthrough and located, edge-on, about 5 mm from the photocathode. The outer edge of the cathode plate is curved back to form a corona shield. The photocathode is shown in its operating position. A Q-switched, Nd:glass laser illuminates the photocathode at an angle of about 65° to the normal. The photocathode substrate is retractable to a position where it is exposed to the cesium and antimony evaporators.

power supply. By using an appropriate delay circuit, we forced the laser beam to emit 0.5 to 1 μs after the Marx generator was fired, which was sufficient time to allow any voltage oscillations on the diode to die out.

Results and Discussion

Cs_3Sb is a positive electron affinity photoemissive material, which is relatively easy to fabricate, and which, when irradiated at the frequency-doubled Nd:glass laser emission of 532 nm (2.33 eV), should operate with a quantum efficiency of about 4%. The threshold of emission for Cs_3Sb is 640 nm (1.94 eV). Nominal energy spreads at 532 nm are expected to be about 0.2 eV.[2]

If this energy spread is maintained at high currents, then the thermal limit of the beam's transverse emittance can be calculated as follows: Define the normalized emittance ϵ_n as

$$\epsilon_n = \pi \, \beta \, \gamma \, r \, \theta \tag{1}$$

where θ is the ratio of the transverse-to-longitudinal-electron momentum,

$$\theta = \frac{v_\perp}{\beta\gamma c} \cong \frac{1}{\beta\gamma} \left(\frac{2\,E_\perp}{m_o c^2}\right)^{1/2} \quad , \tag{2}$$

and r is the radius of the emitter. Substituting Eq. (2) into Eq. (1),

$$E_n \cong \pi \, r \left(\frac{2\,E_\perp}{m_o c^2}\right)^{1/2} \quad . \tag{3}$$

If we can consider the energy spread to be a good approximation for the transverse energy $E_\perp$ of these photocathodes, the thermal limit of the normalized emittance of a 1-cm^2 beam will be about 5 π•mm•mrad. Requirements of the Los Alamos rf linac FEL include a beam emittance in the 10 to 30 π•mm•mrad range.[7] For a current of 200 A, this low emittance would be a significant improvement over the measured values of operating accelerators.[8] How low this small emittance near the cathode can be maintained as the electrons are accelerated through actual devices has yet to be demonstrated.

The experimental data of this study are presented in Figure 2. The photocurrents are seen to be dependent on the applied voltage to the three-halves power. Because of the rounded surfaces of the anode, the effective spacing of the diode was about 5.6 mm. The data show that for a Cs_3Sb photoemissive surface, a peak current of at least 200 A can be drawn. The quantum efficiencies of the photocathodes used in this work were in the range of 2 to 3%. These results are consistent with those predicted by numerical simulations of the diode with its specific geometry. A typical temporally resolved oscillogram trace of the photocurrent is shown in Figure 3. The overall shape is seen to track the laser pulse. The rise time of the pulse is about 10 ns. Stable shot-to-shot operation was noted.

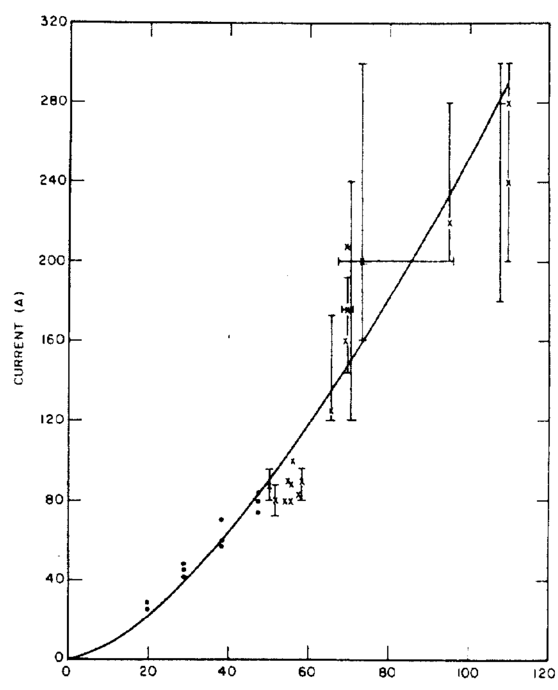

Fig. 2. Space-charge-limited photocurrent measured as a function of the applied voltage, which was either dc (dots) or ac (crosses). (The solid line represents the Child-Langmuir relation with the applied field approximating that pertinent to this diode configuration.)

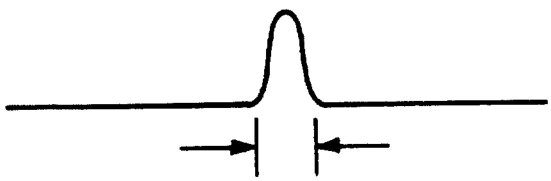

Fig. 3. Oscilloscope trace of the photocurrent profile recorded for an applied voltage of 50 kV. The peak of this profile corresponds to 80 A. Traces obtained with higher peak currents using the marx generator were noisy.

Conclusion

Preliminary photoemissive studies of Cs_3Sb show that this material, when irradiated by an intense, pulsed laser beam, will provide a stable 200-A/cm^2 beam of bunched electrons that may be suitable for use in rf linac FELS.

References

1. C. H. Lee, "High Current Density Photoemissive Electron Source," Appl. Phys. Lett. 44 (1984), 565.

2. C. H. Lee, "Photoelectron Energy Distribution of Cs_3Sb," J. Appl. Phys. 54 (1983), 4578.

3. C. H. Lee, P. E. Oettinger, A. Sliski, and M. Fishbein, "Practical Laser Activated Photoemissive Electron Source," submitted to Rev. Sci. Instr. 56 2 (1985), 560.

4. Y. Kawamura, K. Toyoda, and M. Kawai, "Generation of Relativistic Photoelectrons Induced by Eximer Laser Irradiation," Appl. Phys. Lett. 45 (1984), 307.

5. C. K. Sinclair and R. H. Miller, "A High Current, Short Pulse, RF Synchronized Electron Gun for the Stanford Linear Accelerator," IEEE Trans. Nucl. Sci., 28 (3) (1981), 2649.

6. M. Yoshioka, M. Mutou, 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 (September 1984), 469.

7. J. S. Fraser, R. L. Sheffield, E. R. Gray and G. W. Rodenz, "High-Brightness Photoemitter Injector for Electron Accelerators," these proceedings.

8. C. W. Roberson, "Free-Electron Generators of Coherent Radiation," Proc. Soc. Photo-Optical Instr. Engr. 453 (1983), 320.