First Operation of a High Duty Factor Photoinjector*

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Abstract

Tests of the Boeing Average Power Laser Experiment (APLE) injector have demonstrated first-time operation of a photocathode RF gun electron accelerator at 25% duty factor. The multi-alkali photocathode was illuminated by a frequency-doubled, mode-locked Nd:YLF laser. The cathode was placed in the first cell of four single-cell cavities resonant at 433 MHz. The 4 cavities accelerated the beam to 5 MeV. The pulse duration was 8.3 ms and the repetition rate was 30 Hz. True average beam currents of up to 35 mA have been accelerated to 5 MeV for an average beam power of 170 kilowatts. The 35 mA beam current exceeded previous photocathode performance by a factor of 1000.

I. INTRODUCTION

In order to increase the output power of free-electron lasers (FELs), it is necessary to increase the electron beam duty factor while maintaining excellent beam quality. In recent years, the photocathode RF gun injector has demonstrated the required beam quality at duty factors in the range of a few hundredths of one percent [1]. However, questions remained concerning photocathode lifetime at high RF duty factor due to vacuum contaminants or damage by the drive laser.

The APLE injector test results presented here demonstrate the successful operation of a photocathode RF gun at duty factors up to 25%. The APLE injector operating parameters are given in Table I.

II. DESCRIPTION OF THE PHOTOINJECTOR

The APLE RF photocathode gun injector consists of two low beta RF cavities operating at 433 MHz with a K_2CsSb multi-alkali cathode residing at one end of the first cavity. These two cavities accelerate the electrons to 1.8 MeV and are followed by two additional 433 MHz cavities, which further accelerate the beam to 5 MeV. Solenoids provide an axial magnetic field to contain the electrons during acceleration. The accelerator beamline uses three quadrupole doublets to transport the beam on a path through a three-dipole, doubly-achromatic chicane, or with the chicane dipoles off, straight ahead to a high-power beam dump. The first quadrupole doublet is also used to prepare the beam for the emittance measurements on the view screens SC1 and SC2. Ferrite current monitors and stripline beam position monitors are used to determine the beam charge, current and location without intercepting the beam. The stripline measurements are especially important during high-power operation. A current monitor, CM1, located between the two pairs of RF cavities, and the drive-laser intensity are monitored to determine the photocathode quantum efficiency and lifetime. Figure 1 shows the overall configuration of the APLE injector experiment including both the beamline components and the optical path of the drive laser. The optical path between the laser room and the photocathode in the accelerator pit is approximately 30 meters.

Table I
Operating Parameters of the APLE Injector

Photocathode Parameters:		Laser Parameters:	
Photosensitive Material	K_2CsSb Multi-alkali	Micropulse Length	53 ps, FWHM
Quantum Efficiency	5% to 12%	Micropulse Frequency	27 x 10^6 Hertz
Peak Current	132 amperes	Macropulse Length	10 ms
Cathode Lifetime	1 to 10 hours	Macropulse Frequency	30 Hertz
		Wavelength	527 nm
Gun Parameters:		Spot Size	3-5 mm FWHM at the cathode
Cathode Gradient	26 MV/meter		
RF Frequency	433 x 10^6 Hertz	Angle of Incidence	normal
Final Energy	5 MeV	Distribution	gaussian, space and time
Duty Factor	25%	Micropulse Energy	.47 microJoule
Energy Spread	100 to 150 keV	Energy Stability	1% to 5%
Emittance (four x RMS)	20 to 40 pi*mm*mrad		
Charge	1 to 7 nCoulomb		

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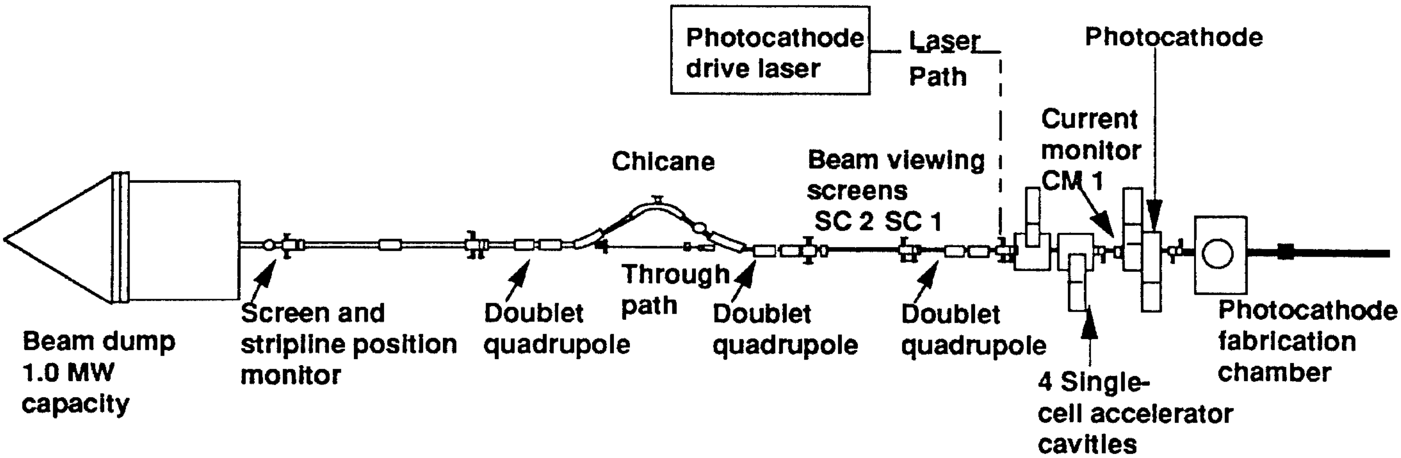

Figure 1. The Average Power Laser Experiment (APLE) RF gun photoinjector. The photocathode resides at one end of the first RF cavity and is illuminated by a 527 nm drive laser. The drive laser is injected using a small off-axis mirror. The emittance growth is controlled by the injector coil and permanent magnet correctors located between the first two cavities.

The photocathode is illuminated by a frequency-doubled, cw mode-locked Nd:YLF drive laser which is injected slightly off axis of the electron beam, striking the cathode at near-normal incidence. The drive laser details have been discussed elsewhere[2]. An optical mask slightly truncates the tails of the gaussian drive laser beam to reduce the beam intensity by only 20 to 30%. Computer simulations[3] indicate the electron beam emittance is sensitive to the drive laser shape and predict that a sharp-edged, top-hat profile leads to the best emittance. Therefore, the emittances presented in this paper are not necessarily the best achievable by this photoinjector.

III. EMITTANCE MEASUREMENTS

The electron beam emittance was determined using the two-screen method[4]. The beam profiles were verified to be gaussian in shape for 90% to 95% of the beam intensity. This justified quoting the four times rms emittance as the approximate 93% emittance.

Figure 2 shows the emittance measured at charges of 1, 3, 5 and 7 nC per micropulse. For these measurements, the beam pulse format was 1 hertz with 100 microsecond-long macropulses. This format was chosen to limit damage to the view screens. The profiles were obtained by orthogonal projection. The experimental data (shown with error bars) are the best emittances at each micropulse charge. The optimum value was experimentally obtained by tuning the injector coil current. The experimental emittance approximately follows the linear dependence of (12.7 π + 4πQ) mm•mR where Q is the micropulse charge in nanocoulombs.

The emittances calculated with a customized version of PARMELA using the experiment conditions are also shown in figure 2.

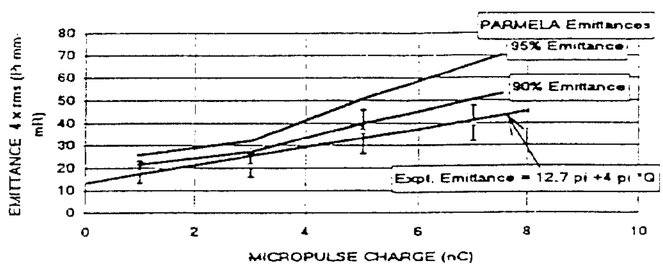

Figure 2. Optimized emittance as a function of micropulse charge. The 90% and 95% PARMELA emittances exceed the measured four times rms emittances.

A customized PARMELA was necessary to properly model misalignments of the injector coil and their correction by permanent magnet dipoles[5]. The emittances are calculated by circumscribing 90% and 95% of the macroparticles (usually numbering 2000) in transverse phase space with ellipses. The ellipse areas are proportional to the emittance.

The calculated emittances are higher than the experimental values at all measured beam charges. A partial explanation involves the five to ten percent of the beam which is outside the assumed gaussian beam shape. Beam halo experiments performed during the high-duty test indicated that the halo emittance at 3 nC per micropulse is approximately 200 π mm•mR. Adding this emittance with the four times rms emittance, with each weighted by its respective fraction gives 38.8 πmm•mR, only five percent larger than 37 πmm•mR, the four times rms value and cannot fully account for the discrepancy with PARMELA.

IV. High-Duty Test Results

At average beam powers in the range of 170 kW, it was essential to operate the injector at low emittance and with minimum beam halo. It was equally important to carefully adjust the beam transport to the dump, since only a tenth of the beam power, if focused, would damage the vacuum pipe, or if defocused, would lead to significant vacuum outgassing. Several beam interlocks were used to turn off the drive laser or *crowbar* the RF system in the event of unsafe operating conditions. These interlocks included the RF cavity and beamline vacua, cavity-reflected RF power, beam-loss radiation detectors, and beamline and beam-dump temperature measurements. In addition, the last current monitor in the beamline was used to detect the absence of electron beam when the drive laser was present. This loss-of-beam interlock had a response time of a few microseconds and was especially effective in protecting the beamline during an RF system crowbar. These interlocks allowed safe operation of the injector at the higher beam powers.

Conditioning the APLE injector for high-duty factor operation was quite similar to the seasoning of a high-power klystron. When the duty factor is increased, the accelerator gas load quickly rises and the beam has to be turned off to allow the beamline and beam dump to recover. During repeated high-duty operation, the beamline and beam dump are *scrubbed* by the electron beam, and the improved vacuum allows longer run times. This means that operating time at high beam power depends both upon the beam quality and transport efficiency, and ultimately, on the history of conditioning performed at high power.

Figure 3 shows the electron beam micropulse charge and the average beam power for three successive runs at duty factors between 15% and 25%. The micropulse charge was 5 nC or greater, and the average beam power ranged from 80 to 170 kW. It is significant that these three runs were performed using the same photocathode which survived repeated beam shut down while operating at high beam power. This result demonstrates that high quantum efficiency, multi-alkali photocathodes can be used to generate high current beams for high duty factor free-electron lasers. The cathode 1/e lifetime in this case was 2.7 hours. The second important feature of figure 3 is that the runs lasted one to three minutes, and were not single high-power shots. As discussed before, the length of the runs was limited principally by beamline and beam dump vacuum conditioning and to a lesser extent by RF power system reliability.

The 1/e lifetimes for the photocathodes used during the high-duty test are given as a function of duty factor in figure 4.

The static, or no beam (0% duty factor data), lifetimes range from less than an hour to ten hours, resulting from experiments performed under a wide range of vacuum and cathode conditions. From 1% to 25% duty factor, the average lifetime is 2.3 hours, which again, demonstrates cathode lifetime is not dependent upon duty factor but depends instead, upon the static or low-power vacuum pressure.

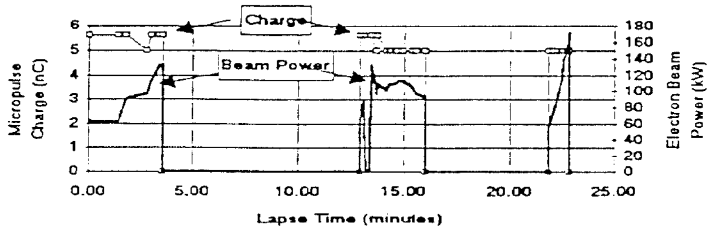

Figure 3. APLE injector accelerated micropulse charge and average beam power for three successive runs on the same cathode. The duty factors ranged between 15% and 25%.

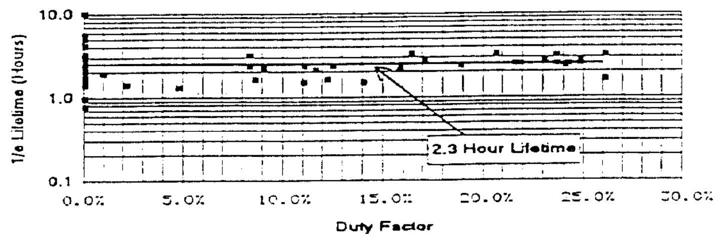

Figure 4. The photocathode 1/e lifetime measured from .1% to 25% duty factor. Above 1%, the average lifetime was 2.3 hours with no significant dependence upon duty factor or beam power.

V. SUMMARY AND CONCLUSIONS

This work demonstrates the first-time operation of a photocathode injector at high-average power. The APLE injector has been successfully operated at average beam powers up to 170 kW, with a beam energy of 5 MeV. The average cathode 1/e lifetime was 2.3 hours and was independent of the electron beam duty factor and beam power. Work is currently underway to incorporate this injector into an 18 MeV accelerator as part of an average-power free-electron laser.

VI. REFERENCES

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