The UCLA Compact High Brightness Electron Accelerator

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Abstract

We report the characteristics and performance of the UCLA S-band compact electron accelerator, consisting of a high brightness, 8 cm long, photo-injector with a copper cathode, followed by a 42 cm long plane wave transformer accelerating structure, delivering a beam energy of 10 MeV. The photo-electrons are produced by a 266 nm laser pulse of less than 4 ps in duration. Over time the laser induced electron emission decreases and the emission from the cathode surface becomes structured. Measurements of the quantum efficiency for Cu before and after this degradation are presented along with images of the non uniform electron emission.

I. INTRODUCTION

The UCLA S-band compact electron accelerator [1] is designed to produce a high brightness beam for experiments in beam-plasma interactions [2] and the generation of coherent radiation [3]. The 4.5 MeV photoinjector is a copy of the original BNL photoinjector with removable photocathode [4], while the main accelerating section is a previously untested structure called a plane wave transformer (PWT) [5]. Because this accelerator is to be used for conducting experiments in a small university laboratory, emphasis in the accelerator design was placed on compactness, reliability and ease of operation. It was with these goals in mind that copper was chosen as the photocathode material.

Neither initial operation of the UCLA photoinjector in 1993 [1] nor the Brookhaven photoinjector [6] indicated any problems with the use of copper photocathodes. It was presumed that copper would be a robust material for which neither special handling nor special vacuum requirements would be necessary. However, our most recent results which were obtained under rf fields of up to 100 MV/m and in vacuum of < 3×10^{-7} Torr, indicate that the copper cathode surface can be poisoned. The electron emission was not only reduced but also became highly structured. This structure results from non uniform emission from the cathode surface which causes beam degradation and limits the beam brightness.

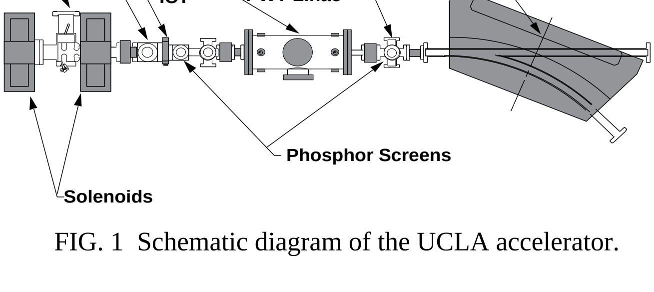

FIG. 1 Schematic diagram of the UCLA accelerator.

II. EXPERIMENTAL SETUP

The accelerator layout is depicted in Fig. 1. The Cu photocathode is placed at the endwall of the 1/2 cell in a 1 1/2 cell rf gun. A pair of solenoids is used to transport the beam to the various beam diagnostics and PWT linac while maintaining a zero magnetic field at the cathode surface.

For single photon photo-emission, the photon energy must exceed the work function of Cu (4.65 eV)[7]. The photoinjector drive laser produces < 4 ps laser pulses at 266 nm (4.66 eV) with up to 300 μJ/pulse. This is accomplished using chirped pulse amplification and compression of a mode-locked YAG laser and frequency upconverting using two KD*P doubling crystals. The laser is injected at 3° from normal incidence to the cathode by a mirror which is mounted in vacuum slightly off of the beam axis.

The electron charge is measured with two independent diagnostics, a Faraday cup and an integrating current transformer (ICT). Both these diagnostics agree with each other to within 10%. However, because the Faraday cup collects significant amounts of dark current (>5 nC), the ICT is used to measure the photo-induced charge per pulse with less than 10% dark current background. A dipole spectrometer is employed to measure the beam energy from both the photoinjector and the PWT linac, while phosphor screens enable verification of the beam position and facilitate the measurement of the beam profile. To fully characterize the beam quality, a venetian blind pepperpot can be inserted for measuring the beam emittance.

Two different Cu cathodes were tested. The first was a commercially polished cathode purchased from Spawr Industries. It was polished to λ/4 at .6 μm flatness and 40/20 scratch and dig. The second cathode was hand polished at UCLA down to 0.3 μm diamond grit size.

III. EXPERIMENTAL RESULTS

A. Commercially polished cathode.

The Spawr cathode was installed in late August, 1994 and rf conditioning continued for 3 months while the PWT was commissioned. Rf breakdown was observed throughout the conditioning process during which the rf power was increased in steps until the occurrence of rf breakdown events reached a prescribed limit of less than three consecutive rf breakdowns and less than a 1% occurrence of breakdown events over a 15 minute interval. When the frequency of breakdown events fell below this limit the rf power was increased until the number of breakdown events once again approached this level. Using

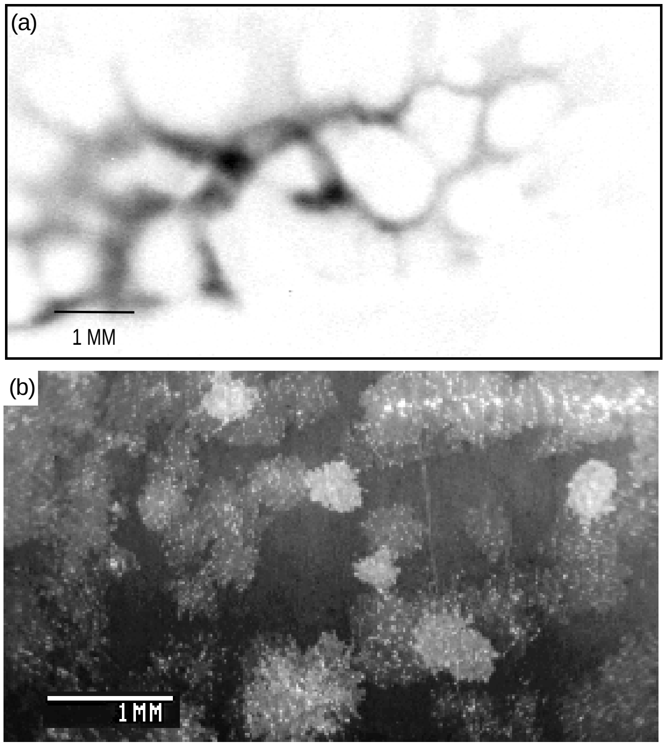

FIG. 3. Spawr Cathode images. (a) Electron beam emission from the cathode surface. (b) SEM micrograph of cathode surface after running in the rf gun.

this guideline the rf power was slowly increased until an input power of 5 MW achieved.

In early December the rf power was raised up to 7 MW and the first quantum efficiency (QE) measurements were made. These resulted in QE up to 1×10^{-4} which is greater than the typical value for Cu in low electric fields (QE = $1\cdot10^{-5}$ [8]). The QE was measured as a function of rf power (Fig. 2) and showed an increase in QE with increasing rf power in agreement with Schottky reduction of the work function from large electric fields present at the cathode surface (> 50MV/m).

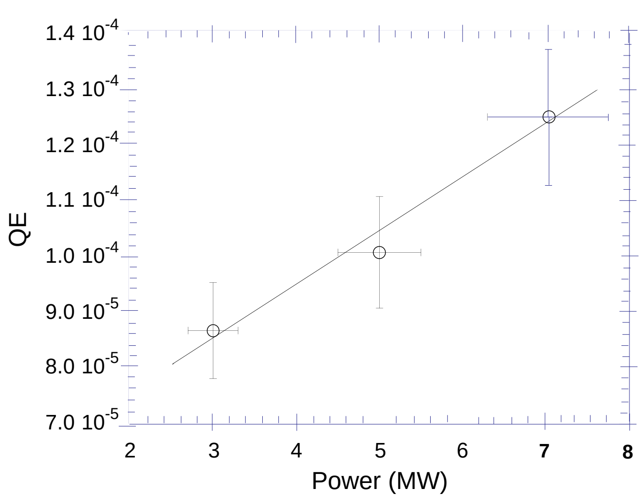

FIG. 2. QE dependence on input rf power to photoinjector.

During the month of December the rf gun and PWT linac were run consistently and measurements of the full beam energy and energy spread were made as a function of rf phase between the photoinjector and the PWT linac. The highest beam energy observed was 10.5 MeV with 3.5 MeV electrons produced at the rf gun, indicating an energy gain of 7 MeV from the PWT linac. As expected, the phase setting which yielded the highest energy also produced the lowest energy spread which was measured to be ≈0.3 %. The energy spread as a function of injection phase was fit to PARMELA simulations with electron bunch length as the fit parameter from which a bunch length of ≈ 5 ps was inferred. The details of these measurements are presented in [5]. Finally, the QE was remeasured in late December and resulted in values within 10% of those measured earlier that month.

In mid January, we noticed that the electron beam had developed severe structure and the solenoid currents were set to image the electron emission from the cathode surface. An image of this emission is depicted in Fig 3(a). Due to this beam structure, the emittance measurement using a venetian blind type of pepper pot could not be performed, so a quad scan was used to measure the emittance of a low charge beam (< 10 pC) at 10 MeV. The measured normalized emittance was 6 π mm-mrad. After this change in cathode emission, the QE was again remeasured and we found that it had dropped by a factor of 3.

We discovered that by keeping the gun under vacuum without rf power for a few days, the QE would recover to a level of 2.6×10^{-5} (still below the levels recorded in December). This level could be maintained for many hours as long as the rf power level was maintained below 6 MW. However, once the rf power was increased to 7 MW the QE deteriorated quickly. In just 7 hours the QE dropped from $2\cdot10^{-5}$ to 1×10^{-5}, a factor of 2. This test was done with the gun vacuum isolated from the rest of the beamline which is typically maintained at slightly higher pressures (1×10^{-6}). A residual gas analyzer was used to measure the primary contaminates of the vacuum system which were H_2O, H_2, N_2, O_2, Ar and CO_2 in order of decreasing partial pressure.

In an attempt to increase the QE, the cathode surface was damaged using the focused UV laser beam. The laser was focused to a 200 µm spot and an array of 5 by 5 damaged spots was created at the cathode center. It was expected that further reduction of the work function could be achieved through the Schottky effect with enhanced electric fields at the surface due to the microprotrusions created by the laser damage. In the initial operation of the rf photoinjector in 1993, QE of 1×10^{-4} were routinely measured from a damaged Cu photocathode and no QE degradation was ever observed [1]. However, on the Spawr cathode, the damaged areas did not produce any change in the QE and the recovery and degradation of the QE continued as described above.

This cathode was then removed from the gun and the surface was imaged using a SEM. Fig. 3(b) depicts surface structure which covers the cathode surface except in the laser damaged area. This structure may be the cause of the

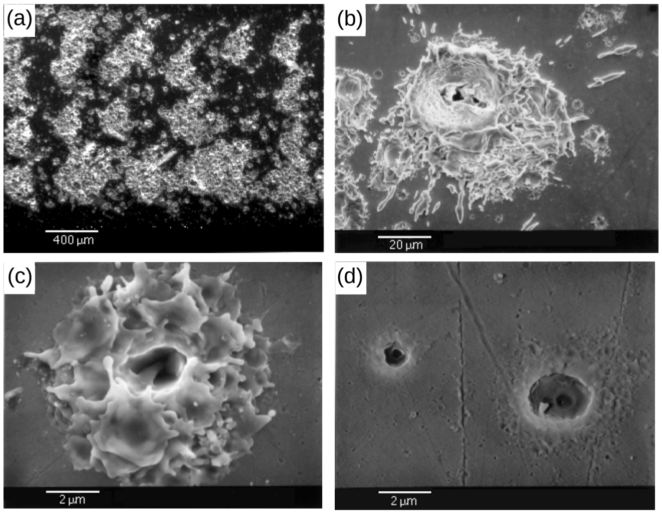

FIG. 4 SEM micrographs of damage on the Spawr cathode. (a) laser damaged region (b) laser produced crater (c) multiple rf breakdown produced crater (d) single rf breakdown crater

nonuniform emission shown in Fig 3(a). The light colored areas show a fractal growth pattern at the edges. This seems typical of a contamination growth on the cathode surface from residual gasses which is facilitated by the field emitted electrons.

Electron micrographs of different types of surface damage produced by laser damage and rf breakdown are shown in Fig. 4. The laser damage typically produces larger scale structures formed from molten copper while the rf damage shows a smaller more symmetric structure.

B. Hand polished cathode.

Following the removal of the commercially polished cathode, a second Cu cathode, was prepared at UCLA. It was machined from OFHC Cu using "Marvel's Mystery Oil" as lubricant. The cathode surface was then polished starting with wet 600 grit sand paper and working down to .3 µm diamond grit. The polishing was done by hand until no surface feature was larger than 1 µm. The cathode was stored in methanol until installation in the rf gun. This cathode was also tested in a dc gun prior to installation in the rf gun and a QE of 1×10^{-5} was measured [8].

During the cathode installation, the rf gun was back filled with nitrogen and maintained at the operating temperature of

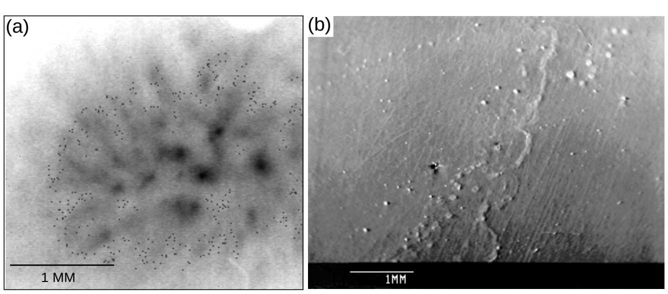

FIG. 5. Hand polished copper cathode. (a) Electron beam emission from the cathode surface. (b) SEM micrograph of cathode surface after running in the rf gun.

55° C. Once vacuum of better than 1×10^{-7} was achieved, the rf conditioning was started. Within a few hours rf power levels of 5 MW where achieved with practically no signs of rf breakdown.

The QE was immediately measured to be 3.3×10^{-5} at an rf power level of only 4 MW. Based on the previous measurements made in December, this would imply a QE of 5×10^{-5} at 7 MW. Furthermore, the beam showed no indication of beam structure.

Two days later, following less than 8 more hours of conditioning which was characterized by minor breakdown in the gun, rf power levels of 6 MW were attained. The QE was again measured and resulted in a reduction from the previous value of more than a factor of 2 to 1.5×10^{-5}. When this beam was imaged, once again beam structure became evident although not as severe as before. (see Fig 5(a)) Because the beam structure was less pronounced, the beam emittance could be measured and resulted in normalized emittances between 5 and 12 π mm-mrad with a beam charge of only 250 pC. Even this beam, however, was not cleanly focused on the slits and therefore the emittance values are most likely a lower bound to the whole beam emittance.

Following the beam quality measurements, this cathode was removed from the rf gun and immediately taken to the dc gun test stand for QE measurements. The QE measurements did not indicate any change in QE, again measuring 1×10^{-5} and also did not show any indication of structure on the cathode surface. When electron micrographs of this cathode were made, almost no structure was seen on the surface (see Fig. 5(b))

IV. CONCLUSIONS

The electron emission from a copper photocathode in a rf photoinjector appears to degrade in time, however, more careful and detailed study is necessary to understand the interaction of the copper surface with both the large rf fields and the UV laser pulses present in rf photoinjectors.

V. ACKNOWLEDGMENTS

The authors acknowledge Richard Lysee for his assistance in making SEM micrographs. This work is supported by US DOE Grant DE-FG03-92ER-40493 and DOE Grant DE-FG03-92ER40727.

VI. REFERENCES

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