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Photo-Cathodes for RF Electron Guns**

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# EXPERIENCE AT FERMILAB WITH HIGH QUANTUM EFFICIENCY PHOTO-CATHODES FOR RF ELECTRON GUNS

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“Somebody leave the light on.”

T. Amos

## 1 INTRODUCTION

As part of the A0 Photo-injector collaboration at Fermilab [1, 2] and the TeSLA collaboration [3], a high brightness, low emittance electron source has been developed. In the process, a system was constructed for coating molybdenum cathodes with a layer of caesium telluride ( $\text{Cs}_2\text{Te}$ ), a photo-emissive material of high quantum efficiency (QE). The use of  $\text{Cs}_2\text{Te}$  was first investigated at CERN [4] and LANL [5]. The development of the systems for the TeSLA Test Facility Linac and the Fermilab Photo-injector was done in Milano [6]. The system at Fermilab incorporates manipulator arms to transfer a cathode from the preparation chamber into a 1.3 GHz photo-electron RF gun while it remains in an ultra-high vacuum (UHV) environment, in order to avoid the deleterious effects of residual gases on the QE. A first prototype electron gun has been operated with a photo-cathode for several months [1]. This paper describes preliminary results obtained with the first 2 photo-cathodes and the first gun.

Some of the desired parameters for the TeSLA Test Facility beam are given in Table 1. The desired characteristics for the photo-cathodes include (i) high QE, (ii) high current density ( $>500 \text{ A/cm}^2$ ), (iii) long lifetime, and (iv) low field emission. The choice of  $\text{Cs}_2\text{Te}$  is a compromise between long lifetime, rugged metal cathodes with low QE (typically between  $10^{-6}$  and  $10^{-4}$ ) and semiconductor cathodes with high QE ( $>10\%$ ), which generally have a short lifetime because of their sensitivity to contamination.

## 2 PREPARATION CHAMBER

To minimise the poisoning by residual gases, the cathodes must be coated under UHV conditions and remain in UHV throughout their useful lives. Thus, all components of the cathode preparation chamber (Figure 1) are compatible with UHV. The chamber is baked at 150 to 200°C after exposure to ambient air. The vacuum is maintained by 2 ion-getter pumps and a titanium sublimation pump. Ionisation gauges and a residual gas analyser (RGA) are used to monitor the pressure. The chamber can accommodate up to 5 cathodes, which could in principle all be used in

Table 1. Selected TeSLA Test Facility beam parameters.

Charge per bunch	8 nC
Bunch spacing	1 $\mu\text{s}$
Bunches per RF pulse	800
Repetition rate	10 Hz
Bunch $\sigma_z$ in gun	4.3 mm



Figure 1. Cathode preparation chamber.

turn without the need to bleed up the chamber. A cathode is moved from the coating chamber to the RF gun via one mechanical actuator and 2 magnetically-coupled actuators. The electrical contact between the cathode and the wall of the gun is made with a toroidal Be/Cu spring.

## 3 COATING OF THE CATHODES

Prior to coating, the sources are degassed by flowing a small amount of current through them. In the mean time, the molybdenum cathode is heated with a halogen lamp to encourage the evaporation of surface contaminants: the temperature is ramped up to 350°C and held at 350°C for 30 to 60 minutes. The cathode is then allowed to cool to 120°C and held at that temperature for the duration of the coating. A quartz crystal thickness monitor is inserted momentarily to calibrate the evaporation rates for the Cs and Te sources. Ultra-violet (UV) light from a mercury lamp ( $\lambda = 254 \text{ nm}$ ) is focussed onto the cathode and the photo-current is monitored during the deposition, as shown in Figure 2. Te is deposited for 10 minutes at a rate of 1 nm/minute, and then Cs is deposited at the same rate for 60 to 120 minutes. The pressure typically increases to between 1 and  $4 \cdot 10^{-9}$  torr during evaporation of Cs or Te. The colour of the photo-emissive film was orange for the first cathode (Cs deposited for 63 minutes) and blue for the

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second cathode (Cs deposited for 110 minutes).

## 4 QE MEASUREMENTS

The UV beam from the mercury lamp is used to measure the QE while the cathode is in the preparation chamber. The QE is defined as

$$QE = \frac{\text{Number of Emitted Photo-electrons}}{\text{Number of Incident UV photons}}.$$

The UV power is measured with a photo-diode. A bias of 200 V is applied between cathode and its surroundings to capture the photo-electrons. The photo-current is measured with a picoammeter; the background current (obtained by blocking the UV light) is subtracted. The DC QE is deduced from the ratio of the photo-current to the UV power. The UV spot size is typically about 5 mm during the DC measurements.

While the cathode is in the RF gun, the UV pulses from the laser ( $\lambda = 263$  nm, 1 to 10 ps pulse length) are used to measure the QE. The UV energy per pulse is measured with a photo-diode. The photo-electron bunch produced by a laser pulse is accelerated by the gun. The charge per bunch is measured with an integrating charge transformer at the exit of gun. The pulsed QE is deduced from the ratio of the charge per bunch to the UV energy per pulse. As can be seen in Figure 3, there is a decrease in the measured pulsed QE at high charge per bunch. This might be due to space charge or an actual dependence of the photo-electron yield on UV intensity.

The QE measurements on the 2 cathodes are summarised in Figure 4. The initial QE of both cathodes exceeds 10%, but the QE after removal from the RF gun is less than 1%. The maximum charge extracted from the cathode was 30 nC for a single bunch and 15 nC per bunch for trains of 9 bunches.

## 5 GAS EXPOSURE

Exposure to residual gases,  $O_2$ ,  $CO_2$ , and  $H_2O$  in particular, causes the QE to decrease with time. The base pres-

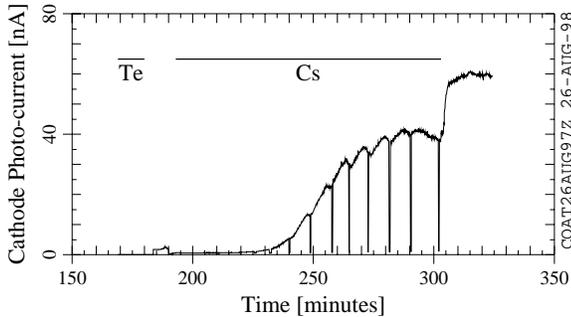


Figure 2. Photo-current as a function of time during the coating of the second photo-cathode. The times during which Te and Cs were being evaporated are indicated by the bars along the top. The downward spikes correspond to the UV light being blocked momentarily to check the background current.

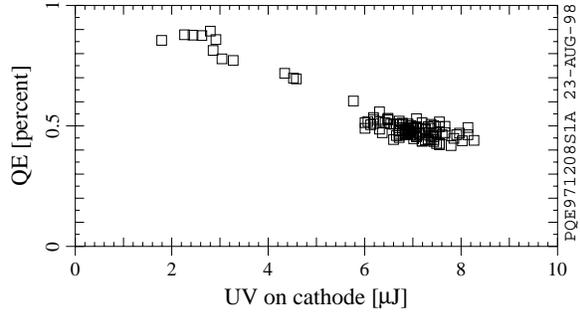


Figure 3. Dependence of the QE on the energy per laser pulse.

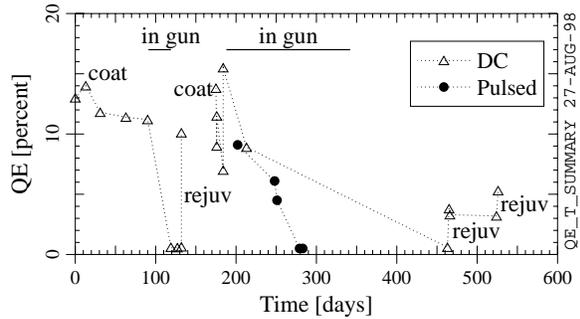


Figure 4. Time dependence in the QE.

sure in the preparation chamber was of order  $5 \cdot 10^{-10}$  torr or lower; RGA measurements indicated that the dominant gas was  $H_2$ , with other species typically down by at least a factor of 4. The pressure in the gun without RF was about  $2 \cdot 10^{-9}$  torr when the first cathode was inserted; it had fallen to  $\leq 5 \cdot 10^{-10}$  torr by the time the second cathode was removed. The pressure with RF on was significantly worse; it got as high as  $5 \cdot 10^{-8}$  torr initially, but did improve with time. Actuator motion inside the vacuum system also produced some short-term increase in pressure.

## 6 REJUVENATION

The decrease in QE due to gas exposure can be partially reversed with a combination of heat and UV light [5, 7]. UV light from the mercury lamp is focussed onto the cathode with a spot diameter of about 10 mm; the UV power is between 6 and 40  $\mu$ W. The cathode is heated to 230°C. The combination of heat and light causes improvement of the QE. The exact process is not yet clear; it may be desorption of residual gas from the surface or diffusion from the surface further into the photo-emissive layer.

Figure 5 shows the increase in photo-current during the rejuvenation of the first cathode. From time  $t = 30$  minutes to  $t = 90$  minutes, the cathode temperature was ramped up to 230°C; the temperature was held at 230°C until  $t = 190$  minutes, at which time the temperature was ramped back to room temperature. As can be seen in Figure 5, the photo-current increases the most rapidly as the temperature is ramped up; it still increases by almost a factor of 2 as the temperature is ramped down (the latter increase was

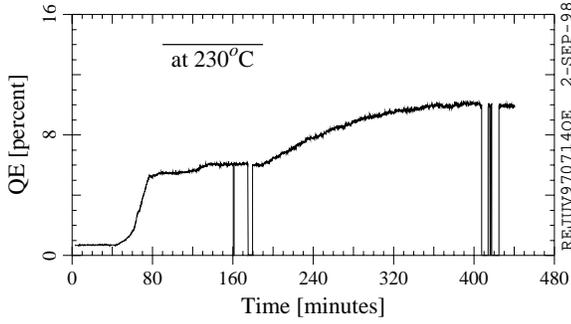


Figure 5. QE as a function of time during the rejuvenation of the first cathode. As before, the downward spikes correspond to the UV light being blocked momentarily.

not observed during the rejuvenation of the second cathode, however). The pressure was highest (between 1 and  $2 \cdot 10^{-9}$  torr) while the temperature was ramped up.

As indicated in Figure 4, the QE of the first cathode increased from 0.65% to 10% during rejuvenation. The QE of the second cathode increased from 0.6% to 5% in 2 iterations.

## 7 MUTABILITY

After coating the second cathode, we observed an increase in the QE with time in the presence of UV light at room temperature, presumably due to the same mechanism as the rejuvenation at elevated temperatures. The QE increased from 7% to 15.5% in about 150 minutes. Much less mutability in the QE was seen after rejuvenation: the QE remained between 2.9 and 3.3% over 130 minutes. The time dependence in the QE is compared in Figure 6.

## 8 QE SCANS

Maps of the QE as a function of position on the cathode were obtained by focussing the UV light from the lamp to a small spot (about 1.25 mm diameter) and scanning the spot over the photo-emissive surface. A mirror on a kinematic mount (allowing us to translate and rotate the mirror reproducibly) was used to divert the UV spot onto a piece of graph paper in order to determine the location of the spot.

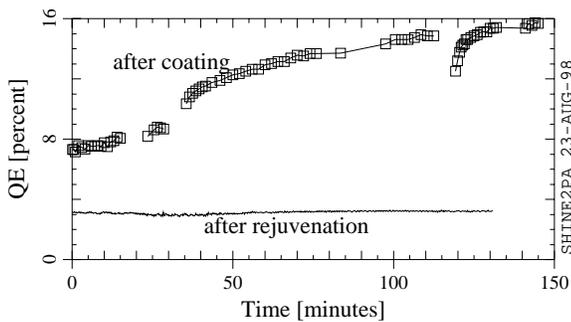


Figure 6. Comparison of the QE versus time before insertion into the gun and after rejuvenation for the second photo-cathode (UV power = 10  $\mu$ W, spot size = 5 to 10 mm).

Visible light was used to determine the location of the cathode in the coordinate system of the graph paper. A QE map taken after the coating of the second cathode is shown in Figure 7. As can be seen, the QE is not uniform over the entire photo-emissive layer (15 mm diameter).

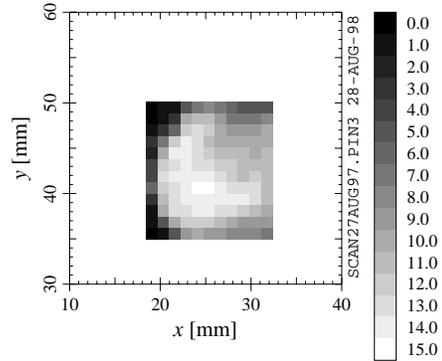


Figure 7. Map of the QE as a function of position on the surface of the second cathode the day after coating. Each pixel represents one QE measurement; the legend on the right indicates the QE values in percent.

## 9 CONCLUSION

We have coated and used two Cs<sub>2</sub>Te photo-cathodes in the first prototype RF gun of the Fermilab photo-injector. We have extracted 30 nC from a single bunch and 15 nC per bunch from trains of 9 bunches. Under operating conditions, the QE falls from  $\geq 8\%$  to  $< 1\%$  over one or more months. Our QE measurements with DC and pulsed light are reasonably consistent, although we see a reduction in the pulsed QE at high UV intensity. Rejuvenation allows us to restore the QE to  $\geq 5\%$ , although we have not yet used a rejuvenated cathode in the gun. It would be desirable to improve the spatial uniformity and lifetime of the cathodes.

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