PHOTOCATHODES AT FLASH

S. Schreiber *, S. Lederer, I. Hansen, H. H. Sahling, DESY, Hamburg, Germany
P. Michelato, L. Monaco, and D. Sertore, INFN Milano - LASA, Segrate, MI, Italy

Abstract

Since several years, caesium telluride photocathodes are successfully used in the photoinjector of the Free-Electron Laser FLASH at DESY, Germany. They show a high quantum efficiency and long lifetime and produce routinely thousands of bunches per second with a single bunch charge mostly in the range of 20 pC to 1.5 nC. Recent studies on lifetime, quantum efficiency, and operating experience is reported.

INTRODUCTION

The outstanding and unique feature of free-electron lasers based on superconducting accelerating technology is their ability to accelerate thousands of bunches per second with unprecedented average brilliance. The electron source of FLASH [1] is a laser driven photoinjector. With electron bunch charges from a few pico- to up to a few nano-Coulombs, the quantum efficiency of the photocathodes must be in the one to ten percent range for an optical or UV wavelength in order to keep the average drive laser power in a reasonable range. FLASH operates in a high duty cycle burst mode: 10 trains per second with thousand and more electron bunches per train and a burst duration of 0.8 ms is accelerated.

The cathode material choice is $\mathrm{Cs_2Te}$. $\mathrm{Cs_2Te}$ has been deployed for the first time at the CLIC Test Facility [2]. With a quantum efficiency around 10% for a photon energy of 4.87 eV, and the ability to extract the required charge in a sub-picosecond time scale, $\mathrm{Cs_2Te}$ is the ideal choice. A long lifetime of the cathode is crucial for operation of user facilities, where uptime close to 100% are expected.

In cooperation with LASA, Milano, a copy of the LASA cathode preparation system has been installed at DESY. First cathodes have been successfully produced and tested at PITZ in 2011 [3].

QUANTUM EFFICIENCY AND LIFETIME

The $\mathrm{Cs_2Te}$ cathode at FLASH is a thin film deposited on a Molybdenum plug. The plug diameter is 16 mm, while the diameter of the cathode is 5 mm. A load-lock system ensures, that the cathode stays under UHV conditions all time.

We define the quantum efficiency (QE) as the ration of the number of electrons measured at the exit of the RF-gun to the number of photons arriving at the cathode.

We measure the QE in two ways. Shortly after production, the initial QE is measured with a cw Mercury lamp. In this set-up, no external field is applied to the cathode, except for a small field to avoid space charge effects. During operation in the RF gun, we measure the QE from time to time with nominal FLASH operation conditions: forward RF power of 3.9 MW, corresponding to 48 MV/m accelerating gradient at the cathode (on-crest), and a launch phase of 38°. The zero-crossing defines the phase of 0°, on-crest is 90°. The number of extracted electrons is obtained by a charge measurement at the gun exit with a calibrated toroid. The number of photons is measured with a calibrated joulemeter [4]. The transmission of the vacuum window and the reflectivity of the mirror mounted in the beamline vacuum is taken into account. Usually, we measure the extracted charge Q as a function of laser energy E_L. The QE is calculated from a linear fit to the data points at low charge densities, where space charge effects are negligible and the relation $Q(E_L)$ is linear. Since the charge output of the gun is a strong function of the RF phase [5], we have the convention to always give the QE at the default launch phase working point of 38° off zero crossing.

During operation in the RF gun, the QE drops with time. We define the lifetime of a cathode from the time it is used in the RF gun until the QE drops to a value of 0.5% or less. The lifetime also ends, if the QE homogeneity drops below a few percent, or if the dark current produced by the cathode gets too high to allow a secure operation of the facility. The latter two criteria are not precisely defined, since in doubt, cathodes are changed even though any of the lifetime criteria are not yet exactly fulfilled.

Now with an operational experience of several years, we know that the initially high quantum efficiency is maintained in the FLASH RF gun for a couple month and drops only slowly. A critical lifetime issue is to keep a very good ultra-high vacuum well below a pressure of $1{\cdot}10^{-9}$ mbar at all time. Figure 1 shows the lifetime of cathodes operated at FLASH from 2009 to 2012. The quantum efficiency ranges initially between roughly 10% and 20% and drops within 150 days of continuous operation to levels below 5%. In 150 days, FLASH accumulates a total charge of typically 2 C.

SPECTRAL RESPONSE

As a standard, we measure the spectral response of all cathodes just after deposition and after operation in the RF gun. The spectral response is a measurement of the quantum efficiency as a function of the photon energy. We use a

* siegfried.schreiber@desy.de

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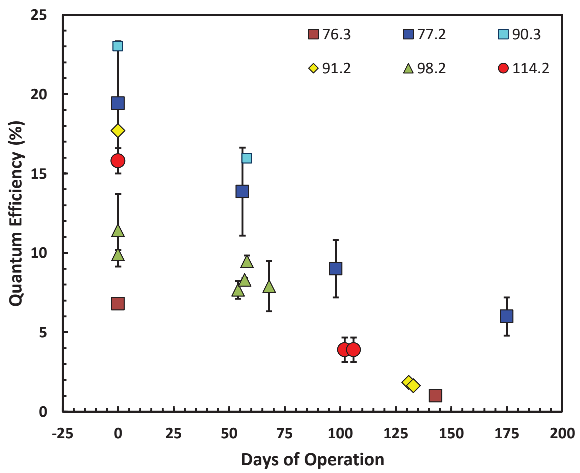

Figure 1: Operational lifetime of cathodes used at FLASH from 2009 to 2012. The legend shows the cathode ID.

high pressure Mercury lamp together with suitable optical bandpass filters. The incident light power is measured with a calibrated photo diode [6]. The emitted electrons are collected by a biased anode and the number of electrons is calculated from the current through the anode measured with a pico-amperemeter. Figure 2 shows the spectral response of four cathodes recently produced at LASA.

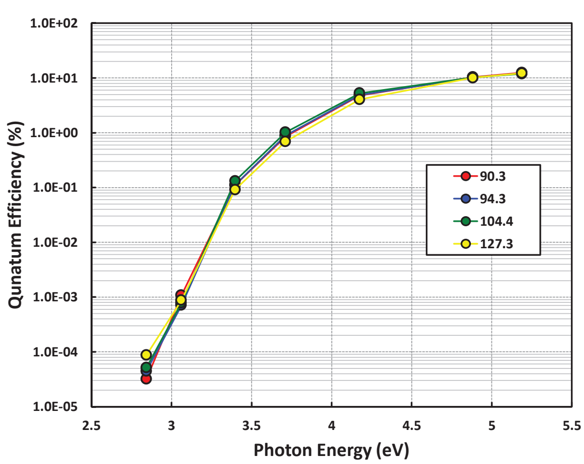

Figure 2: Spectral response of four recently produced Cs_2Te cathodes. Within the measurement error, the spectral response of all cathodes is equal.

The QE dependence on the photon energy E_{ph} at the photoemission threshold can be described by the following equation:

$$\mathrm{QE} = A\,(E_{\mathrm{ph}} - W)^m \tag{1}$$

where W is the work function of the material. In case of the semiconductor Cs_2Te, W is the sum of energy band gap E_G and electron affinity E_A.

$$W = E_G + E_A \tag{2}$$

The parameter m carries information on the emission process [7].

A typical feature of Cs_2Te cathodes prepared by the well established recipe is the appearance of a second QE trend for smaller photon energies [3]. By using new tools during preparation as described in [8], this low energy shoulder may not appear anymore. To take the shoulder or in other words an additional spectral response at lower photon energies into account, the data are fitted in terms of two independent emission mechanisms:

$$\mathrm{QE} = A_1\,(E_{\mathrm{ph}} - W_1)^{m_1} + A_2\,(E_{\mathrm{ph}} - W_2)^{m_2} \tag{3}$$

The fit results for the four cathodes together with the QE at 254 nm are summarized in in Table 1.

Table 1: Analysis of the spectral response of recently produced cathodes. The quantum efficiency QE is given for a wavelength of 254 nm.

cathode	90.3	94.3	104.4	127.3
$(E_G + E_A)_1$ (eV)	2.77	2.73	2.82	2.70
m_1	2.50	2.50	1.12	2.50
A_1	0.02	0.01	0.04	0.01
$(E_G + E_A)_2$ (eV)	3.26	3.27	3.28	3.23
m_2	1.83	1.75	1.63	2.02
A_2	4.09	4.26	4.58	3.42
QE(%)	10.4	10.1	10.2	10.1

For all cathodes, the work function $E_G + E_A$ for higher photon energies is in fair agreement with the theoretical value. Powel *et al.* [9] estimated for the band gap of Cs_2Te 3.3 eV and for the electron affinity 0.2 eV.

ANOMALIES

In two cases we observed a what we call ”black spot” on the cathode surface during operation at FLASH. The spots have been discovered during regular QE measurements.

Figure 3 shows a picture of cathode 114.2 with such a black spot. The dimension is about 0.5 mm in diameter. The irregular shape and appearance is not typical for a formation by a spark in the gun cavity.

Curiously, a map of the quantum efficiency (QE-map) shows a significant higher QE of about 50% at the spot location than the average over the cathode surface. The area hit by the laser beam is visible due to discoloration, but does not show any QE degradation.

To investigate this unexpected black spot, we used the energy dispersive x-ray emission spectroscopy technique (SEM-EDX). Since the SEM-EDX system is incompatible with the load-lock system for cathode handling, the transfer box containing cathode 114.2 was vented with dry nitrogen and the cathode removed. Until insertion into the SEM-EDX system, the time with unavoidable exposure to air was kept as short as possible.

The measurements discussed have been performed with a primary electron energy of 25 keV. The detector of the EDX is an XFlash5010 [10].

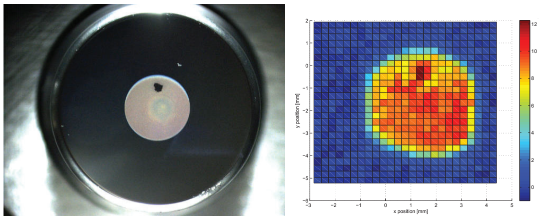

Figure 3: (Left) Cathode 114.2 showing a "black spot". The spot with a dimension of about 0.5 mm appeared during operation in the RF gun at FLASH. In addition, discoloration is visible where the laser beam has hit the cathode. The tiny white spot above the cathode is a particle. (Right) A QE-map of the cathode. The "black spot" on the left picture has a higher QE than the average. The color code scale is the measured charge in pC.

In Fig. 4 the SEM image of the interesting part of the cathode surface is shown. The black spot appearing on the picture of Fig. 3 is clearly visible in the SEM.

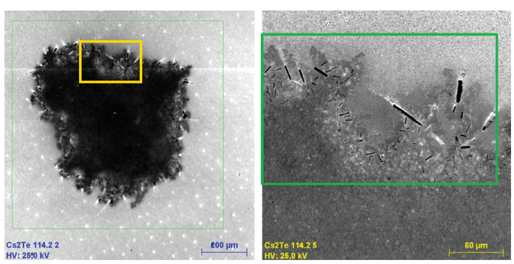

Figure 4: (Left) SEM image of the "black spot" of Fig. 3. The scale (lower left blue bar) is 200 μm. (Right) Magnification of the area shown by a yellow rectangle (scale 60 μm).

Figure 4 also shows a zoom into this area. Besides the central homogeneous part of the spot, the figure clearly shows some kind of material deposition in form of bars at the spot edge. To identify the origin of the bars, the highlighted part of the image is analyzed by elemental sensitive mapping for Mo, Cs, and Te. The maps are shown in Fig. 5.

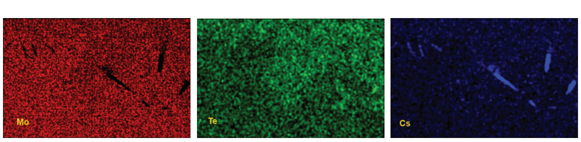

Figure 5: Elemental sensitive mapping for Mo, Te, and Cs of the part in Fig. 4 indicated with a green frame (left to right).

The molybdenum signal is strongly reduced at the bars. This we interpret by a higher thickness of these bars compared to the homogeneous areas. On the other hand, the Cs intensity is increased while the Te map does not show the bars at all. The higher amount of Cs is comparable to the QE increase at lower photon energies as shown in Fig. 6.

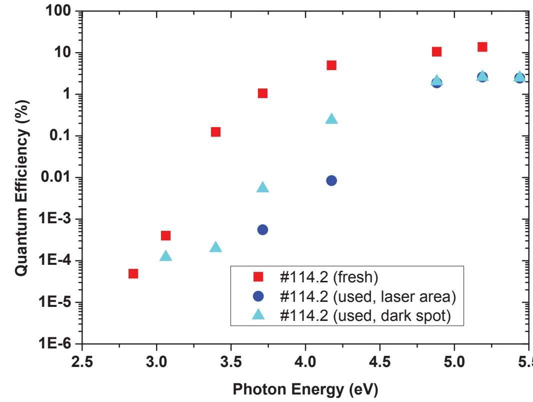

Figure 6: Spectral response of cathode 114.2. The response of the fresh cathode is compared with the "black spot" and the area, where the laser beam hit the cathode. Remarkable is the reduction of QE for lower photon energies.

A second result of the elemental mappings is pronounced visible on the Te-map. If we neglect the Cs signal, the Te intensity mirrors exactly the SEM image. Therefore we conclude that either the Te concentration on the black spot is reduced, or that the photocathode is simply thicker at the "normal" part of the SEM image outside of the black spot.

To further and deeper understand these results, a more detailed analysis of the EDX measurements is in preparation. The cathode with the second spot is still in operation and will be analyzed next occasion.

SUMMARY AND OUTLOOK

In this contribution we presented continued investigations on $\mathrm{Cs_2Te}$ photocathodes operated at FLASH. One crucial parameter is the photocathode lifetime. Meanwhile, a lifetime of a couple months is established as standard.

In two cases, we observe a "dark spot" appearing at the cathode surface during operation. In one case, the QE of the spot is about 50% higher than the surrounding area. EDX analysis show, that Cs is deposit at the edge of the spot. The lower concentration of Te inside the spot is puzzling and requires more detailed investigations.

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