# PHOTOCATHODES AT FLASH

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*Abstract*

For several years now, 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. The injector produces routinely thousand of bunches per second with a single bunch charge in the range of 0.1 to 1.5 nC. Recent results on lifetime, quantum efficiency, dark current, and operating experience is reported. At DESY, a new preparation system has been set-up. First cathodes have been produced and tested successfully.

## INTRODUCTION

The operation of $Cs_2Te$ photocathodes for production of electron bunches with reasonable thermal emittance requires a drive laser with a wavelength in the UV. The quantum efficiency has to be high in order to keep the average laser power in a reasonable regime for high duty cycle operation. Usually starting from about 10 %, the QE degenerates during operation in RF-guns. For user facilities like FLASH or the future European XFEL, long lifetimes of the cathodes are a crucial issue. First investigations on the lifetime of cathodes operated in the new RF-gun (DESY-Gun4.2), installed at FLASH beginning of 2010, are presented.

During the operation of the previous RF-gun at FLASH, DESY-Gun2, the dark current increased up close to a level, where it would have prohibited operation of the accelerator.[1] After the gun exchange, the dark current level decreased by an order of magnitude. To study possible aging effects of the cavity, the field emission is continuously studied. Results of current investigations together with a history over the last year of operation are presented in the second part of the contribution.

Up to now all photocathodes used at FLASH were produced from INFN-Milano, LASA. In 2010 a photocathode preparation system based on the Milano system was set-up and commissioned at DESY. Having two independent systems for cathode production improves the reliability, especially with respect to the upcoming increasing number of cathodes necessary in view of the European XFEL. First photocathodes at DESY have been produced beginning of 2011. Results of first operation of these cathodes in an RF-gun are given in the last part of this report.

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## CATHODE LIFETIME

The lifetime of the photocathodes is for user facilities like FLASH a crucial parameter. During operation of $Cs_2Te$ cathodes their quantum efficiency (QE) drops over time. The minimal usable QE is determined by the available drive laser energy and the charge dedicated to be extracted per pulse. For FLASH the rule of thumb for a dead cathode is a QE below 0.5 %.

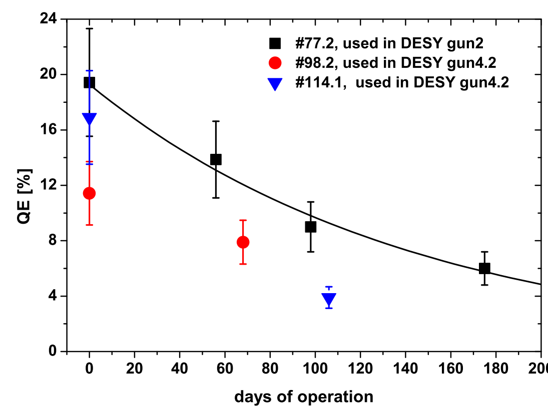


Figure 1: Quantum efficiency versus days of operation. Cathode #77.2 has been operated in DESY-Gun2, cathodes #98.2 and #114.2 in DESY-Gun4.2

Beginning of 2010, a new RF-gun cavity (DESY-Gun4.2) has been installed at FLASH. With the previous DESY-Gun2 we observed since 2007 cathode lifetimes of several months, while no cathode exchange was motivated by a low QE. [2] Continued studies with the new RF-gun are presented in Fig. 1. The plot shows the QE versus days of operation for cathode #98.2 and #114.2, together with #77.2, the last one operated in DESY-Gun2.

For measuring the QE, as for standard operation, the drive laser of the photoinjector is used to excite the valence electrons of the cathode (pulsed measurement), The emitted electrons are accelerated by the RF-field inside the gun cavity and the bunch charge is measured with a toroid. The number of photons is calculated from the laser pulse energy measured with a calibrated joulemeter (Molectron J-5, [3]) and taking the transmission of the view port as well as the reflectivity of the in-vacuum laser mirror into account. From the linear rise of the charge as a function of laser energy the QE is calculated. Here, space charge does not yet effect the QE. The solenoid is adjusted for maximum charge at the toroid. For all pulsed measurements the

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phase between laser and RF is set to 38° in respect to zero crossing, corresponding to the nominal operation phase of FLASH. All measurements presented in Fig. 1 have been performed at a forward RF power to the RF-gun of 3.9 MW.

## DARK CURRENT

The dark current emitted from the RF-gun body and the cathode is a crucial issue for operating linacs at long RF-pulses in combination with high electric fields. For FLASH this issue is even more important because of the installation of the 3.9 GHz module downstream the RF-gun just after the first superconducting accelerating module, and also the increase of the repetition rate from 5 to 10 Hz in 2009. High losses of dark current along the machine may increase

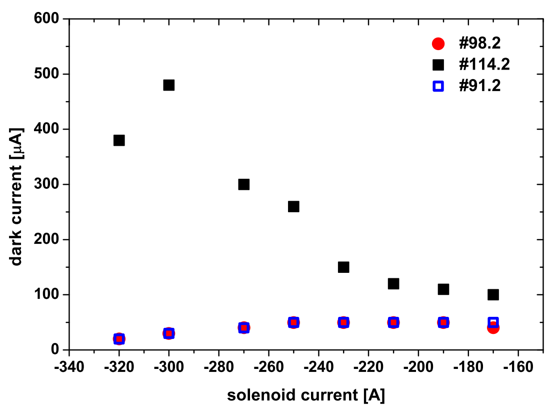


Figure 2: Dark current as function of solenoid current for three different cathodes. $P_{\mathrm{fwd}}$ = 3.9 MW for all measurements.

the heat load to the superconducting cavities. This is especially true for the 3.9 GHz cavities, which have a smaller size than the usual 1.3 GHz cavities. Also undulators suffer from radiation, which decreases the lifetime of the permanent magnets. A dark current of more than 1 mA would make the operation of FLASH impossible. A dark current kicker and a collimator just after the RF-gun are used to reduce the amount of dark current transmitted from the gun section into the linac. A scintillator panel is used to prevent operation when the dark current reaches a certain dangerous threshold. The dark current is monitored routinely with a Faraday cup close to the RF-gun.

Figure 2 shows the measured dark current as function of main solenoid current for three different cathodes. The figure clearly shows the influence of the cathode onto the emitted dark current. For cathode #114.2 the dark current is factors higher than for #98.2 and #91.2 and at the edge of usability. Supported by images taken by a Ce:YAG screen at the same position as the Faraday cup, we relate this increase to a strong emitter. For illustration, Fig. 3 shows dark current images for cathodes #91.2 and #114.2. For both measurements the machine was set up in the same way ($P_{\mathrm{fwd}}$ = 3.9 MW, solenoid current −300 A). Besides common features in both images, cathode #114.2 shows a

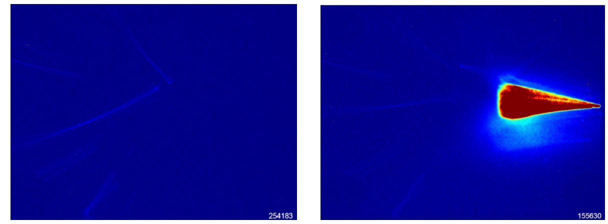

Figure 3: Dark current images for cathode #91.2 (left) and #114.2 (right) under same operational conditions ($P_{\mathrm{fwd}}$ = 3.9 MW, solenoid current −300 A.

strong emitter, responsible for the increased dark current for this particular cathode.

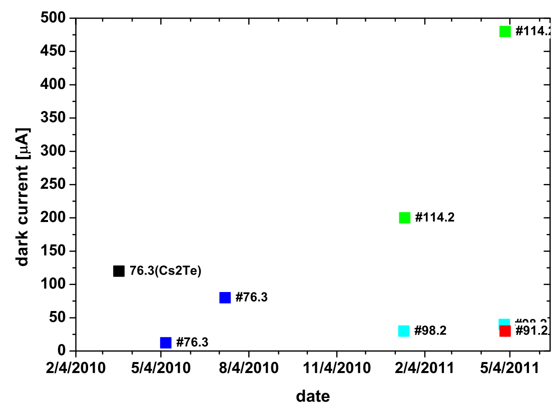


Figure 4: Dark current for $P_{\mathrm{fwd}}$ = 3.9 MW and solenoid current for standard operation as function of time for different cathodes.

Figure 4 shows the dark current history of DESY-Gun4.2 at FLASH. The values shown are all measured at $P_{\mathrm{fwd}}$ = 3.9 MW and a fixed solenoid current of −300 A. The usual solenoid scan to determine the maximum dark current emission has not been done for this measurements. Over the last year of operation, no increase which could be related to the RF-gun body itself is visible. The increased currents measured with cathode #114.2 are related to the cathode itself.

## CATHODE PRODUCTION AT DESY

In 2010 a system for preparation of photocathodes was commissioned at DESY. The design of the system is based on the one used at INFN-Milano, LASA, and has been fabricated and initially assembled by LASA in close collaboration with DESY. All components directly necessary for the cathode production are to 100 % compatible to the Milano system. In addition, the recipe for cathode production is the same to profit from the long experience at LASA.[4] First cathodes (#22.6, #613.1, and #625.1) have been produced beginning of 2011 and tested at the Photo-Injector Test Facility at DESY, Zeuthen site, (PITZ) in summer 2011.

While for cathode #613.2 and #625.1 the whole produc-



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tion process (Mo-plug fabrication, polishing, and cathode deposition) was performed at DESY, cathode #22.6 is a reused Mo-plug, fabricated and polished in Milano. For this cathode, only the deposition of the photoemissive film was done at DESY.

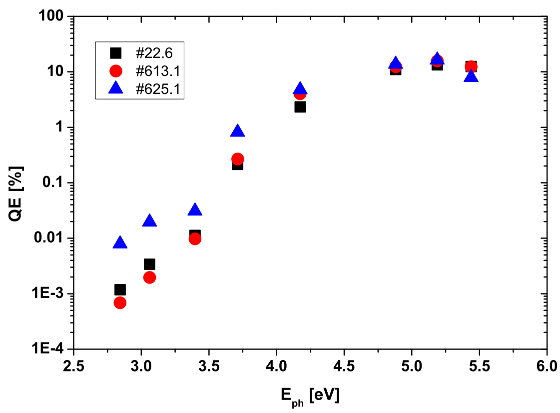


Figure 5: QE as function of photon energy.

First characterization of the cathodes – as it is standard for all cathodes– was done inside the transport box by measuring the dependency of the quantum efficiency on the energy of the impinging photons, called spectral response. For this type of measurements the cathodes are illuminated by photons of defined wavelength. The wavelength is adjusted by means of bandpass filters which are inserted in the path of the light originating from a Hg-lamp to the cathode. The power of the light is measured with a photo diode (PD300-UV, [8]). 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. The so obtained spectral responses for #22.6, #613.1, and #625.1 are shown in Fig. 5. The QE dependence on the photon energy $E_{\rm ph}$ at the photoemission threshold can be described by the following equation:

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

where $W$ is the work function of the material, in case of the semiconductor $\mathrm{Cs_2Te}$ the sum of energy band gap $E_G$ and electron affinity $E_A$. From the parameter $m$ information on the emission process itself can be derived.[6] A typical feature of $\mathrm{Cs_2Te}$ cathodes prepared by the well established recipe is the appearance of a second QE trend for smaller photon energies. By using new tools during preparation as described in [5] this low energy shoulder does not appear anymore. To reduce the complexity during preparation of the first cathodes at DESY, this new technique was not applied but the one established over years. Because of the second QE dependence, the measured data are fitted in terms of two independent emission mechanisms:

$$\mathrm{QE} = A_1\,(E_{\rm ph} - W_1)^{m1} + A_2\,(E_{\rm ph} - W_2)^{m2} \qquad (2)$$

The obtained values for $E_G + E_A$ and $m$ of the relevant high energetic parts for all three cathodes are summarized in table 1. It also shows the QE measured with the drive laser of FLASH at a wavelength of $\lambda = 262\,\mathrm{nm}$.

Table 1: Analysis of Spectral Responses and Extrapolated QE at $\lambda = 262\,\mathrm{nm}$.

| cathode | $E_G$+$E_A$ | m | QE |
|---|---|---|---|
| #22.6 | 3.54 eV | 1.87 | 7.89 % |
| #613.1 | 3.66 eV | 1.2 | 10.23 % |
| #625.1 | 3.61 eV | 1.3 | 11.12 % |

For all three cathodes the obtained $E_G + E_A$ is in good agreement with the theoretical value. Powel *et al.* estimated for the band gap of $\mathrm{Cs_2Te}$ 3.3 eV and for the electron affinity 0.2 eV.

First operation in an RF-gun of the cathodes produced at DESY was performed at PITZ. Since PITZ is dedicated to characterize and optimize RF-guns for FLASH and the European XFEL, it gives the opportunity to test photocathodes at RF-powers of up to 7 MW. In contrast to FLASH, the charge is measured at PITZ with a Faraday cup and the laser energy by a photodiode (PD10-PJ, [8]). Table 2 summarizes the pulsed QE measurements for the three cathodes. Two different gradients were chosen to match operational conditions of FLASH (47 MV/m, $P_{\rm fwd}$ = 3.9 MW) and the European XFEL (60 MV/m, $P_{\rm fwd}$ = 6.4 MW). The measurements have been performed comparable to FLASH at a launch phase of $+38°$ w.r.t. zero crossing. For a direct comparison with FLASH where the laser wavelength is 262 nm, one has to keep in mind that the PITZ laser has a slightly different laser wavelength of 257 nm.

Table 2: QE Measurements at PITZ for two RF-gradients

| cathode | QE(45 MV/m) | QE(60 MV/m) |
|---|---|---|
| #22.6 | 11.0 % | 11.4 % |
| #613.1 | 9.6 % | 12.2 % |
| #625.1 | 13.5 % | 13.7 % |

In addition to the QE itself, the homogeneity of electron emission over the cathode surfaces was studied with so-called QE-maps. Figure 6 shows the QE-maps obtained for the three cathodes at $P_{\rm fwd}$ = 3.8 MW. To avoid space charge effects on the emission profile and with a rather small laser spot size of 110 $\mu$m rms, the charge for maximum QE is in the order of 20 pC. Even though that some improvements in the homogeneity are necessary – especially at the edges of the emissive films – the QE-maps proof the usability of these cathodes.

The last quantity tested at PITZ is the dark current. As for the QE measurements the full potential in terms of RF power of the RF-gun at PITZ was used. The measurements have been performed from 3.6 MW up to 6 MW (operational point of the XFEL). For each RF-power setting, the current of the main solenoid was scanned over the full range (0-500 A) and the field emitted current was measured with the Faraday cup. The maximal collected currents within a scan are shown in Fig. 7 as function of



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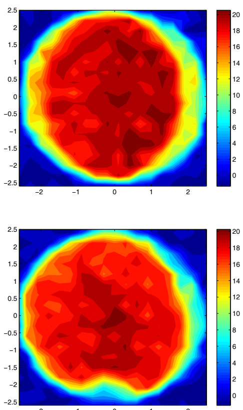

Figure 6: QE maps of cathodes #22.6 (upper left), #613.1 (upper right), and #625.1 (lower left) at $P_{\mathrm{fwd}}$ = 3.8 MW.

RF-power. The figure clearly shows that all three cathodes would be usable at FLASH without problems. The dark current in the region of 4 MW is comparable to the ones routinely measured at FLASH (Fig. 4). But even for RF-powers of up to 6 MW, only cathode #625.1 would be above 500 $\mu$A.

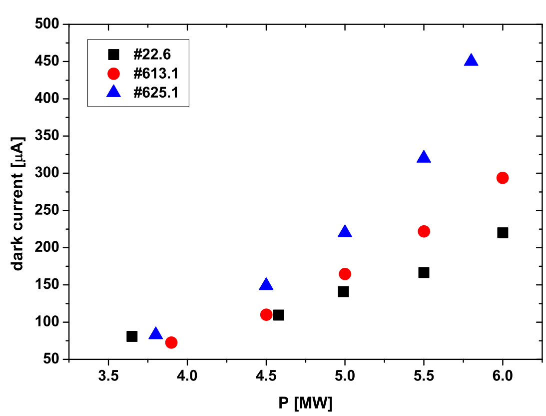


Figure 7: Maximal dark current vs. RF-power for cathodes #22.6, #613.1, and #625.1.

As described beforehand cathode #22.6 was polished at INFN-Milano, while the complete production of the other two was done at DESY. Figure 7 shows clearly, that from this cathode the lowest amount of dark current is emitted. One reason could be an imperfect finish of the surface leading to a higher roughness of #613.1 and #625.1. One has to keep in mind, that the whole preparation process is still in the commissioning phase.

On the other hand, the higher dark current could well be related to field emitters on the cathodes surface. This is supported by dark current images in Fig. 8. For both images, the RF-gun was set up in the same way ($P_{\mathrm{fwd}}$ = 6 MW, solenoid 390 A). While most of the features are common for both cathodes, cathode #613.1 shows an additional strong emitter.

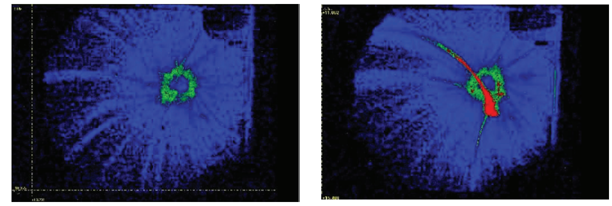

Figure 8: Dark current images for cathode #22.6 (left) and #613.1 (right) under same operational conditions ($P_{\mathrm{for}}$ = 6 MW), solenoid current 390 A.

## 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 several months is established as standard. These long lifetimes have been observed for the previous FLASH RF-gun (DESY-Gun2), and holds as well for the presently installed RF-gun DESY-Gun4.2.

In addition, long term investigations of the dark current emitted from the RF-gun and cathodes are shown. Over the last year no hints for damages at the RF-gun which yield to an increased field emission could be identified.

Beginning of 2011, first $\mathrm{Cs_2Te}$ photocathodes have been produced at DESY. The quantum efficiency of these cathodes is comparable to the ones prepared at INFN-Milano. First tests inside an RF-gun have been performed at PITZ, where the cathodes showed good performance in terms of QE, homogeneity of emission, and dark current.

The next parameter crucial for the cathodes is the long term behavior which will be studied in the near future.

## ACKNOWLEDGMENT

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