LIFETIME OF Cs$_2$Te CATHODES OPERATED AT THE FLASH FACILITY

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Abstract

The injector of the free-electron laser facility FLASH at DESY (Hamburg, Germany) uses Cs$_2$Te photocathodes. We report on the lifetime, quantum efficiency (QE), and darkcurrent of photocathodes operated at FLASH during the last year. Cathode 618.3 has been operated for a record of 439 days with a stable QE in the order of 3 %. The fresh cathode 73.3 shows an enhancement of emitted electrons for a few microseconds of a 1 MHz pulse train.

INTRODUCTION

FLASH [1–3], the free-electron laser (FEL) user facility at DESY (Hamburg) delivers high brilliance XUV and soft X-ray SASE radiation to photon experiments. FLASH is a user facility since 2005.

The maximum electron beam energy is 1.25 GeV, allowing SASE lasing down to 4 nm. The FLASH1 undulator beamline is in operation since 2004, a new FLASH2 beamline since 2014. More details on the FLASH facility and its present status as well as on simultaneous operation of two beamlines can be found in these proceedings [3, 4].

A unique feature of FLASH is its superconducting accelerating technology. It allows to accelerate several thousand electron bunches per second. The bunches come in bursts with a repetition rate of 10 Hz. The maximal burst duration is 0.8 ms, the smallest distance between single bunches is 1 µs allowing a maximum number of 800 bunches per burst or 8000 bunches per second.

THE ELECTRON SOURCE

The electron source of FLASH is a photoinjector based on a normal conducting L-band 1.5 cell RF-gun. The gun is operated with an RF power of 5 MW at 1.3 GHz, corresponding to a maximal accelerating field at the cathode of 52 MV/m. The RF pulse duration is up to 850 µs, sufficient for generation of the required bunch trains of 800 µs duration. The repetition rate is 10 Hz. The beam momentum at the gun exit is 5.6 MeV/c.

As discussed in the introduction, FLASH can accelerate many thousands of electron bunches per second. In order to keep the average power of the laser system reasonably small, a photocathode with a high quantum efficiency is used.

Cesium telluride (Cs$_2$Te) has been proven to be a reliable and stable cathode material with a good quantum efficiency (QE) for a wavelength around 260 nm [5, 6]. The bunch charge required for FLASH SASE operation is between 20 pC and a bit more than 1 nC. For a QE of 5 %, a single laser pulse of 100 nJ at 262 nm produces a charge of 1 nC (linear regime). For a burst of 800 pulses with 1 MHz and 10 bursts per second, this corresponds to a burst power
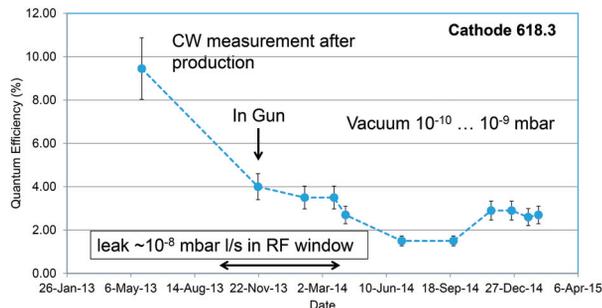
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Figure 1: Quantum efficiency of cathode 618.3 during operation at FLASH.

of 100 mW and an overall average power of 0.8 mW. With a laser pulse duration of 6.5 ps (rms), the peak power is 80 kW. These are all reasonable low numbers to avoid damage or ablations of the cathode thin film or of laser beamline components. For details on the FLASH injector laser systems, the reader is referred to [7] and references therein.

QUANTUM EFFICIENCY

For practical reasons, we define the quantum efficiency (QE) as the ratio of the numbers of photons impinging the photocathode and the number of electrons emitted – while the RF-gun is operated at its nominal working point. The extracted charge is measured with a calibrated toroid at the RF-gun exit, the laser energy with a calibrated joulemeter [8] in front of the vacuum window. The transmission of the quartz window and the reflectivity of the in-vacuum mirror is taken into account. Finally the QE is obtained by a linear fit of the charge as a function of laser energy – before space charge effects saturate the emission. For an example of such a fit, the reader is referred for instance to [9, 10].

The nominal working point of the RF-gun is at an accelerating field of 52 MV/m (on-crest) and a launch phase of 38° from the zero-crossing point. This phase has been chosen years ago and has been kept as a reference since then. The launch phase for maximum energy gain and minimum energy spread is 45° and is used for SASE operation.

Longterm Operation of a Cs$_2$Te Cathode

Figure 1 shows the quantum efficiency of cathode 618.3 during operation at FLASH for a period of 439 days. The cathode has been produced with the usual recipe. A thin film of Cs$_2$Te with a diameter of 5 mm is deposited on a polished molybdenum plug. Figure 2 shows a photo of the cathode. For details on the production of cathodes see [10, 11].

The QE is always measured at the center of the cathode with RF-gun operation parameters as discussed above. Figure 1 also shows the QE measured just after production with a Hg-lamp at the preparation chamber. During operation in
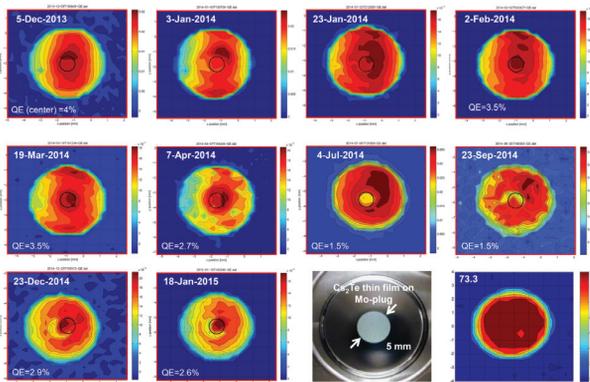
Figure 2: QE-map evolution of cathode 618.3 from December 2013 to January 2015. Each map shows the measured charge as a function of the horizontal and vertical position of the laser beam spot on the cathode surface. The charge is color coded and is given in nC. The maximum charge is adjusted to 20 to 30 pC. The cathode diameter is 5 mm. The black circle indicated the approximate size and position of the laser beam during beam operation. The QE measured in the center of the cathode is indicated at the lower left corner of each map and is also shown in Fig. 1. In the lower right corner we show as an example the inital QE-map of cathode 73.3 right after production and a photo of the cathode plug with the thin film cathode visible by the light blue color.

October 2013, the RF-window of the RF-gun developed a small leak to air of 10^{-8} mbar l/s. The leak had only been discovered later and was repaired in April 2014 by exchanging the RF-window.

This explains the low but stable quantum efficiency around a good 3 %. During conditioning time of the new window from April to June 2014 the QE dropped to 2 % and recovered later due to the improved vacuum pressure when a stable operation with the new window has been achieved. Previous studies have shown, that the QE strongly depends on vacuum conditions [12]. The total amount of charge extracted by this cathode is 3.2 C.

QE-Map Evolution

A QE-map is obtained by scanning a laser beam with constant energy over the cathode. The size of the laser beam is $100\,\mu\text{m}$ in diameter obtained with a hard edge aperture imaged onto the cathode. The scanning step size is $85\,\mu\text{m}$. We use absolutely calibrated linear translation stages moving beamline mirrors in horizontal and vertical direction. For each scan point, the average charge of a train of 30 bunches is measured with a toroid right after the gun, averaged over 5 trains. The charge is adjusted to 20 to 30 pC, small enough to avoid space charge related saturation effects.

Figure 2 shows a series of QE-maps measured during the 439 days of operation of cathode 618.3 in the RF-gun. The slight left-right QE reduction visible at most maps is due to the narrow aperture of 5 mm of the in-vacuum mirror in horizontal direction. The overall picture is, that initially the
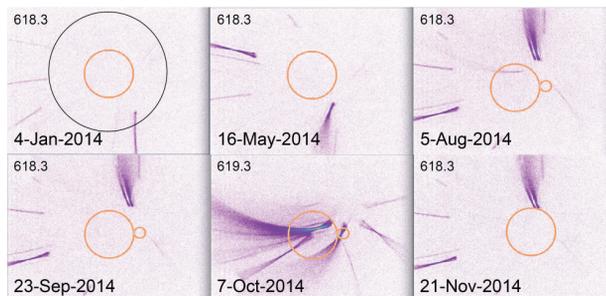

Figure 3: Darkcurrent of the RF-gun with cathode 618.3 and 619.3 measured with a Ce:YAG powder screen during operation in 2014. The red circle indicates the position of the Cs_2Te film, the black circle the rim of the cathode. The streaks are due to the solenoid field. Pictures were taken under normal operating conditions of the gun (see text).

QE degrades faster at the cathode center where the laser hits. The surrounding QE reduces slowly but steadily, where the center part recovers. Due to the vacuum conditions, we expected a slow reduction of the overall QE. The recovering of the QE at the center might be explained by laser cleaning effects.

DARKCURRENT

Darkcurrent is usually emitted by particles on the cathode or defects of the copper structure close or at the RF-contact spring [13, 14]. The RF-gun has been cleaned with dry-ice reducing the darkcurrent emitted at the gun backplane by an order of magnitude. Most of the residual darkcurrent is due to particles on the cathode plug surface.

The cathode is produced in the preparation chamber, either at LASA (cathode 73.3) or DESY (cathode 618.3), put into a transport box keeping ultra-high vacuum conditions. The transport box is shipped to FLASH where it is connected to the cathode load-lock system, pulled out of the carrier and inserted into the gun. During operation, whenever for example titan sublimation pumps are activated, the cathode has to be pulled back from the gun. Due to these frequent handling of the cathode plug, particles may appear and also disappear.

Figure 3 shows several images of darkcurrent taken from January 2014 to November 2014 with cathode 618.3 and one image with cathode 619.3. The images are taken with a Ce:YAG powder screen 1.6 m from the cathode downstream the RF-gun. The RF-gun was operated with standard parameters: with a field of 52 MV/m on the cathode (on-crest), an RF-pulse length of $500\,\mu\text{s}$, and a solenoid focusing field of 180 mT. Since the emitted darkcurrent has a large energy spread, streaks develop due to the focusing solenoid field. The camera settings and RF-pulse length have been equal for all images of cathode 618.3, so that the relative strength of the darkcurrent emitter can be compared. The image for cathode 619.3 has been taken with a by a factor of 10 reduced pulse length of $60\,\mu\text{s}$. The absolute darkcurrent measured with a Faraday cup (same size as the screen) is $5\,\mu\text{A}$. During
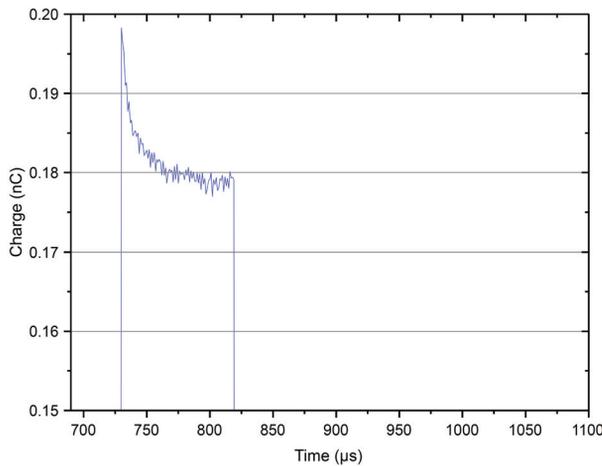
Figure 4: Measured charge along the electron bunch train for a flat laser pulse train as shown in Fig. 5. The bunch to bunch distance is 1 us.

Figure 5: Oscilloscope trace of the laser pulse train used in this experiment. The spacing of the individual pulses is 1 μs (1 MHz), the train length is variable, in this example 200 μs. The wavelength is 262 nm. The laser pulse energy is measured with a UV sensitive photodiode.

standard operation the amount of darkcurrent entering the linac is reduced with a resonant kicker operating at 1 MHz together with a circular collimator.

The images show, that new emitters have been appearing in May 2014 and Aug 2014. The emitter from May disappeared shortly, the emitter from August stayed at a constant level.

Cathode 619.3 from the same production batch shows, that cathodes might actually be contaminated by emitters (Fig. 3). Cathode 619.3 emitted a darkcurrent of 20 μA and has therefore not been used for beam operation.

EMISSION ISSUE

Cathode 618.3 has been replaced by cathode 73.3 in February 2015. The motivation for the change was to test a fresh cathode. Certainly cathode 618.3 could have been operated for much longer than 439 days.

As already observed earlier, fresh cathodes do not emit uniformly along a bunch train. Figure 4 shows a non-flat emission of a 1 MHz pulse train – even though the laser pulse energy was flat along the train (Fig. 5). More charge is emitted for the first bunch and then drops within a few microseconds by 10 % and stays flat until the end of the bunch train. Assuming an exponential decay $Q(t) = Q_0 \exp(-t/\tau)$, the decay rate is $\tau = 10\,\mu s$. As said, the distance of the bunches within the train is 1 μs.

In this section, we show, that the enhanced emission is due to the emission process of the cathode and is not related to an artifact of the laser nor the accelerating field amplitude or phase of the RF-gun.

To exclude an effect of the RF-field, we shifted the laser pulse train along the RF-pulse by more than 100 μs. No change of the spike could be observed.

To exclude an artifact of the laser pulse train, we used two independent laser systems, laser 1 and laser 2. Both lasers have been adjusted to have a flat pulse train measured
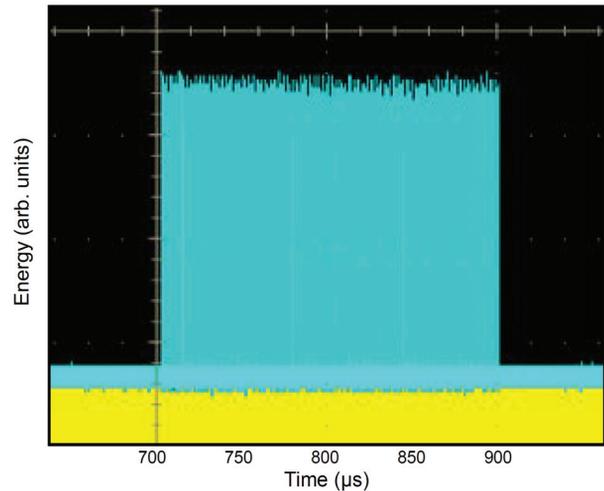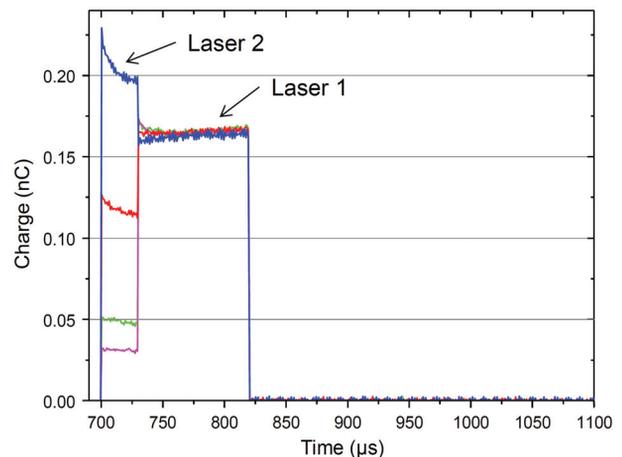

Figure 6: Measured charge along the pulse train generated by two independent laser systems, laser 1 and laser 2. The bunch distance is 1 μs. Initially, the electron bunches created by laser 2 show the emission spike, while the bunches generated by laser 1 not. The charge for laser 1 is intentionally reduced to show this effect. Gradually reducing the laser 2 pulse energy reduces the emission spike for laser 2 and enhances the spike for laser 1 (note : the color changes from blue, red, green to magenta). With laser 2 switched off (not in this plot), the emission spike by laser 1 is exactly the same as for laser 2 (Fig. 4).
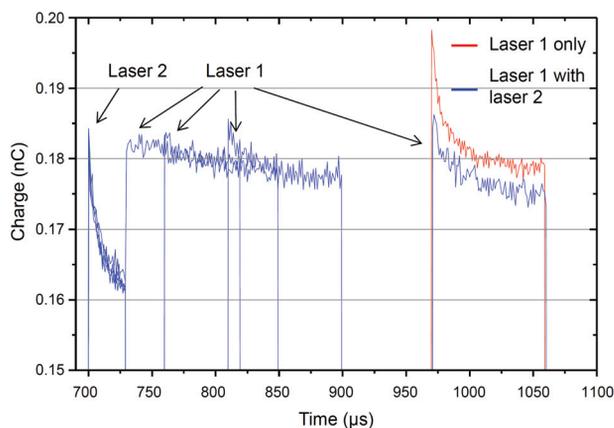
Figure 7: Measured charge along the pulse train generated by two independent laser systems, laser 1 and laser 2 (blue). The bunch distance within the train is 1 µs. The electron bunches created by laser 2 show the emission spike, while the bunches generated by laser 1 – when attached to the laser 2 train – not. Gradually shifting laser 1 in time away from laser 2 enhances the spike for laser 1. After a shift of 250 µs the spike generated by laser 1 is almost as pronounced as if laser 2 was switched off (red).

by a UV-sensitive fast photodiode using an oscilloscope as shown in Fig. 5. For both lasers alone, the emission spike appears as in Fig. 4.

To exclude a measurement artifact with the photodiode, we used both lasers at the same time. Laser 2 starts at 700 µs (an arbitrary chosen starting time but within the flat top of the RF-gun pulse) with a flat-top length of 30 µs and with a 1 µs bunch to bunch distance (1 MHz) – long enough to develop the decaying emission spike. Laser 1 runs also at 1 MHz with a longer pulse train of 100 µs.

The trick is, that laser 1 starts just where the laser 2 train ends, at 730 µs. With laser 2 switched on, the electron emission for laser 1 is flat! However, switching laser 2 off, the emission spike now appears for laser 1.

Figure 6 shows this effect: when the energy of laser 2 is gradually decreased, the laser 2 pulse train flattens and at the same time, the emission spike appears for laser 1. This excludes an effect of the lasers and shows, that the enhanced emission is due to a yet unknown property of the emission process of the cathode.

Keeping laser 2 on, and delaying laser 1 further in respect to laser 2, an emission spike for laser 1 appears step by step and is almost fully exploited after a delay of 250 µs (Fig. 7).

Further observations are, that laser 2 can only switch the emission spike for laser 1 off as in Fig. 6, if the charge of laser 2 is actuality extracted. Moving the start of the RF-field exactly between laser 2 and laser 1, the emission spike now appears for laser 1 (laser 2 does not emit electrons).

Another observation is, that reducing the accelerating field of the RF-gun from 52 MV/m below 20 MV/m, the enhanced emission is gone.

A last important finding is that the decay time of the enhanced emission at the beginning of the bunch train increases slowly with time, in other words, the trains become flatter. After 4 months of continuous operation, the decay time of the enhanced emission increased from the initial $\tau = 10\,\mu s$ to $130\,\mu s$.

ACKNOWLEDGMENT

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