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

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Abstract

The photoinjector of the free-electron laser facility FLASH at DESY (Hamburg, Germany) uses Cs$_2$Te photocathodes. We give an update on lifetime and quantum efficiency of cathodes operated at FLASH during the last years. At the time of the conference, cathode 73.3 has been operated with a record of 933 days with a stable quantum efficiency of in average 8.8 %.

INTRODUCTION

Since 2005, FLASH [1–4], the free-electron laser user facility at DESY (Hamburg, Germany), successfully delivers high brilliance femtosecond short XUV and soft X-ray SASE radiation pulses to photon experiments.

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 with a single bunch charge between 20 pC and a bit more than 1 nC. With a beam time of more than 8000 h per year, a maximum of about 200 C would be extracted from the cathode per year. In practice, not all users require maximum charge and maximum number of bunches per second so that the charge actually extracted is much lower and depends on the experimental requirements. The cathode of the electron source has to cope with these requirements.

THE ELECTRON SOURCE

The electron source of FLASH is a photoinjector based on a normal conducting L-band 1.5 cell RF-gun (1.3 GHz). [5] The RF-gun is version 3 (G3.1) with the usual racetrack spring RF-contact between the gun backplane and the cathode. The RF-gun was built in 2005, conditioned at the PITZ facility (DESY, Zeuthen) in 2006 and finally installed in April 2013 as a preemptive maintenance measure replacing gun G4.1. The gun is operated with an RF power of 5 MW corresponding to a maximal accelerating field at the cathode of 52 MV/m, which leads to a beam momentum of 5.6 MeV/c. The gun is designed to provide the same RF-pulse length as the superconducting accelerator: the RF pulse flat top duration is up to 800 µs with a repetition rate of 10 Hz. The average RF power of 40 kW is efficiently cooled away by a dedicated water cooling system [6] keeping the gun temperature within 0.02 K [7].

The RF-gun and cathode system vacuum is pumped with several ion-getter pumps (IGP) most of them with a pumping speed of 60 l/s each. A few IGP's are equipped with an additional titanium-sublimation pump (TSP) adding 1000 l/s. The vacuum set-up is very similar to Fig. 4 in [5]. The base pressure without RF is kept below 2×10^{-10} mbar, with RF, the pressure increases roughly by a factor of 2. Note, that the pressure is not measured inside the gun body nor at the cathode surface.

To generate thousands of bunches per second with a charge in the nC-scale, we use a high quantum efficiency cathode. Cesium telluride (Cs$_2$Te) has been proven to be a reliable and stable cathode material with an excellent quantum efficiency (QE) for a laser wavelength around 260 nm [8–10]. The bunch charge required for FLASH operation is between 20 pC (for ultra-short SASE pulse operation) and a bit more than 1 nC (for efficient THz-generation).

Typical numbers are illustrated in the following example: We extract a charge of 1 nC with a laser pulse energy of 50 nJ having a QE of the Cs$_2$Te cathode of 10 %. The laser wavelength is 262 nm. For a burst of 800 pulses with 1 MHz and 10 bursts per second, this corresponds to a burst laser power of 50 mW. The laser pulse duration is 6.5 ps (sigma) leading to a peak power of 3 kW only. The laser spot shape is a truncated Gaussian with a diameter of 1.2 mm yielding a fluence in the burst of 4.4 mJ/cm^2, far away from typical damage thresholds of a few J/cm^2. These are all reasonable low laser power values which eases the design of the laser system and, damages or ablations of optical components or of the cathode thin film itself are avoided. The laser is sent to the cathode through a high quality fused-silica vacuum window [11] and is reflected to the cathode with a custom made mirror [12] inside the vacuum. For details on the FLASH injector laser systems, the reader is referred to [13] and references therein.

QUANTUM EFFICIENCY

For practical reasons, we define the quantum efficiency (QE) as the ratio of number of photons impinging the photocathode and the number of electrons emitted – while the RF-gun is operated at its nominal working point.

The nominal working point of the RF-gun is at a forward power of 5 MW which yields in an on-crest accelerating field of 52 MV/m. The launch phase is set to of 38° from the zero-crossing point. This phase has been chosen years ago and has been kept as a reference phase for all QE-data presented since then. The launch phase for SASE-operation is usually around 45°.
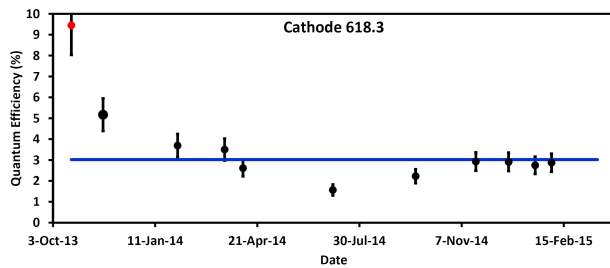
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Figure 1: Quantum efficiency (QE) of cathode 618.3 during operation at FLASH. The cathode was in operation for 439 days. The blue line shows the average QE of 3 %. The red dot indicated the QE measured immediately after production with a Hg-lamp in May 2013.
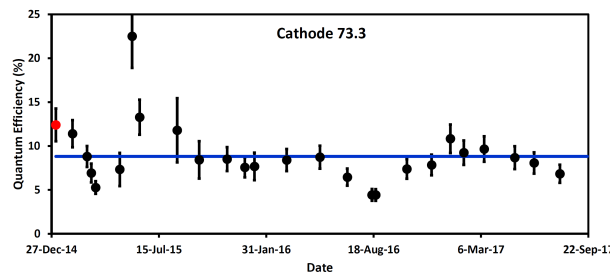

Figure 2: Quantum efficiency (QE) of cathode 73.3 during operation at FLASH. By the time of the conference, the cathode is in operation for 933 days. The blue line shows the average QE of 8.8 %. The red dot indicated the QE measured immediately after production with a Hg-lamp in June 2013.

The extracted charge is measured with a toroid at the RF-gun exit, the laser energy with a joulemeter [14] in front of the vacuum window. The transmission of the vacuum window and the reflectivity of the in-vacuum mirror is taken into account. However, a possible long-term degradation of transmission of the vacuum window due to radiation or a degradation of the reflectivity of the in-vacuum mirror has not been taken into account for this study.

The charge is measured as a function of laser energy while the laser energy is varied using a combination of a half wave-plate with a polarizer. The QE is always measured at the center of the cathode with laser spot diameters of 1 and 1.2 mm, while the cathode diameter is 5 mm. Usually a laser spot of 1.2 mm is used for SASE-operation.

Finally the QE is obtained by a linear fit on the data points not yet in saturation. From a certain laser energy density on, space charge effects reduce the amount of emitted electrons. For an example of such a fit, the reader is referred for instance to [15, 16]. The measurement error is in the order of 15 %.

Longterm Operation of Cs2Te Cathodes

In the early years of RF-gun operation at the TESLA Test-Facility and FLASH, 1998 to 2013, many different cathodes have been in use, mostly for a short time only. For more information on lifetime of various cathodes, the reader is referred to [9, 15–21].
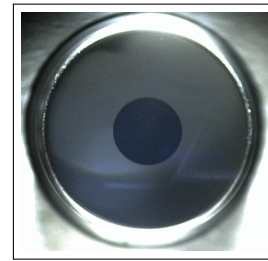
Figure 3: Picture of a cathode plug in a transport chamber. The molybdenum-plug has a diameter of 16 mm, the Cs_2Te thin film of 5 mm. The Cs_2Te film has in this example a dark blueish color.

Since November 2013, only two different photocathodes have been in operation at FLASH: cathode 618.3 produced at DESY in May 2013 and 73.3 produced at LASA, Milano in June 2013.

The cathodes have been produced with the usual recipe. A thin film of Cs_2Te with a diameter of 5 mm is deposited on a polished molybdenum plug. Figure 3 shows a picture of a cathode. Cathodes 618.3 and 73.3 have the 3rd thin-film of Cs_2Te deposited onto plug 618 and 73 resp. For details on the production of cathodes see [16, 18].

In February 2015, cathode 618.3 has been exchanged with 73.3 after 439 days of stable operation at a QE of 3 % (Fig. 1). The reason for the change was nor low quantum efficiency nor any other defect. We simply wanted to verify, that cathode 73.3 stored for almost 2 years was still good – since it was, we kept it in.

The lifetime of both cathodes is remarkable. Cathode 618.3 already showed a lifetime record of more than 400 days, cathode 73.3 surpassed this with 933 days of continuous operation – by the time of the conference. FLASH usually runs more than 8000 hours per year thus the cathode has a small idle time of 10 % of the yearly operation time. Cathode 73.3 is still in operation with a QE average of 8.8 ± 1.3 % (Fig. 2). The total amount of charge extracted by cathode 618.3 was 3.2 C, by cathode 73.3 18 C up to now.

The drop of QE of cathode 618.3 when firstly operated – compared to the initial QE after production – is explained by a small vacuum leak developed in October 2013 at the gun RF-window 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 3 % of cathode 618.3. During conditioning time of the new window from April to June 2014 the QE dropped further to 2 % and recovered later due to the improved vacuum pressure when a stable operation with the new window has been achieved.

This shows, that the key for a long lifetime is to maintain a good vacuum pressure in the RF-gun. Also cathode 73.3 has partially suffered from vacuum leaks in the beamline section downstream the RF-gun and on the RF-window (July 2016). In contrast to 618.3, these leaks have been discovered early
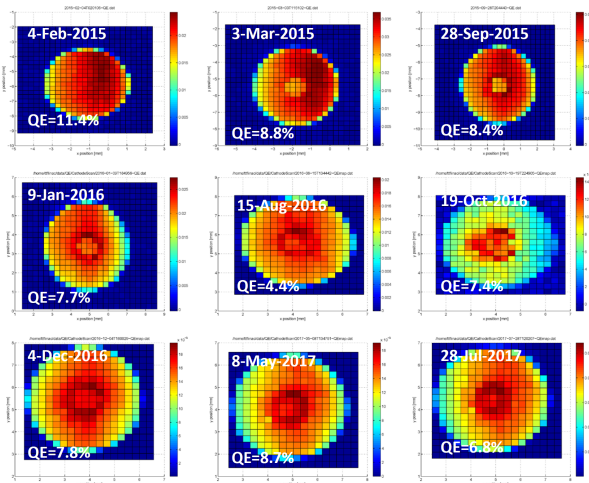
Figure 4: QE-map evolution of cathode 73.3 from February 2015 to July 2017. Each map shows the measured charge as a function of the horizontal and vertical position of the laser beam spot on the cathode surface. The charge is color coded and is given in nC. The QE value measured in the center of the cathode is indicated in the lower left corner of each map.

and could be repaired in a timely manner, so that the QE has not suffered too much and recovered quickly.

As to remind the reader, previous studies e.g. [22] have already shown, that the QE strongly depends on vacuum conditions and that pollution with oxygen or other molecules containing oxygen has to be avoided. The same study also showed, that partial recovery of the initial QE by UV light exposure is possible.

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 $100\,\mu m$ in diameter ($\sigma = 25\,\mu m$) obtained with a hard edge aperture imaged onto the cathode. The scanning step size is $85\,\mu m$. We use calibrated linear translation stages moving beamline mirrors in horizontal and vertical direction. For each scan point, the charge is measured with a toroid right after the RF-gun. The single bunch charge is adjusted to a maximum of 10 to 30 pC, small enough to avoid space charge related saturation effects.

Figure 4 shows a series of QE-maps of cathode 73.3 measured during the last 900 days of operation.

Initially the QE degrades at the cathode center where the laser hits. The cathode has a diameter of 5 mm, while the laser spot during FLASH operation is 1.2 mm (flat top). The surrounding QE reduces slowly but steadily with time. Due to non-perfect vacuum conditions, we expect a slow reduction of the overall QE.

The QE at the cathode center remains stable at a high level of 8 %. We explain this by laser cleaning of the cathode surface. A similar behavior has been observed with cathode 618.3 [10]. This again confirms the result of previous pollution studies [22].
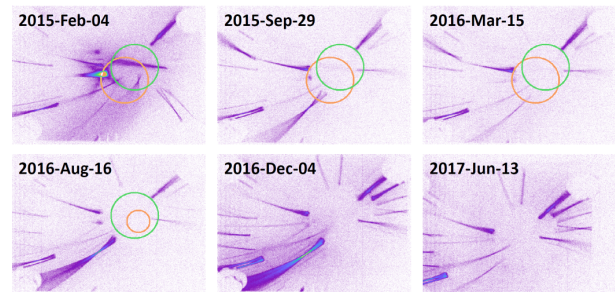

Figure 5: Darkcurrent emitted by cathode 73.3. The images are taken between February 2015 and Jun 2017. The green circle indicates the approximate position of the Cs_2Te film, the orange circle is a marker for another purpose not discussed here. The darkcurrent point sources appear as streaks due to the field of the gun solenoid (180 mT).

DARKCURRENT

Darkcurrent which is transported with the beam is usually emitted by particles close to or on the cathode [23, 24]. The RF-gun has been cleaned with dry-ice reducing the darkcurrent emitted at the gun backplane by an order of magnitude. Even though care is being taken to avoid particle contamination, contamination due to cathode handling cannot be totally excluded. The cathode is produced in a preparation chamber (at LASA or DESY). A stack of four fresh cathodes sitting in a carrier is transferred to a so-called transport box – maintaining ultra-high vacuum conditions all time. The transport box is shipped to FLASH where it is connected to the load-lock system of the RF-gun. One cathode plug is pulled out of the carrier and inserted into the gun. Due to this handling, contamination with emitting particles may occur.

Figure 5 shows images of darkcurrent taken from February 2015 to June 2017 with cathode 73.3. We use a screen of Ce:YAG powder about 1.6 m from the cathode downstream the RF-gun. For all images, the RF-gun is operated with standard parameters (see above), and a solenoid 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 so that the relative strength of the darkcurrent emitters can be compared. The absolute darkcurrent measured with a Faraday cup at the same location and with the same size as the screen is 5 µA. The uncertainty of the current measurement is 20 %.

The first image of Fig. 5 shows the darkcurrent of the freshly inserted cathode. A strong emitter is present, which disappeared later. A few other smaller emitters disappeared with time until a new emitter started mid 2016. The darkcurrent increased by a factor of 2 during this incident. The emitter was conditioned away by normal operation by January 2017. Since then the situation is stable again, the darkcurrent is back to the usual 5 µA level.

What the operation of the RF-gun is concerned, the tracking of darkcurrent images is a useful tool to detect defects at

the gun backplane and the RF-contact between the cathode and the gun. In the past, at several occasions damages have been observed forcing a change of the cathode or even the gun body itself. Moreover, high darkcurrent leads to serious activation of beamline components in the accelerator and is also a cryogenic load, which needs to be avoided. We use a kicker/collimator system to suppress darkcurrent to a large amount after the RF-gun at 5.6 MeV.

CONCLUSION

A Cs_2Te cathode has been operated at FLASH with a lifetime record of more than 900 days with a stable quantum efficiency of in average 8.8 ± 1.3 %. The cathode is operated with beam 90 % of the year and has extracted a total of 18 C of charge up to now. The QE maps show a quick reduction of quantum efficiency of the fresh cathode at the place where the laser hits. The overall QE of the whole cathode degrades with time as expected. In contrast, the QE at the cathode center remains stable due to laser cleaning effects. The long lifetime is clearly connected to a very good ultra-high vacuum being maintained in the RF gun. The darkcurrent from the cathode is stable at a low 5 µA level. A few emitters of the fresh cathode have been successfully conditioned away.

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