PHOTOCATHODES FOR THE ELECTRON SOURCES AT FLASH AND EUROPEAN XFEL

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Abstract

The photoinjectors of FLASH at DESY (Hamburg, Germany) and the European XFEL are operated by laser driven RF-guns. In both facilities cesium telluride (Cs_2Te) photocathodes are successfully used since several years. We present recent data on the lifetime and quantum efficiency (QE) of the photocathodes currently in operation. In addition we present the latest data of the cathode #680.1 which holds the operation record time of 1452 days with a total charge extracted of 32.2 C.

INTRODUCTION

The FLASH accelerator is a free-electron laser (FEL) user facility since 2005 [1–4], located in DESY (Hamburg, Germany) and provides ultra-short femtosecond laser pulses in the extreme ultra-violet and soft X-ray wavelengths range with unprecedented brilliance to two photon experimental halls. The macro-pulse repetition rate is 10 Hz with a usable length of the RF pulses of 800 µs. With a micro-bunch frequency of 1 MHz up to 8000 bunches per second are accelerated at FLASH. The bunch charge depends on the requirements on the FEL-light and is usually within a span of 20 pC to 1 nC. After the electron beam is accelerated to 1.25 GeV, the electron bunches are distributed into two different undulator beamlines.

The European XFEL [5] is the longest superconducting linear accelerator in the world driving a hard X-ray free-electron laser. The accelerator is operated by DESY. After a successful commissioning in 2016 [6] and first lasing in May 2017 [7], first user periods have been successfully accomplished [8]. The European XFEL runs now in full swing delivering high brilliance femtosecond short X-ray pulses in the energy range of 0.25 to 25 keV. The European XFEL uses upgraded TESLA type superconducting linac technology similar to FLASH with 10 Hz macro-pulse repetition rate. With a micro-bunch frequency of up to 4.5 MHz and an RF-pulse length of 600 µs, the European XFEL can deliver 27000 bunches per second.

ELECTRON SOURCES

The electron sources of FLASH and the European XFEL are very similar. Both photoinjectors are driven by a normal conducting 1.3 GHz L-band RF-gun, based on the design by [9]. Cs_2Te cathodes have been chosen to generate the photoelectrons bunches in both facilities. The electron bunches at FLASH are generated by three drive laser systems operating at a wavelength of 262 nm and 257 nm [10], while both laser at the European XFEL operates at 257 nm. All Cs_2Te photocathodes have a high quantum efficiency (QE) that keeps the required average laser power for multi-bunch operation in a reasonable regime. The vacuum pressure in the RF-guns during operation is in the low 10^{-9} mbar range. These excellent vacuum conditions are crucial for the lifetime of Cs_2Te cathodes.

Currently the accelerating field at the photocathode during standard operation at FLASH is 50 MV/m and 54 MV/m for the European XFEL. In both facilities the whole gun setups are interchangeable between each other. Gun 3.1 is was in operation at FLASH since 2013 [11] and has been exchanged in December 2019 for Gun 4.4 due to a leak in the cooling water circuit. Installed in 2013, Gun 4.3 was the first RF-gun operated at the European XFEL, during commissioning phase and first user runs. In December 2017 it was exchanged for Gun 4.6 and serves now as hot spare.

The photocathodes are either prepared at INFN-LASA in Milano, Italy, [12] or at DESY Hamburg. The transfer to the accelerators is done with ultra-high-vacuum (UHV) transport boxes, maintaining a pressure in the low 10^{-10} mbar range. The transport boxes can be equipped with up to four cathodes, one place is void. In both facilities a very similar load-lock transfer system is used to insert the Cs_2Te photocathodes under the required UHV conditions into the RF guns [12].

QUANTUM EFFICIENCY AND LIFETIME

QE Measurement Procedure

The QE is monitored after cathode production in the lab where the spectral response is measured with a Hg-lamp for 6 different wavelengths. A QE map is generated after production to understand its uniformity and to be able to compare the map afterwards with in situ measurements.

In situ, the cathode performance is monitored on regular bases. The QE measurements in the gun are always taken under comparable conditions, such as:

- The on-crest accelerating field during the measurements is in the order of 52 MV/m.
- The charge is measured with a toroid right after the RF-gun (uncertainty 1%).
- The launch phase is set to 38° w.r.t. zero crossing. This phase was chosen years ago and kept as reference for all QE measurements.

Regarding the phase, the measurement is neither at the on-crest phase nor at the launch phase during standard operation

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of the accelerators, which is at 45°. On-crest, about 30% more charge is extracted than at 38°, at 45° about 10% more.

To determine the QE, we measure the charge as function of the laser energy. At FLASH the laser energy is measured by a calibrated pyroelectric joulemeter in front of the vacuum window (uncertainty 2%). At the European XFEL the measurement is done by a photo diode which is cross-calibrated with a pyroelectric detector. To obtain the laser energy at the cathode the transmission of the vacuum window and the reflectivity of the in-vacuum mirror are taken into account in the data analysis. Laser spot at the photocathodes during the measurements is 1.0 mm and 1.2 mm – typical truncated Gaussian spot sizes during operation. The QE is determined by a linear fit of the slope of the measured charge versus laser energy in the region, where space charge effects are negligible. [13]

Lifetime at European XFEL

Cathode #680.1 holds the operation record time of 1452 days with a total charge of 32.2 C extracted (Fig. 1). The cathode was exchanged for #681.1 after its QE dropped significantly to a 2 % level.

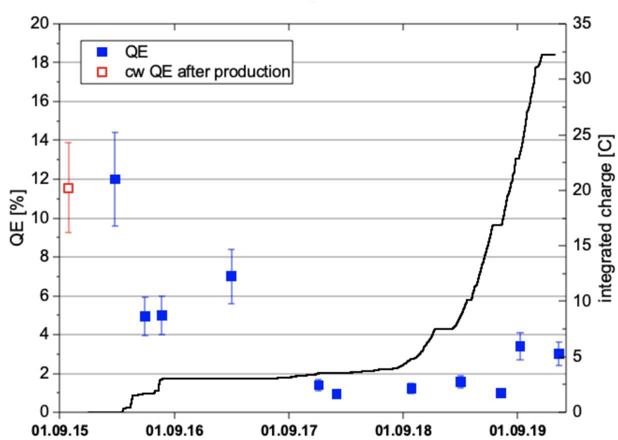

Figure 1: Quantum efficiency (blue solid squares) and integrated charge vs. time (black line) for cathode #680.1, which was in operation at the European XFEL. The red square data point shows the QE right after production measured with a Hg-lamp at 254 nm.

Figure 2 shows the quantum efficiency of cathode #681.1. The cathode is being in operation at the European XFEL since the 14th of January 2020.

Cathode #681.1 has been prepared in September 2015 at DESY and is being in operation since January 2020 at the European XFEL. The QE is being stable after the first year of operation. During operation a total integrated charge of 49.8 C has been extracted from cathode #681.1.

Lifetime at FLASH

Cathode #73.3 was in operation from February 2015 to December 2018. This cathode held the previous record of

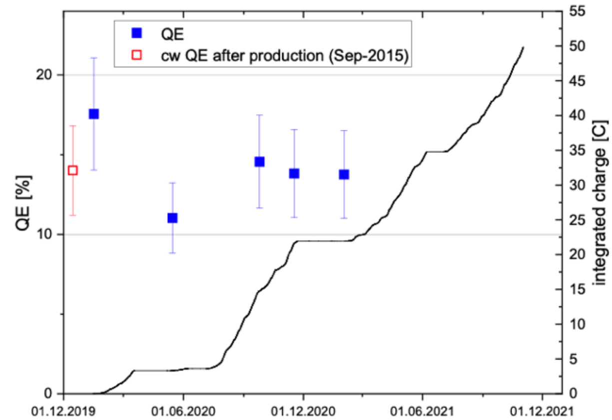

Figure 2: Quantum efficiency (blue solid squares) and integrated charge vs. time (black line) for cathode #681.1, operated at European XFEL. The red square data point shows the QE right after production measured with a Hg-lamp at 254 nm.

1413 days in operation with an integrated charge of 25 C extracted. [14] Since December 2018, the FLASH accelerator operates with cathode #105.2.

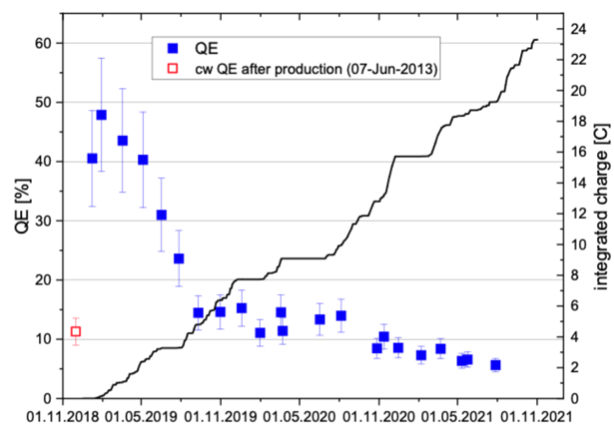

Figure 3: Quantum efficiency (blue solid squares) and integrated charge vs. time (black line) for cathode #105.2, operated at FLASH since December 2018. The red square shows the QE right after production measured with a Hg-lamp at 254 nm.

Figure 3 shows the QE of cathode #105.2 as well as the integrated extracted charge over the whole operation time. The QE has settled at a 7% level with an integrated charge of 23 C up to now.

In addition to the regular QE measurements at FLASH, the homogeneity of electron emission from the photocathodes is studied by QE-maps. For this investigations a small spot laser beam of σ = 25 µm is scanned horizontally and vertically over the cathode in steps of 85 µm. The emitted charge is measured with a high resolution toroid (detection threshold <1 pC). The laser energy is adjusted such to generate a maximum charge of 10 pC to 20 pC.

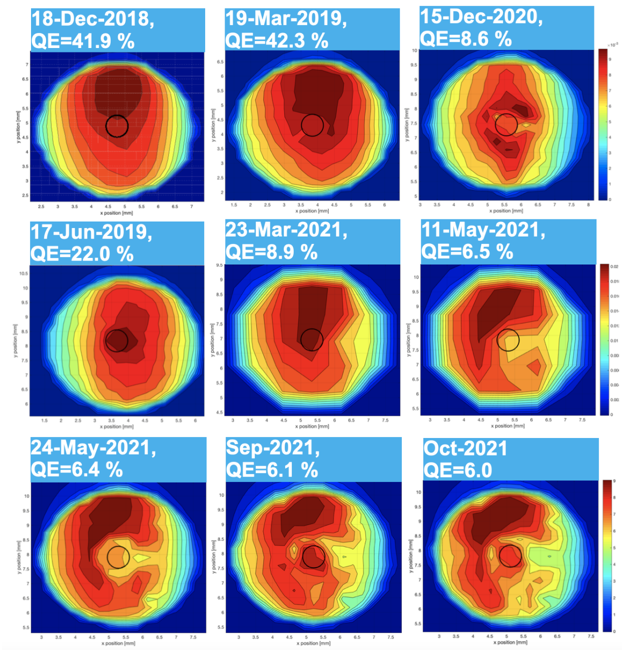

Figure 4: Quantum efficiency map evolution of cathode #105.2 from December 2018 to October 2021. The black ring in the middle indicates the typical size of the laser beam of 1.2 mm during operation.

Figure 4 shows the evolution of QE-maps for cathode #105.2. An non-homogeneous emission over the cathode is observed, the top has a higher QE than the bottom. A decrease of the overall QE is partially compensated by the cleaning effect of the UV laser beam hitting the cathode in the middle. [11, 15, 16].

In order to understand better the QE map measured in the gun, an experiment was performed to understand if the QE at the cathode left/right was actually lower than top/down or is an effect of the narrow acceptance of the last mirror mounted in the gun vacuum, about 70 cm away from the cathode. Due to the 45° angle the mirror has an acceptance of only 5 mm in the horizontal plane, the size of the cathode. In the vertical the acceptance is 10 mm. During the scan, the laser spot is moved with linear stages only and thus moves over the vacuum mirror.

In the experiment, the laser spot angle was changed such, that the laser hits the outer edges of the cathode, keeping the spot in the center of the vacuum mirror. Figure 5 shows the QE maps taken while the laser was moved in order to reach the edges of the cathode. The top maps show the QE map with the laser centered on the cathode and on the vacuum mirror, but moved during the scan on the vacuum mirror. The bottom maps show the QE map with the laser centred on the mirror while hitting the right edge of the cathode (left map) and the top edge of the cathode (right map). Also in this case, the laser was moved over the vacuum mirror during the scan.

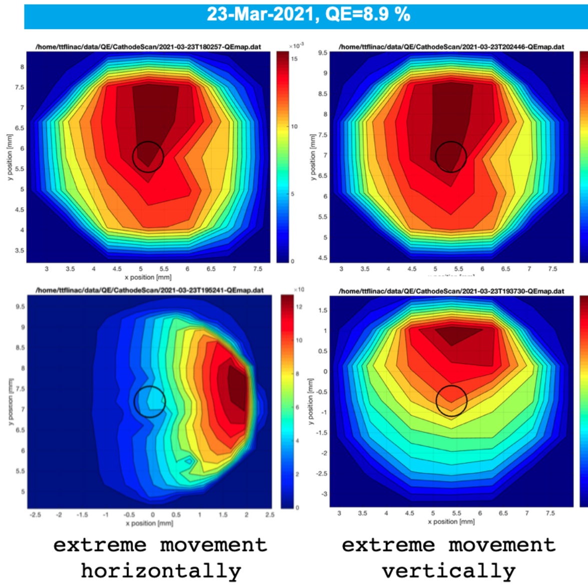

Figure 5: Quantum efficiency map of cathode #105.2 measured on March 2021 with a QE of 8.9%. The top maps: laser centered on the cathode. The bottom maps: laser is hitting the right edge of the cathode (left) and the top edge of the cathode (right).

The high QE at the right/top edges with the laser initially moved to these edge shows, that the limited horizontal acceptance of the vacuum mirror in the usual QE map (top) artificially reduces the QE left/right and is not a real reduction of the QE. The very low QE on the left and bottom of the bottom maps is explained by the same argument with a stronger reduction in the horizontal plane.

In order to solve this systematic issue of the QE map, one should scan the laser spot over the cathode keeping the laser in the middle of the vacuum mirror. This is a complicated procedure which takes a lot of beam time (8 hours) and thus does not allow quick regular scans. The simplified scan is done in 20 minutes and is short enough for regular measurements during FLASH operation.

CONCLUSION

The Cs_2Te photocathodes operated at FLASH and the European XFEL during the last years show a remarkable lifetime. Cathode #680.1 was exchange at the European XFEL holding an operation record of 1452 days with a total extracted charge of 32.2 C. Cathode #681.1 is being used for 910 days with a total extracted charge of 20.7 C.

Cathode #105.2 is in use at FLASH for 1058 days with a total extracted charge of 23.3 C. This cathode has shown a remarkable high quantum efficiency. This cathode proceeds the #73.3 which was in use for 1413 days with an extracted charge of 24.4 C.

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