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Photocathodes for the electron sources at FLASH and European XFEL

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Abstract. FLASH at DESY (Hamburg, Germany) and the European XFEL photoinjectors are operated by laser driven RF-guns. For both user-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 current photocathode at FLASH #105.2, operated before and after a long shutdown. In addition, data for the cathodes that recently have been exchanged at the European XFEL will be presented.

1. Introduction

The FLASH accelerator is a free-electron laser (FEL) user facility since 2005 [1, 2, 3, 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 techno-logy 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.

2. 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 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 set-ups are interchangeable between each other. Gun 3.1 started operation from 2013 at FLASH [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].

The FLASH long-shutdown for major upgrades of the accelerator was performed from November 2021 to August 2022, the nine months shutdown was finished up with the cool down of the superconducting accelerated modules. The RF gun has been restarted during the cool down. After the accelerator commissioning the QE in the cathode was measured, followed by a QE-map comparison.

3. Quantum Efficiency and Lifetime

3.1. 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 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].

3.2. Lifetime at European XFEL

Cathode #685.1 has been in operation in the European XFEL since October 2022, the previous cathodes #681.1 and #680.1 characteristics i.e. QE and life time was presented at [14], cathode #680.1 still holds the operation record time of 1452 days with a total charge of 32.2 C extracted.

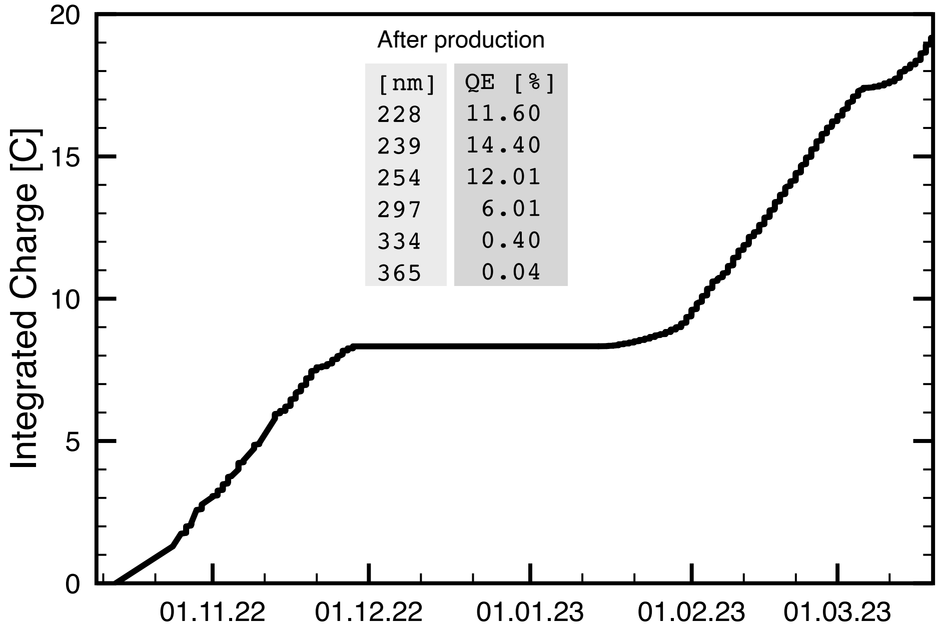

Figure 1. Integrated charge vs. time for cathode #685.1 operated at European XFEL, the table shows the QE of the cathode after production measured with a Hg-lamp.

The cathode #685.1 was produced in September 2015 at DESY Hamburg, with an initial QE of 12.01 % at 254 nm measured in the photocathode's lab as shown in Figure 1 a total integrated charge of 19.3 C is being extracted until today.

The previous cathode, #681.1 was prepared in September 2015 at DESY Hamburg and was in operation since January 2020 at the European XFEL. During its operation a total integrated charge of 49.8 C was extracted.

3.3. Lifetime at FLASH

The FLASH shutdown for major upgrades of the accelerator was performed from November 2021 to August 2022, the nine months shutdown was finished up with the cool down of the superconducting accelerated modules. The RF gun has been restarted during the cool down. After the accelerator commissioning the QE in the cathode was measured, followed by a QE-map comparison.

Cathode #105.2 is in operation at FLASH since December 2018 until August 2021, when the shutdown started, and continued to be used after the shutdown. In sum, with around 1500 days inserted in the RF-gun and 1250 days in operation. Previously, the cathode #73.3 was in operation until December 2018 with a record of 1413 days in operation [15].

Figure 2 shows the QE of cathode #105.2 as well as the integrated extracted charge over the cathode's whole operation time. QE measurements are continuously performed on periodical bases. The RF-Gun is operated at its nominal RF power of 4.8 MW and at an RF phase of 38°off zero-crossing. Zero-crossing refers to the phase between the laser and the accelerating

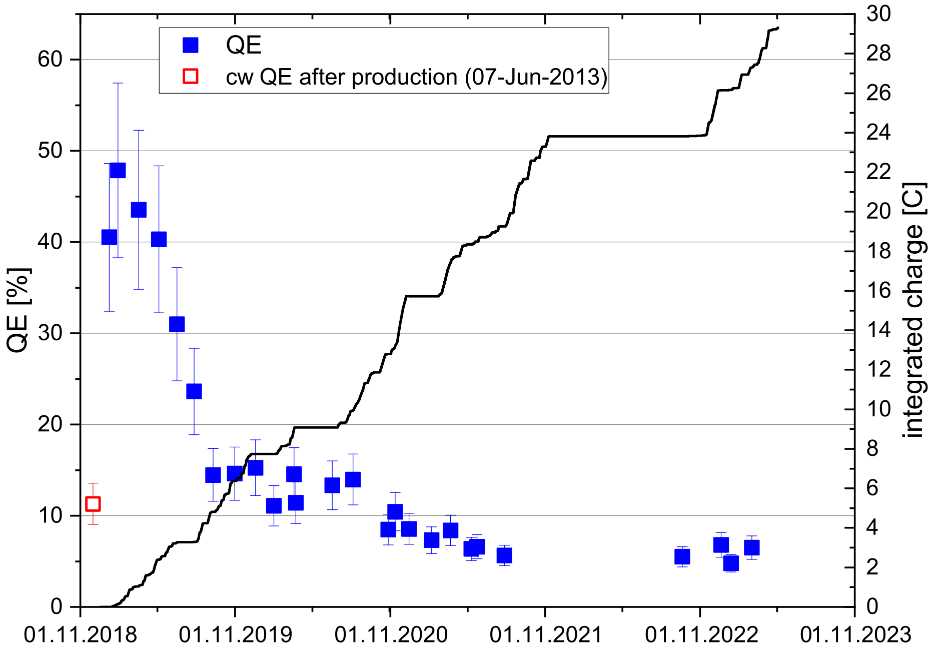

Figure 2. Cathode #105.2 is currently in operation at FLASH. The red square indicates the initial QE measured in the lab after production. The blue solid squares are the QE measurements performed in the electron RF-gun. A charge of 29 C has been emitted (black line).

field from which electrons can be emitted and transported out of the RF-gun. This cathode is of particular interest in the photocathode community, its stable high QE measured in the RF-gun over 4 years is astonishing. We had a similar performance with the previous cathode #73.3. Another interesting feature of cathode #105.2 is an initial QE going up to 40-50 % much higher than the QE measured after production. The cathode was stored for 4.5 years under ultra-high vacuum conditions and had obviously maintained good surface properties and little contamination. Once being operated in the RF-gun for nine months, the cathode's surface changes, reducing the QE quickly to a level of 15 % in September 2019. Afterwards a balance of degradation and rejuvenation by the UV laser during operation stabilises the QE at a 15 % level for a year until August 2020 and then reduced to a stable 6 % level. During the 9 month shutdown 2021/22, the cathode stayed in the RF-gun under the usual UHV conditions, but did not produce charge and was not hit by the laser. Nevertheless the QE stayed stable over that time in the range of 6.5 to 7 %. This is certainly due to the stable vacuum conditions during the shutdown work close the RF-gun. After restarting the RF-gun, a few RF breakdown events occurred, which had not been seen before the shutdown.

In addition, QE-maps measurements are performed at FLASH to study the homogeneity of electron emission from the photocathodes. For the measurement a small spot laser beam of $\sigma = 25\,\mu\text{m}$ 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 3 shows the evolution of QE-maps for cathode #105.2. A 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

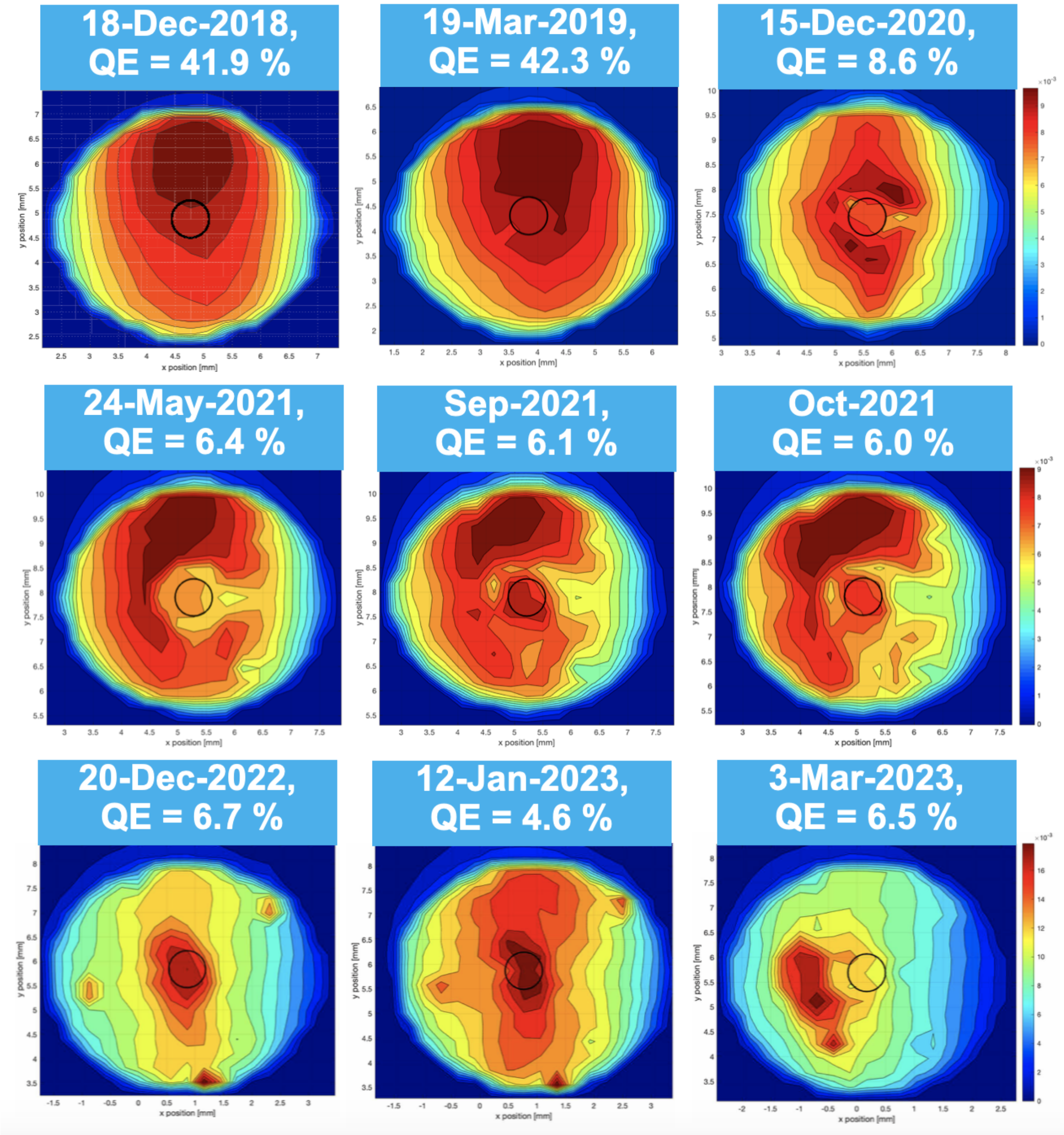

Figure 3. Quantum efficiency map evolution of cathode #105.2 from December 2018 to March 2023. The black ring in the middle indicates the typical size of the laser beam of 1.2 mm during operation.

the middle [16, 17, 11].

Figure 4 shows the QE map of the cathode before and after the shutdown. The circle indicates the size of the laser beam centred on the cathode. The differences could be described in the following way: on the top of the cathode a drop of QE is noticed, in the middle right, the QE is a bit higher than before. But in general, no major areas of QE drop can be seen and from the QE measurements performed before and after cathode's QE remain reasonably the same

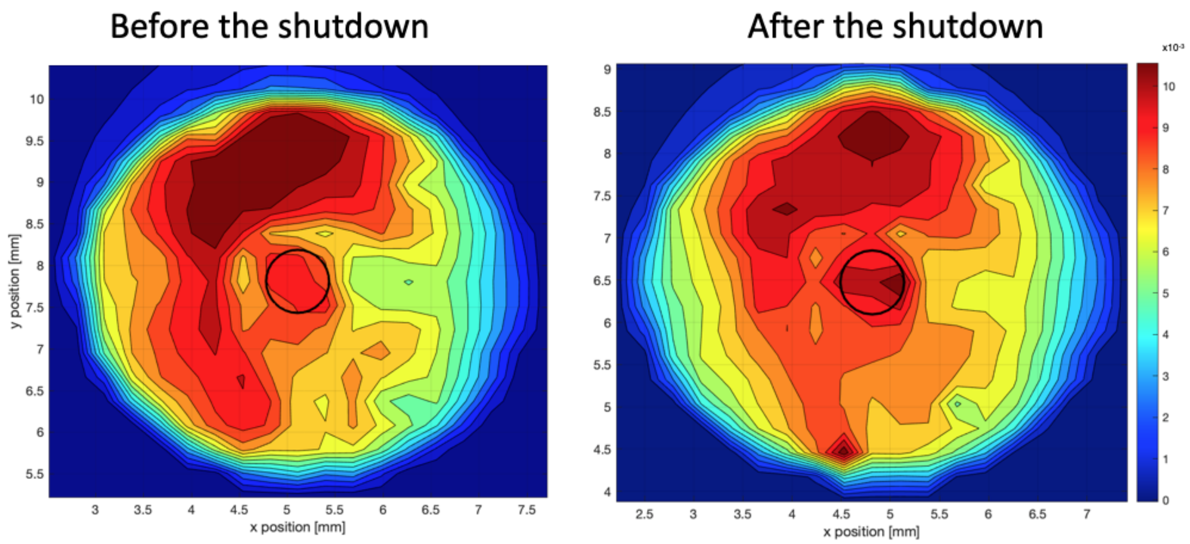

Figure 4. QE map comparison of cathode #105.2 before (left) and after (right) the long FLASH shutdown from November 2021 to August 2022. The QE stayed remarkably stable: QE = 7.0 % before and QE = 6.5 % after the shutdown.

between 6.5 and 7%. Nevertheless the QE stayed around the same and a total current of 27 C has been emitted from this cathode.

4. CONCLUSION

The cathodes operated at FLASH and the European XFEL are Cs_2Te that show remarkable lifetime. Cathode #681.1 was exchanged at the European XFEL after 910 days with a total extracted charge of 32.2 C.

Cathode #105.2 is being in operation at FLASH with around 1500 days inserted in the RF-gun and 1250 days in operation with a total extracted charge of 23.3 C. This cathode has a remarkably high quantum efficiency. During the long shutdown at FLASH, the cathode remains under operational conditions in order to keep it running until today. Is worth mentioning that no cathode's lifetime issue has occurred with Cs_2Te cathodes over the last years. One of the crucial points is the cleanliness of the vacuum system, where contaminants are kept small enough to do not harm the cathodes[1]. UV rejuvenation is being considered as well. A change of cathode was always triggered by less homogeneous emission and QE deterioration.

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