CERN – European Organization for Nuclear Research
European Laboratory for Particle Physics

CTF3 Note 020 (Tech.)
(Photocathodes)

PRODUCTION OF A HIGH AVERAGE CURRENT ELECTRON BEAM WITH Cs-Te PHOTOCATHODES

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Abstract

The ability of photocathodes to sustain high-average laser power and high-average current was tested. The cathodes are shown to survive in a DC gun and produce the required charge density and laser power density for CLIC at the specified Quantum Efficiency of 1.5 %.

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Contents

1 Scope of the experiments

In this document, we summarize a test, which was performed in the DC gun of the photoemission laboratory, to show the usefulness of Cs-Te photocathodes for high average current operation. Cs-Te cathodes have shown their usefulness to produce high charge short pulses not only at CTF II, but also in a number of other accelerators. The highest single bunch charge produced in CTF II were 100 nC in a 10 ps pulse. Lifetimes in CTF II are of the order of weeks or months depending on the working point.

As shown in Table 1, the average current is the matter of concern. Cs-Te cathodes are also used in photomultipliers were average currents should not exceed typically 100 nA[1], whereas photodiodes with Bialkali photocathodes can deliver an average current of 300 μA[2]. At CTF II typical average currents are of the order of 7.5 μA.

The test aimed to bridge the gap between the demonstrated behaviour at low current to the needed performance at CLIC. Obviously, the CLIC parameters are reachable only with the CLIC laser, which is currently being developed at RAL. Therefore we chose a laser capable of delivering 300 mW average power on the cathode [3], compatible with our standard power supply which can deliver 1 mA and with radiation levels in an open laboratory.

2 The laser

The laser, rented from Excel Technology[3]is a lamp pumped Nd:YLF laser. The fundamental radiation is intra-cavity frequency-doubled and quadrupled to a wavelength of $\lambda = 262$ nm, which is used to illuminate the cathode. The laser can be operated in the UV at repetition rates of up to 10 kHz, above which pulse-to-pulse jitter becomes too big. In addition, the pulse energy becomes too small to quadruple efficiently. The discharge in the lamp is continuous, therefore the pulselength is a function of the deposited energy in the active material and, therefore, a function of repetition rate, as shown in Fig. 1. The lifetime of the lamps is specified to be ≈500 hours, for the complete test 4 lamps were used.

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[1] C31034 Series photomultipliers[1]

[2] PD108[2]

[3] Darmstadt, Germany, Manufacturer Quantronix, USA

	Unit	Achieved in CTF 2	High Q Test	CTF-3	CLIC 0.5 TeV	CLIC 3 TeV
μ pulse charge	nC	100	950	2.4	11.7	17.5
Pulse width (FWHH)	ps	10	100 ns	10	12	12
Peak current	A	10000	7.5	240	975	1450
Number of μ pulses	-	48	1	2145	10720	42880
Distance between pulses	ns	0.333	-	0.666	2.13	2.13
Macro pulse (Mp) charge	mC	0.75	-	5.2	125	750
Mp duration	ms	0.016	-	1.4	23	92
Charge stability	% rms	5	2	< 0.5	0.1	0.1
Repetition rate	Hz	10	1000	5	200	100
Mean current	mA	0.0075	0.95	0.026	25	75
Photo cathode	-	Cs2Te	Cs2Te	Cs2Te	Cs2Te	Cs2Te
Working wavelength λ	nm	262	262	< 270	< 270	< 270
QE_{min} @ λ	%	1.5	1.5	1.5	1.5	1.5
Minimum lifetime τ @ QE_{min}	h	200	460	100	24	24
Total shot number during τ	x 109	0.15	4	3.9	185	371
Produced charge	C	1.5	1.22 k	10	2.2 k	6.5 k
Laser energy at the cath. / Mp	mJ	0.3	0.2	1.6	39	233
Laser power at the cathode	W	0.003	0.2	0.008	7.8	23.3

Table 1: Main Parameters

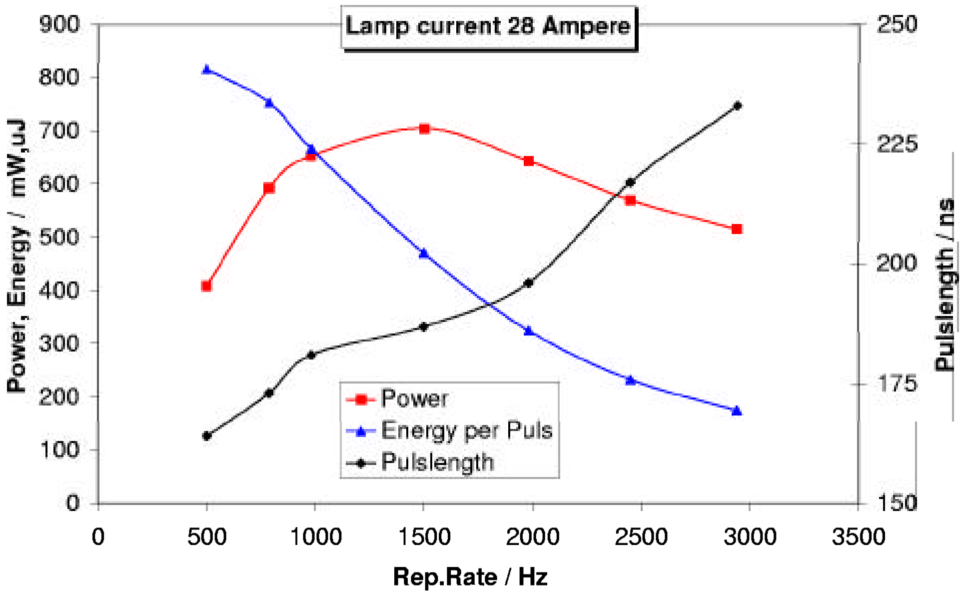


Figure 1: Dependence of main parameters of Quantronix 262-DPI on the repetition rate. Although this plot shows otherwise, for the following experiments, the pulsewidth at 1 kHz was around 100 ns, due to allignement and other lamps.

3 Cathode 117

This cathode was originally used in CTF II. It was used in the DC gun in the photocathode lab for alignment purposes and first tests only. However, we saw during these tests an increase in quantum-efficiency (QE), which led us to leave this cathode in the DC-gun. Fig. 2 shows the complete "life". This increase in QE might be due to cleaning of the surface by the impinging UV photons. Fig. 3 shows a "zoom" of Fig. 2. To be noted is the vacuum behaviour: In non-regular intervals, the vacuum pressure increases. This could be interpreted as small breakdowns, caused by sudden photo-electron emission from the cathode at sites where QE was suddenly higher, probably caused by laser cleaning. This behaviour did not change after a long exposure to the laser, as shown in the lower part of Fig. 3.

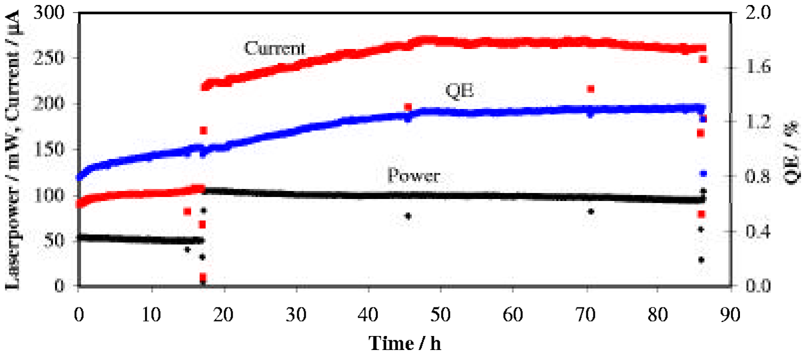


Figure 2: Behaviour of cathode 117, which was already used in the RF gun in CTF II. Total extracted charge: 70 C.

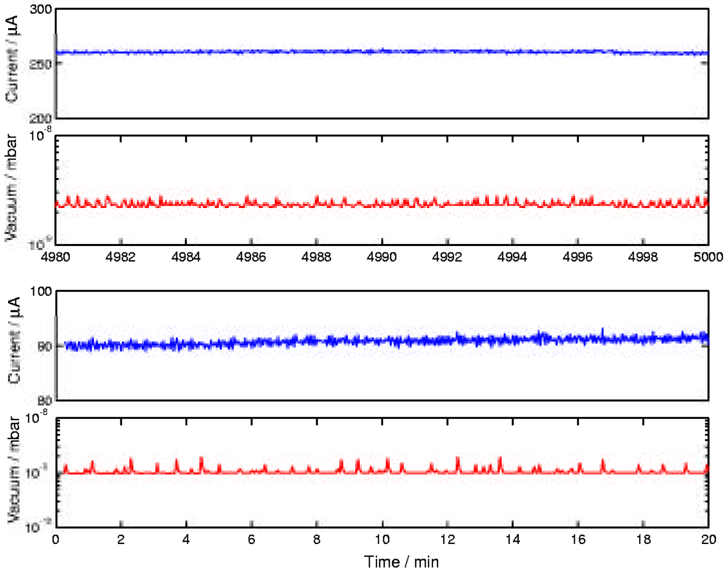


Figure 3: Zoom into Fig. 2, remarkable: vacuum acivity without change of other parameters.

4 Cathode 123

Before evaporation of Tellurium and Cesium, a 50 nm gold layer was evaporated onto the copper plug. A standard evaporation of 10.2 nm Te and 17.7 nm Cs followed, as shown in Fig. 24. The quantum efficiency measured immediately after evaporation was 9 %. Fig. 4 shows the QE distribution map of cathode 123 after evaporation.

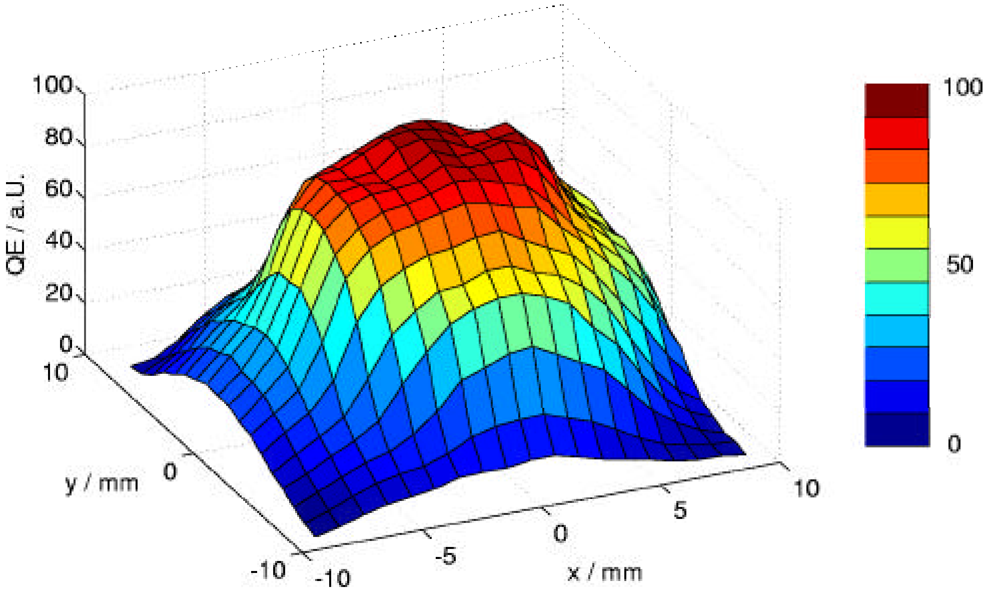


Figure 4: QE distribution map of cathode 123 after evaporation. QE_{max}: 9 %.

The cathode was then put into the DC gun and illuminated by the laser. The measurements are shown in Fig. 5. The dependence of the vacuum level on the extracted charge (or on the laser power) is clearly visible. The decrease of the initial QE to 2 % and the lack of laser power regulation as a function of emitted current led to a rather low mean current of $\overline{I} = 449\,\mu A$ in the first 15 h during night. The manual regulation of laser power allowed then an extraction of $\overline{I} = 790\,\mu A$. The cathode was exchanged at the minimum QE=1.3 %. The distribution (Fig. 6) shows that the laser burned a hole in the QE distribution. The "hole" can also be seen by visual inspection (Fig. 7). Although exposure to air leads to an oxide layer, which exceeds the original cathode layer in thickness by far, the deposition of this layer depends on the material underneath it. Fig. 7 indicates that the morphology of the cathode layer changed as a function of laser energy.

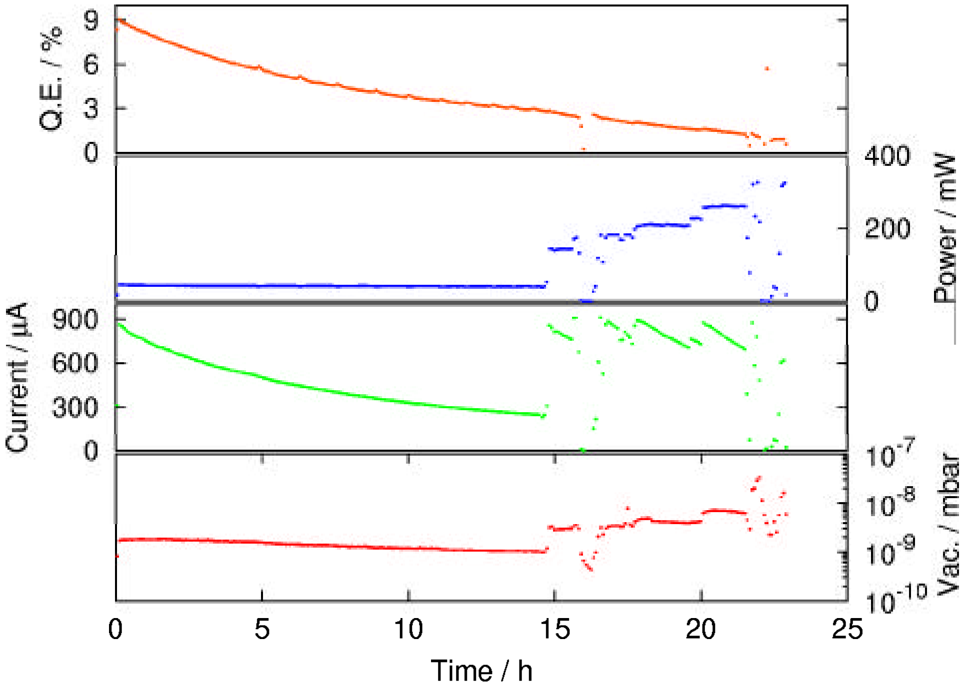


Figure 5: "Life" of cathode 123, the total extracted charge was 43 C

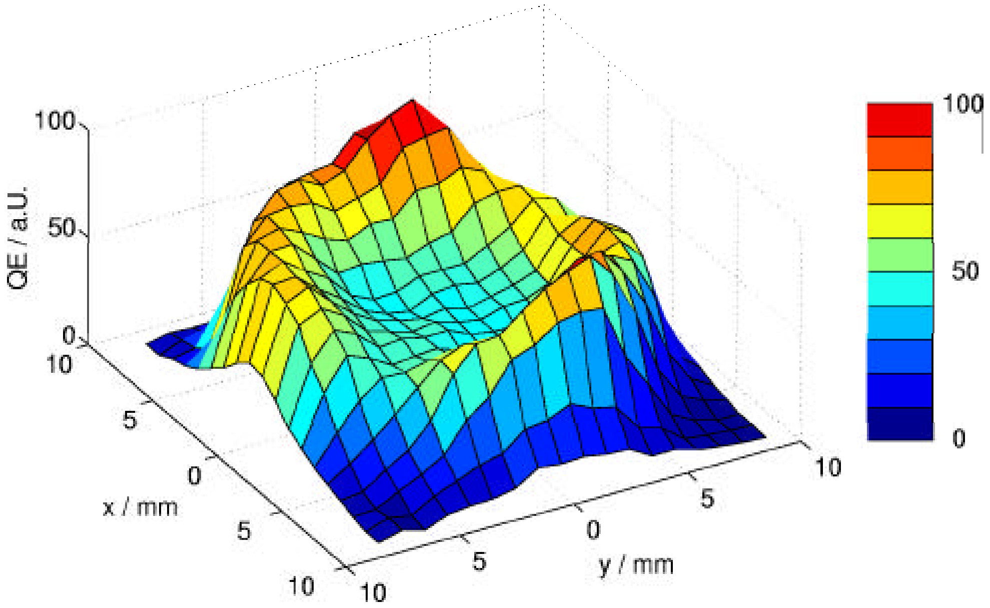


Figure 6: QE distribution map of cathode 123 after use, it seems the laser has "burned" a hole. QE at x=0 mm,y=0 mm was 1 %.

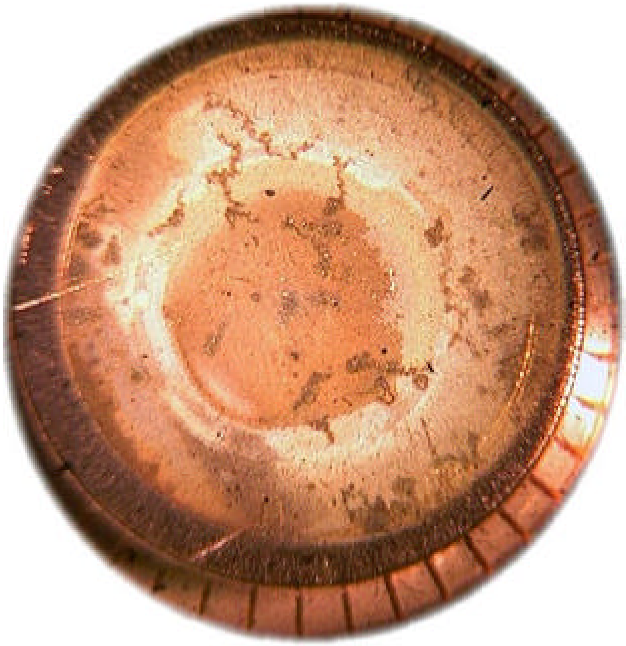


Figure 7: Photo of cathode 123 after use. Note the resemblance to Fig. 6.

5 Cathode 124

This cathode was evaporated onto a plug formerly used in CTF II, then cleaned by ion bombardment (ICE). The evaporation protocol is shown in Fig. 25. Initial QE was 4.8 %, unfortunately, no plot of the QE distribution-plot could be done. However, x/y-scans of the cathode were done, see Fig. 20.

The cathode was used for 90 h before the Christmas break. During this time, the QE dropped only to 4 %. After the pause, due to laser failure, the cathode stayed 2 weeks without illumination in the gun. As shown in Fig. 8 the QE dropped from 4 % to 3 %, the reason for this is not clear, since the dark life time of cathodes in the DC gun was verified to be in the order of months. Cathode 124 underwent several tests: First, a moderate current test with $\overline{I} = 170\,\mu\text{A}$, marked **1** in Fig. 8, after which a test on a number of shots comparable to CTF 3 ($4 * 10^9$ shots) with low average current ($\overline{I} = 60\,\mu\text{A}$) was conducted, with a repetition rate of the laser of $f = 10\,\text{kHz}$ ("CTF3" in Fig. 8). The cathode was then submitted to relatively high laser power to extract an high average current, marked **2** in Fig. 8, with $\overline{I} = 782\,\mu\text{A}$. In total, cathode 124 delivered 160 C at QE>1.5 %. In contrast to cathode 123, see Fig. 6, cathode 124 did not show a hole in the QE distribution but

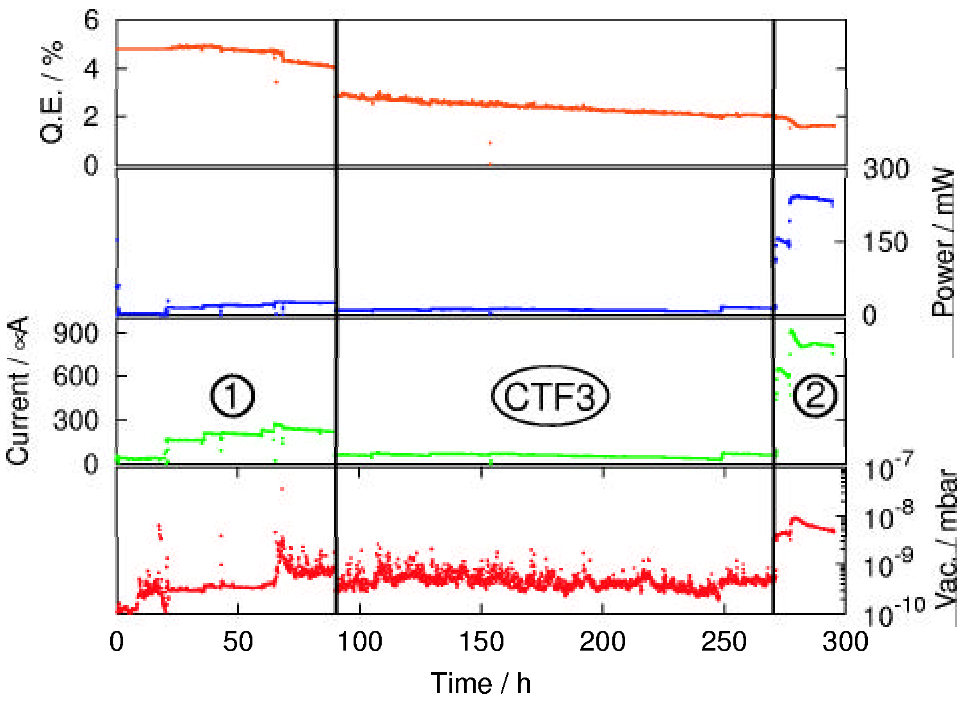


Figure 8: Cathode 124, complete, delivered charge 160 C.

a peak (Fig. 9), where QE was higher than measured with a big laser spot, which averages over regions with less or more QE. This behaviour gives an additional hint that the cathodes are cleaned when hit by the laser and poisoned by vacuum elsewhere.

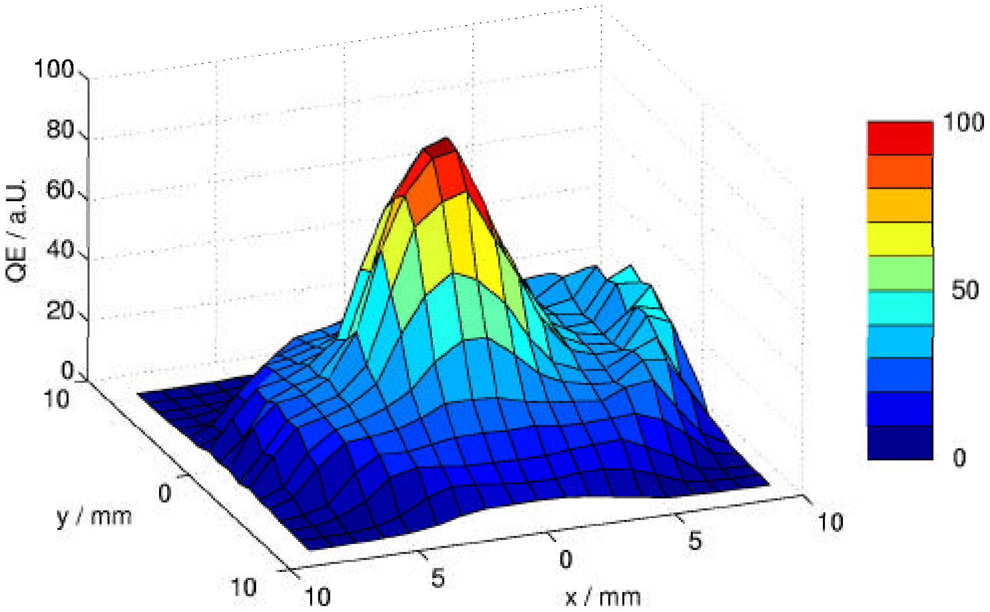


Figure 9: QE distribution map of cathode 124 after use, remarkably: no hole, but a peak where the laser hit, with QE_{max}=2.9 %.

6 Cathode 125

Cathode 125 was evaporated on 100 nm gold. A remarkably uneven repartition of the QE-Distribution is shown in Fig. 10. This might be due to a misalignment of the evaporators. Nevertheless, this cathode resisted very well to high current, as shown in Fig. 11. The cathode was removed from the gun after 104 hours. It delivered a total charge of 253 C. The origin of the steplike behaviour marked "1" in Fig. 11 is unclear. The zone marked "2" is due to a failure of the laser powermeter, which gave no reading during this time. Fig. 12 shows the distribution of QE at the end of the test.

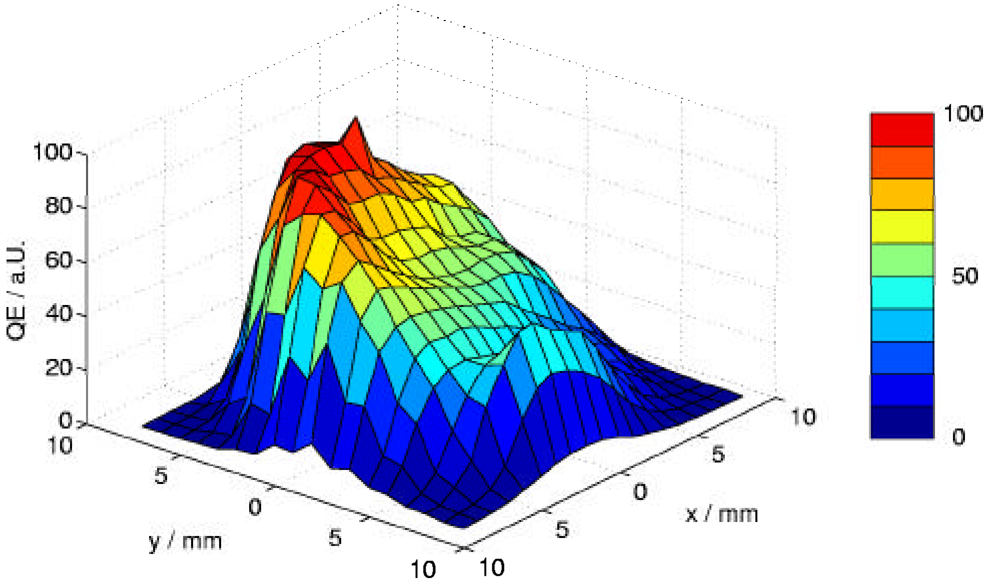


Figure 10: QE Distribution of Cathode 125 after evaporation .

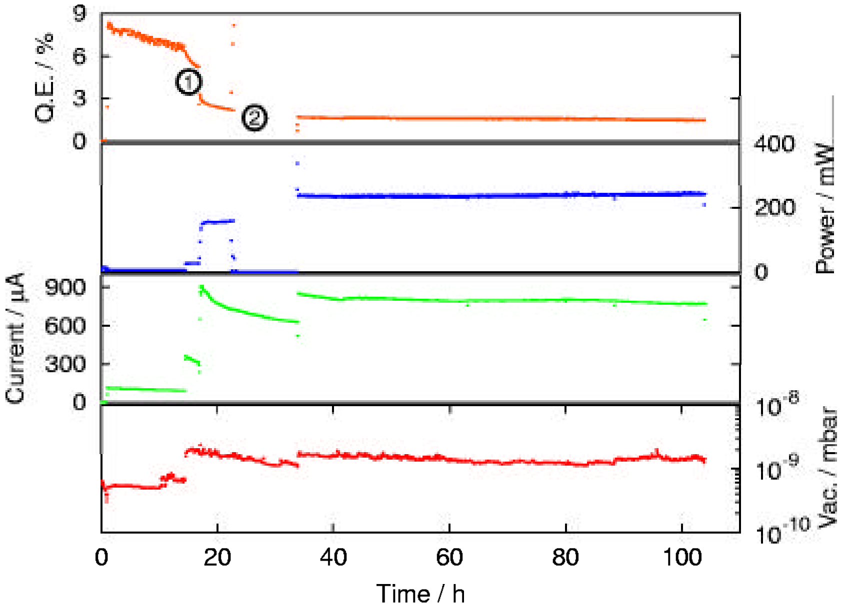


Figure 11: Cathode 125, complete, delivered charge 253 C.

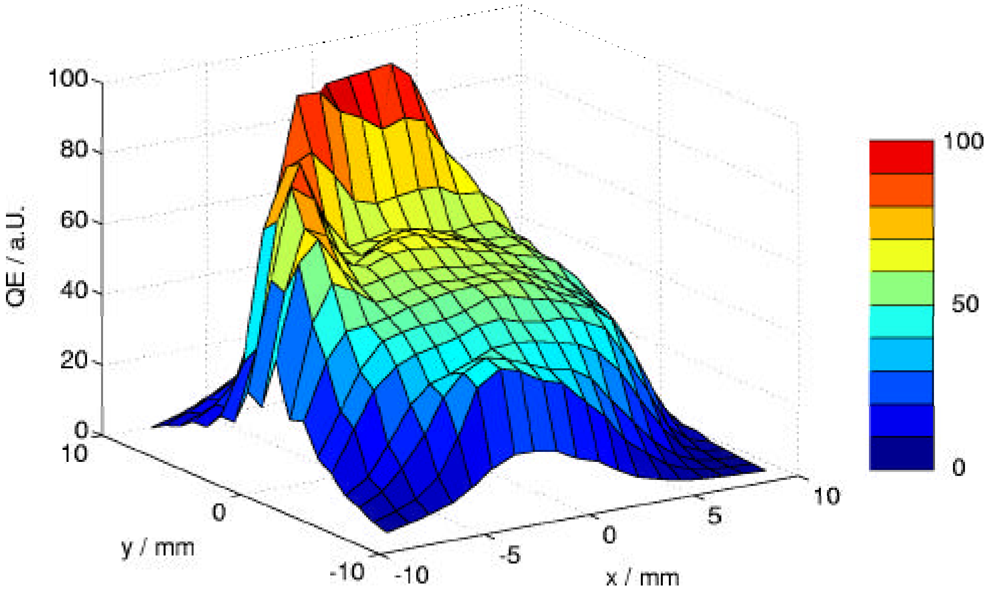


Figure 12: QE Distribution of Cathode 125 after use. Maximum QE was 2.7 %, at the center of the cathode 1.5 %.

7 Cathode 126

The plug for Cathode 126 was cleaned by ICE from a former cathode. Then 10 nm of tellurium and 8 nm of cesium were evaporated. Fig. 27 shows the protocol of the evaporation process. After a realignment of the evaporators, the QE-map was a flat-top distribution, as shown in Fig. 13. The QE directly after evaporation was 5 %. The laser spot at beginning of a long test at high current is shown in Fig. 14.

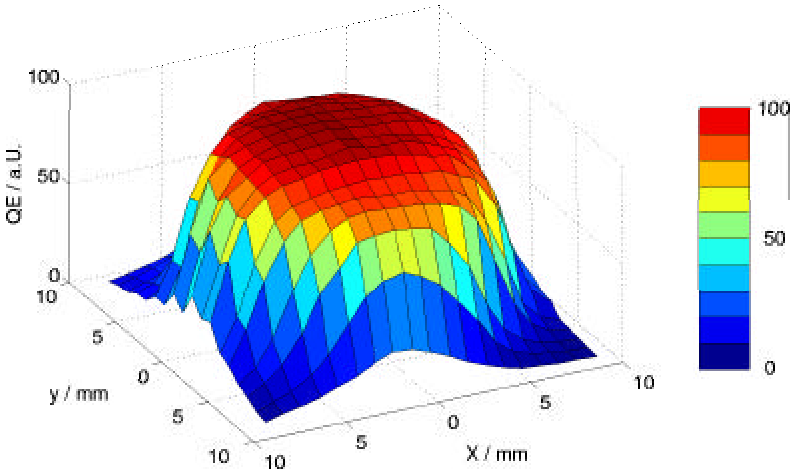


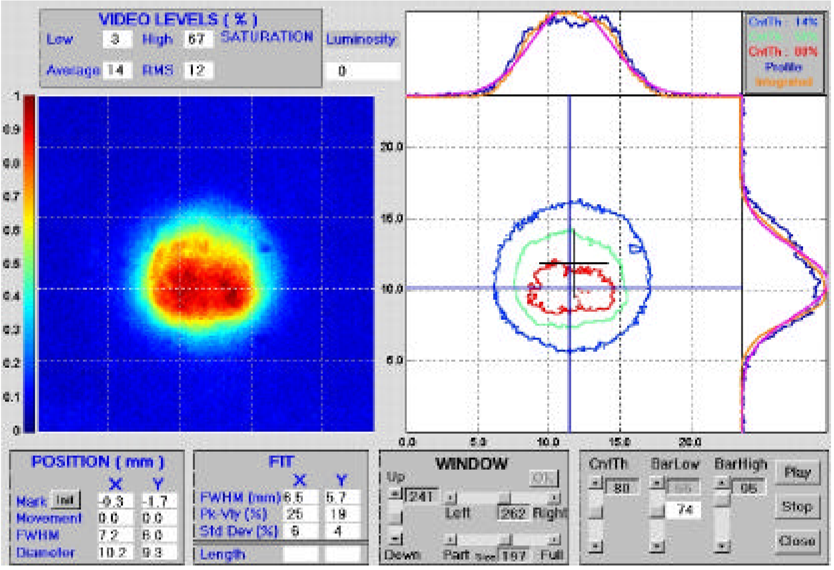
Figure 13: QE-map of cathode 126 after evaporation, max. QE=5 %

Either because the cathode was put directly after evaporation in the gun and it finished a slow process of combining the evaporated products, or because of the laser hitting on it, the QE increased during the first 6 hours from 4.5 % to 5.1 %. The QE then decreased to 1.5 % in 90 hours. The QE distribution over the cathode surface decreased in a manner similar to cathode 124 (Fig. 9). Instead of having a "hole" in the middle, as cathode 123 (see Fig. 6), where the laser is most intense, this cathode has a higher QE, at that point, see Fig. 16. We attribute this to the cleaning effect of the laser, which removes poisonous atoms from the cathode surface.

The QE stayed approximately constant for an additional 200 hours. During this test, this cathode produced a total charge of 1006 C, with an average current of 751 μA.

After that, the cathode exhibited a distribution of QE shown in Fig. 17, with a QE integrated over the laser spot of 1.5 %.

Again, no "hole-drilling" comparable to the other cathodes was seen. So it was decided to do an additional test with this cathode, namely to extract a high charge from a small spot.



VIDEO LEVELS (%)

Low 3 High 67 SATURATION

Average 14 RMS 12

Luminosity 0

POSITION (mm)

	X	Y
Mark	-0.3	-1.7
Movement	0.0	0.0
FWHM	7.2	6.0
Diameter	10.2	9.3

FIT

	X	Y
FWHM (mm)	6.5	5.7
Pk-Vly (%)	25	19
Std Dev (%)	6	4
Length		

WINDOW

Up 241

Left 262 Right

Down

Part Size 197 Full

CntTh 80

BarLow 74

BarHigh 95

Figure 14: Laserbeam for high current test of cathode 126.

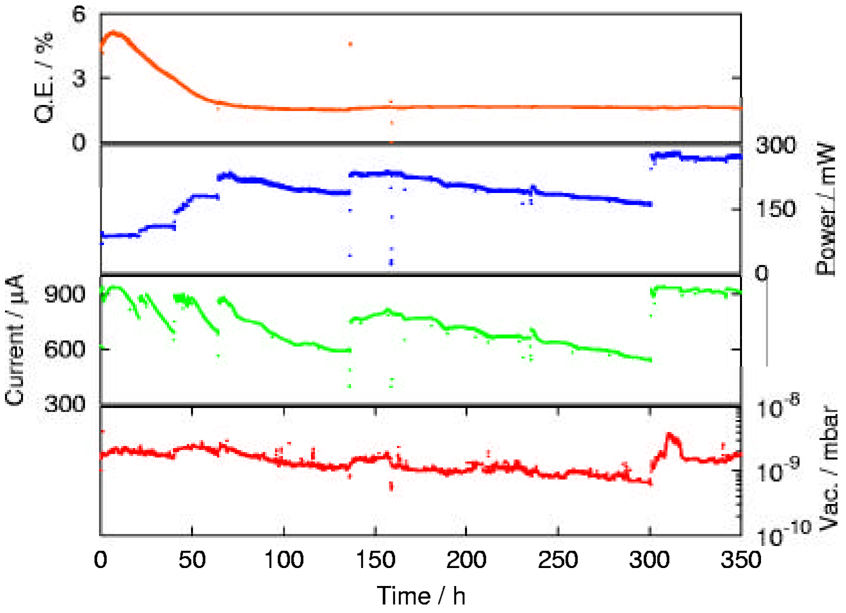


Figure 15: Life of Cathode 126 under high current, complete delivered charge 1006 C.

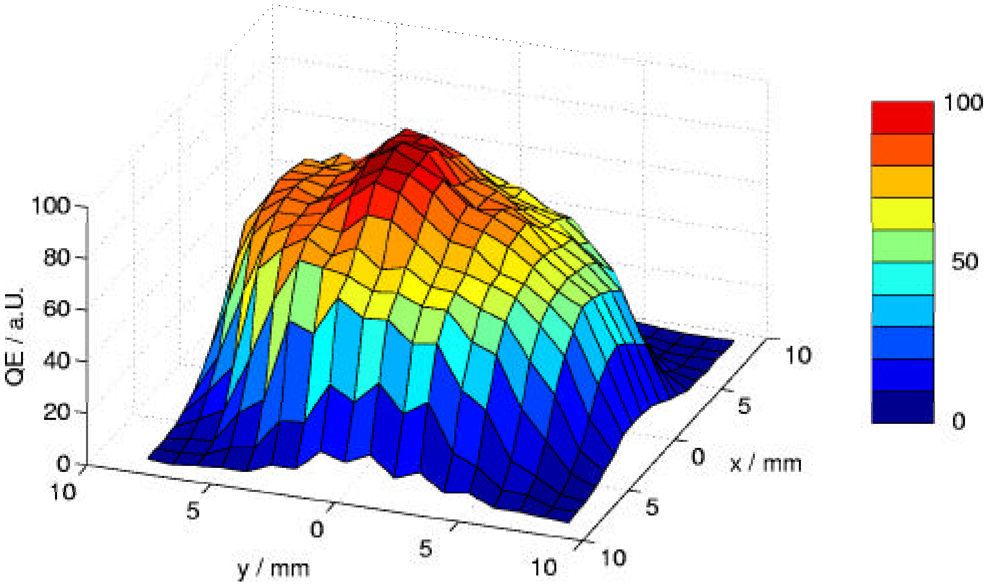


Figure 16: QE-map of cathode 126 at QE=1.5 %

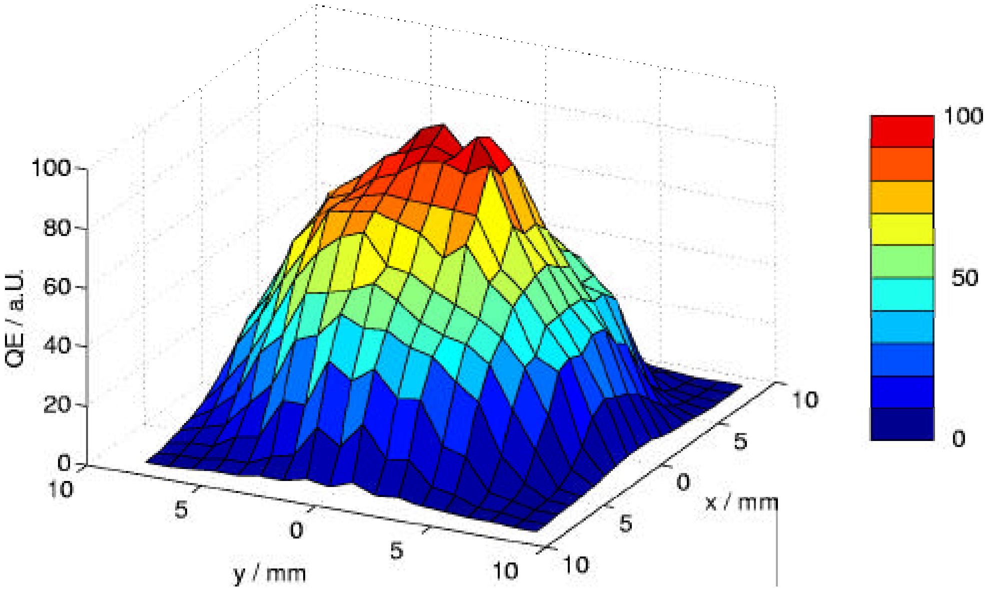
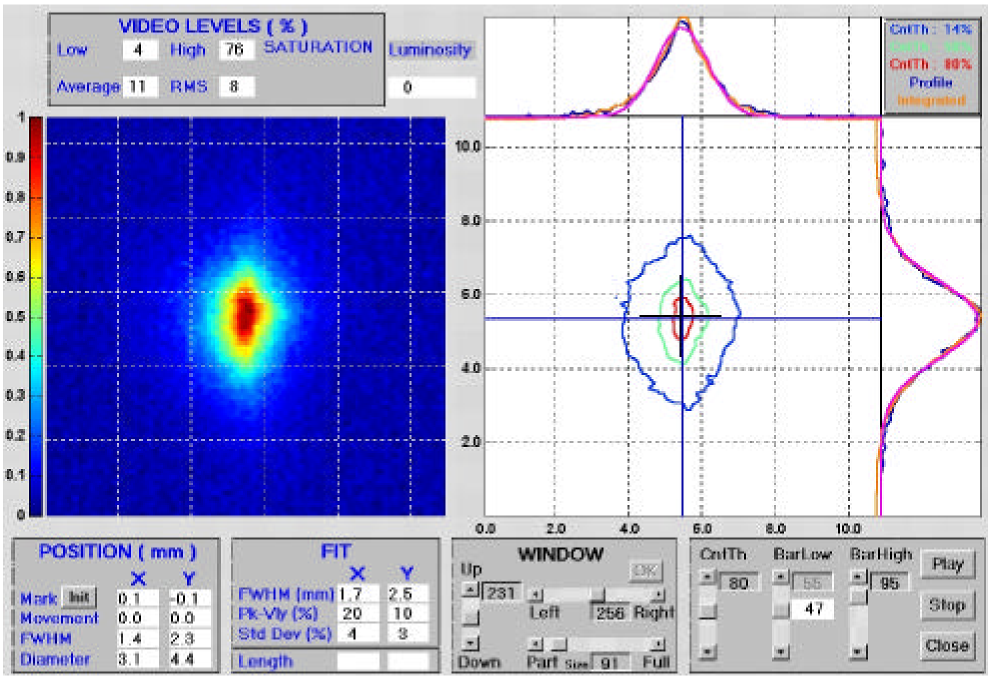


Figure 17: QE-map of cathode 126 after use

7.1 High Density test

For this test, the laser was focused to a elliptical spot of 1.7x2.5 mm FWHM, shown in Fig. 18. This is equivalent to an emission surface of $A = 3.34\,\text{mm}^2$.



VIDEO LEVELS (%)

Low 4 High 76 SATURATION

Average 11 RMS 8

Luminosity 0

POSITION (mm)

	X	Y
Mark	0.1	-0.1
Movement	0.0	0.0
FWHM	1.4	2.3
Diameter	3.1	4.4

FIT

	X	Y
FWHM (mm)	1.7	2.5
Pk-Vly (%)	20	10
Std Dev (%)	4	3
Length		

WINDOW

Up 231

Left 256 Right

Down

Part Size 91 Full

CntTh 80

BarLow 55 47

BarHigh 95

CntTh : 14%

CntTh : 80%

Profile

Integrated

Figure 18: Laserbeam for high density test

This laser spot was directed to the place of maximum QE on the cathode surface. The QE there was 2.35 % at the beginning of the test. The average current during this test was $\overline{I} = 701\,\mu\text{A}$, thus this current delivered a current density J of

$$J = \frac{\overline{I}}{A} = 21\,\frac{\text{mA}}{\text{cm}^2}$$

During this test, the cathode delivered 220 C from this spot, thus a total charge density of $6.6\,\frac{\text{kC}}{\text{cm}^2}$.

If conditions during this test are valid for CLIC, too, this test implies that a cathode surface of $4\,\text{cm}^2$, thus an active diameter of 23 mm is sufficient to produce 100 mA of current, as required by CLIC parameters.

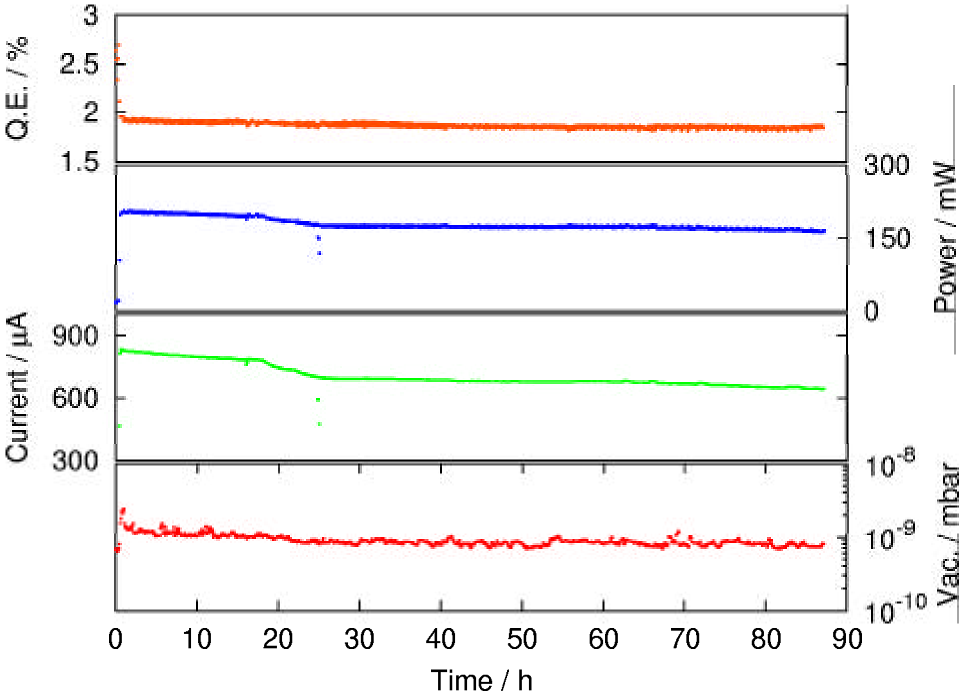


Figure 19: Cathode 126, with small ($3.34\,\mathrm{mm}^2$) laserspot.

8 Comparison of the used cathodes

Comparing the 5 used cathodes is a difficult task, since the limited time for which the laser was rented did not allow to gather statistics. However the reasons for a decrease in QE should be somewhat common:

- Pollution by the rest gas
- Back bombardment of ions onto the cathode surface
- The laser light hitting the cathode
- The charge leaving the cathode

These points are addressed in the following, where it has to be kept in mind that they can not be treated separately: The laser light might do damage to the cathode, but it might also clean it in-situ, thus canceling the effect of poisoning. The same applies for the charge which, if heating the cathode, might also serve to vaporize adsorbed gas. For better comparison, the QE is normalized to the maximum QE for each cathode. Cathode 117 is not compared, since it was a used in CTF II already. Just as a short reminder: Cathode 124 and 126 are on copper, treated with ICE. Cathode 125 is on 100 nm gold, cathode 123 on 50 nm gold. Fig. 20 shows a comparison of the

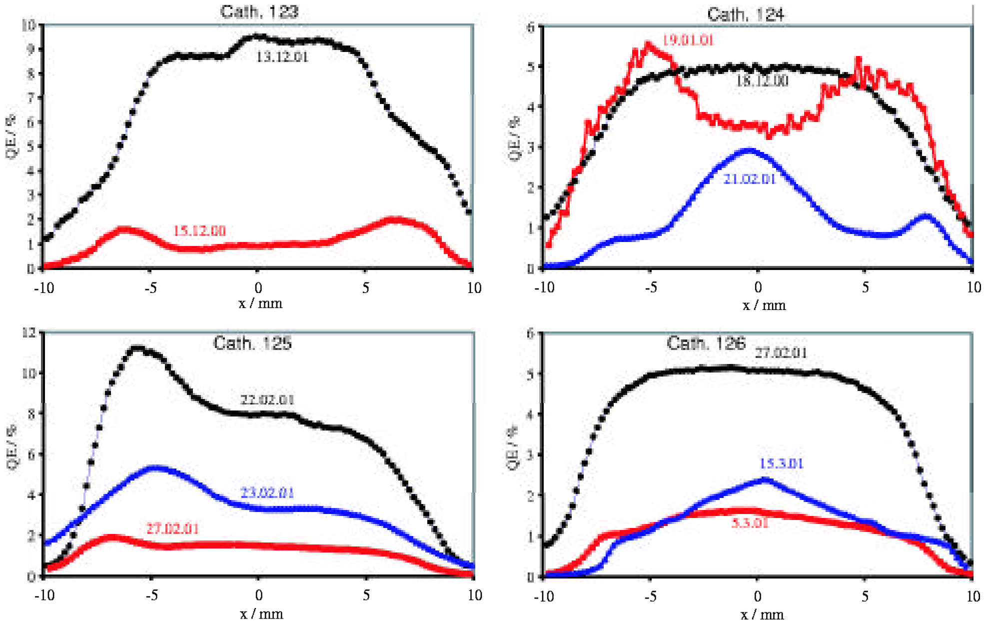


Figure 20: Scans of the cathodes used

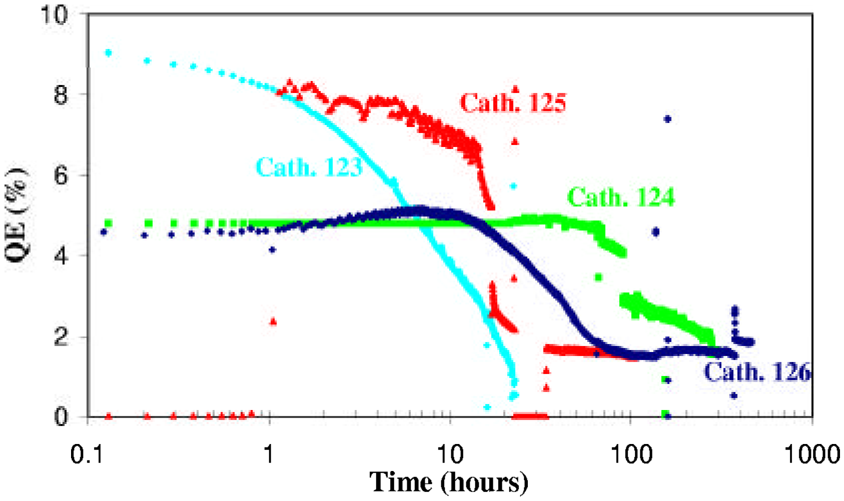


Figure 21: Comparison of the cathodes as a function of time.

different cathodes in terms of their QE-distribution. It is remarkable that the cathode 123 and 124 (at least for the first time of use) exhibit in that respect a similar behaviour, although in lifetime they are not comparable. It is, especially for cathodes 124 later and cathode126 evident that the laser helps keeping poisonous gases away from the surface. Fig. 21 and Fig. 22 show a comparison between the different cathodes in terms of QE, as a function of time and of the accumulated charge respectively.

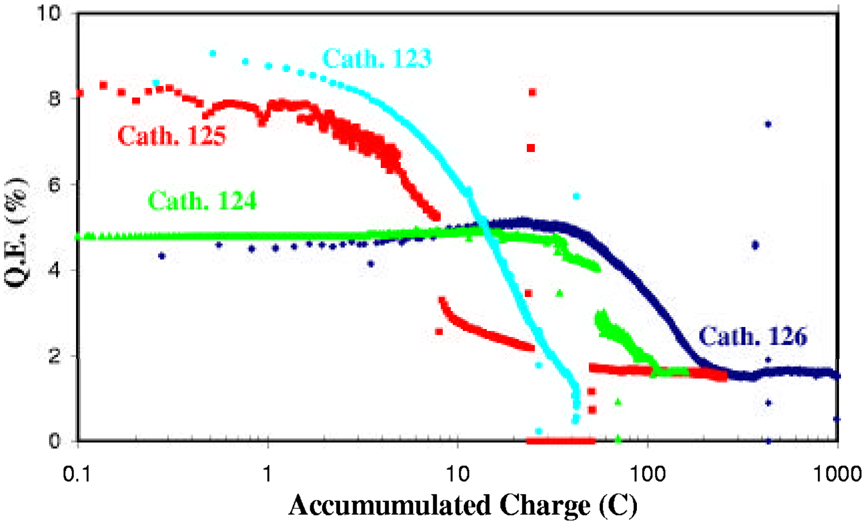


Figure 22: Comparison of the cathodes as a function of accumulated charge.

Although there are individual differences, a certain trend seems to be that cathodes prepared onto gold have higher QE at the beginning, but that their QE decreases more rapidly, in the case of cathode 123 under 1 % in the case of cathode 125 to around 1.5 % so for the latter one can not be certain that the lifetime would not be comparable with cathode 126, if we had left it longer in the gun.

As mentioned, another source of damage to the cathodes might be the ions produced in the rest-gas by the electron beam. These ions, if they reach the accelerating gap between cathode and anode, get accelerated and hit back on the the cathode surface, with an energy of up to 80 keV. Therefore a quantity was searched to reflect both, the vacuum conditions and the current delivered by the cathode. The quantity "Langmuir" L is used in vacuum technology and signifies one mono-layer of adsorbed gas in one second. It is defined as $L = p\,[10^{-6}\text{mbar}] \cdot t[\text{s}]$. In addition, the number of ions produced

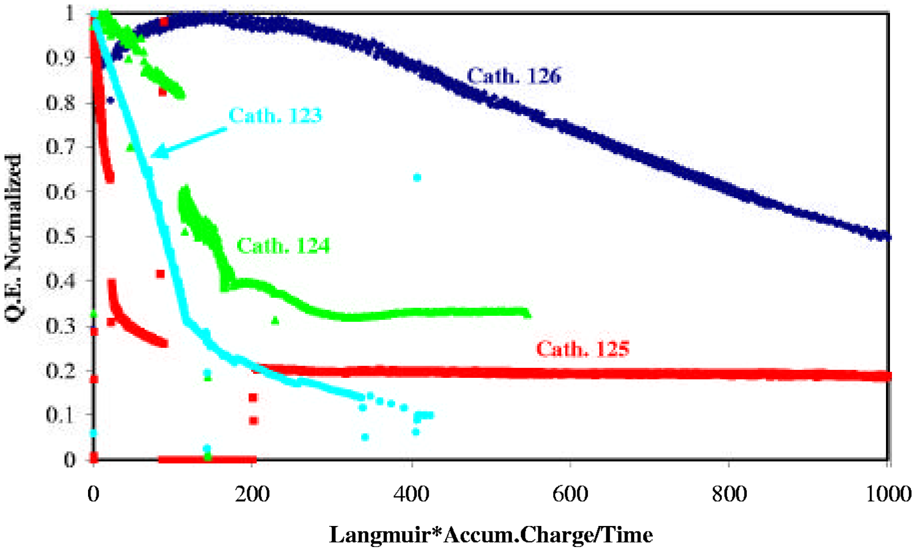


Figure 23: Comparison of the cathodes as a function of deposited Langmuir times accumulated charge per time, a quantity which is proportional to the number of ions produced via rest-gas ionisation. For better comparison, cathode 126 is only partly shown.

is proportional not only to vacuum, but also to the number of electrons produced, thus to the charge. The damage is proportional to the accumulated dose of ions $\overline{D}$, therefore to the product of accumulated monolayers and accumulated charge divided by time. As shown in Fig. 23, no clear grouping of different cathode types can be done.

9 Conclusions

The test has shown that the Cs-Te cathodes are able to deliver a high average current electron beam. We could show that, depending on the way the cathode was produced, a high average current beam was produced for more than 400 hours. The minimum QE quoted so far for the design of the photoinjector(1.5 %) was demonstrated for this duration, too. The average current density the cathodes could sustain in this test show that an illuminated cathode diameters of 2.3 cm would be sufficient to produce the CLIC drive beam. Further developments might improve this long term limit, which seems not to be connected to the initial QE, therefore relaxing the demand on laser energy.

A Evaporations

A.1 Cathode123

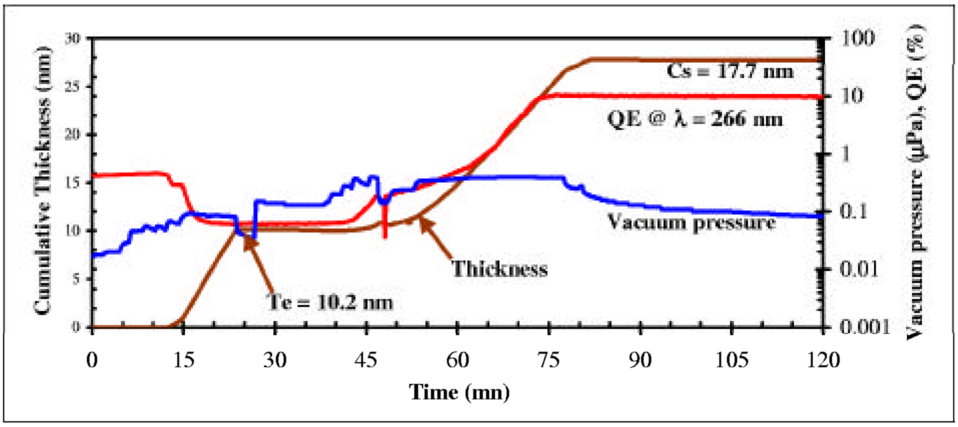


Figure 24: Evaporation protocol of cathode 123, onto a layer of 50 nm of gold

A.2 Cathode124

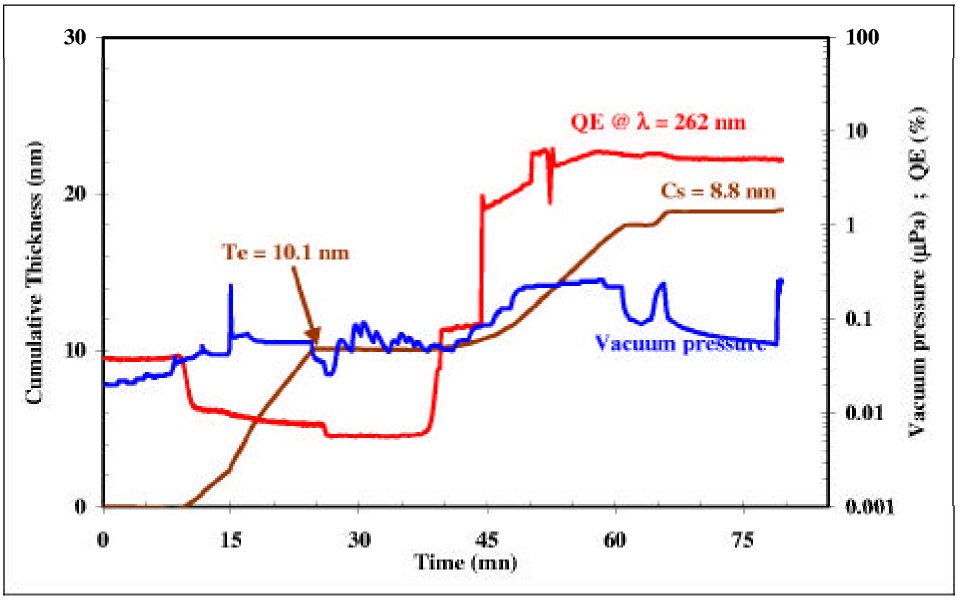


Figure 25: Evaporation protocol of cathode 124

A.3 Cathode125

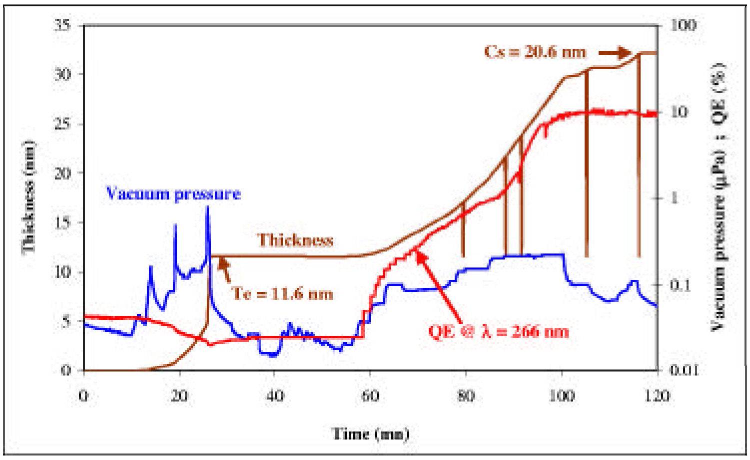


Figure 26: Evaporation protocol of cathode 125

A.4 Cathode126

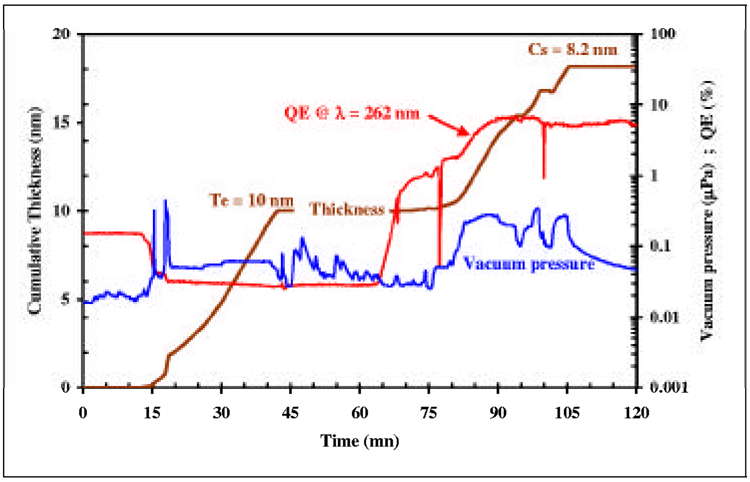


Figure 27: Protocol of evaporation process for cathode 126

References

[1] Burle Electron Tubes. Technical report.

[2] Photek Ltd. Technical report.

[3] H. Trautner G. Suberlucq. Photocathodes pour le Drive Beam du CTF3 et du CLIC, Préparation du test "mC" dans le canon DC. CERN CTF3 Tech-Note 2000-03/Injector, CERN, 2000.