

High average photocurrent research at MAMI

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Abstract. We have measured the extractable charge during one lifetime (Charge lifetime, Q_τ) of a NEA-GaAs-photocathode for two beam diameters. A limitation of Q_τ to 1100 Coulomb due to ion-back-bombardment was observed for a 1.5 mm diameter emission site. When increasing the laser diameter from .3 to 1.5 mm we observe an increase of Q_τ by a factor ≈ 5 , which is in disagreement with the assumed proportionality of the charge lifetime with emission area. Possible reasons for this discrepancy are analyzed.

1. Introduction

The purpose of this article is to present investigations which serve to demonstrate capabilities of photoemission sources for future projects, the demands of which are summarized in table 1.

Semiconductor cathodes with negative electron affinity (NEA-) surfaces are very efficient photoemitters, which even allow for spin-polarized photoemission. Unfortunately, the NEA state is a very delicate one, therefore the cathodes are unstable - they suffer from a reduction of quantum efficiency (q.e.) which is characterized by the time constant τ , the so-called 'lifetime'. For future large scale facilities as listed in table 1, lifetimes exceeding one month could be considered as acceptable.

Table 1. MAMI photoemission source performance compared to demands for future facilities. Charge and fluence lifetime (definitions see text) refer to a lifetime of one month.

Project	average current $I_b [A]$	av. current density $j_b [A/cm^2]$	Charge lifetime $Q_\tau [C]$	Fluence lifetime $F_\tau [C/cm^2]$
MAMI (achieved 2004 [1], pol)	$2 \cdot 10^{-4}$	0.2	200	$2 \cdot 10^5$
ERL based EIC (pol)	0.1	0.1	$3 \cdot 10^5$	$3 \cdot 10^5$
Electron cooler (unpol)	1	1	$3 \cdot 10^6$	$3 \cdot 10^6$
ERL light source (unpol)	0.1	10	$3 \cdot 10^5$	$3 \cdot 10^7$

One of the most prominent effects which tends to reduce τ is the so-called ion back-bombardment (IBB). IBB results from ionization of residual gas by the beam itself. In an electrostatic gun these ions travel backwards to the cathode, where they hit it with a kinetic energy that corresponds to the potential of the ionization site. In a homogeneous acceleration

field only the emission site is affected by this impact. The rate of damage will be proportional to the ion current density on the surface which is itself \propto to the electron current density: $j_{ion} \propto j_b = I_b/A$ (I_b = beam current, A =beam cross section), hence $\tau_{IBB} \propto j_b^{-1} = A/I_b$. Furthermore, the number of ions produced will be proportional to the residual gas pressure p_{res} and to the length of the acceleration stage which in turn is inversely proportional to the electric field (E). Putting all relations together we find : $\tau_{IBB} = kEA/(I_b p_{res})$ with a constant k that contains the sensitivity of the photocathode or its surface region against ion impact. The 'charge lifetime' is defined as $Q_\tau = I_b \tau_{IBB}$. We find:

$$Q_\tau = k \frac{EA}{p_{res}} \quad (1)$$

$$F_\tau = k \frac{E}{p_{res}}.$$

Q_τ and the 'fluence lifetime' $F_\tau = Q_\tau/A$ can be increased by reducing the gas pressure or by increasing E . A further conclusion from the relations is that the charge lifetime is supposed to be proportional to the emitting area. Nowadays operation at c.w. machines like CEBAF or MAMI is characterized by relatively low currents - fractions of milliamperes - which are drawn from small areas - $< 1 \text{ mm}^2$. The result in table 1 indicates that one seemingly approaches the requirements of an ERL based polarized EIC (EIC: Electron Ion Collider). The achieved F_τ is close to the requirements, which means that the desired charge lifetime is achievable if area scaling as stated in equation 1 would hold. This, however, needs experimental verification. One of the goals of our experiments was therefore to try to observe if there exists an increased charge lifetime for beams of larger beam diameter.

Comparing the achieved result with the requirements for an ERL based electron cooler or a light-source, we see that the existing performance is insufficient. However, these projects do not require polarized beam. This opens the possibility to improve the performance by using a NEA cathode with high energy photons. A probably more efficient approach is to resort to positive electron affinity (PEA) devices which should be much more stable, i.e. should show a larger value of k in eq. 1. Such a photocathode could be the well known KCsSb cathode which has an electron affinity of +1.1 eV and a photoemission threshold of 2.1 eV [2].

In the next section we present new apparative developments. We then describe the determination of other experimental parameters which also have influence on the observed lifetime. Section four presents the results achieved with NEA GaAs and an analysis of the q.e. pattern after the irradiation. We close with an outlook towards further experiments.

2. Apparative developments

2.1. Source with improved vacuum system

The 100 keV photosource used for our investigations is a back-up system which was buildt to replace the MAMI production source in case of a major failure. It has been optimized with respect to the specific pumping speed by designing a vacuum chamber which allowed to arrange 14 SAES WP700 modules (700l/s pumping speed for H_2 each) around the beam acceleration stage. This increased the specific pumping speed by about a factor 10. The HV parts remained unchanged to be compatible with the production source. The first 1.6 m long part of the beamline is electrically insulated, this region extends from a few centimeters behind the anode of the source towards about half a meter behind a 90 degree beam deflection by a "alpha" magnet. It is therefore possible to measure transmission losses in this part of the beamline with a resolution of nA, which can easily be checked if the beam is directed onto the beam pipe by miss-steering it. If the beam was properly adjusted no detectable loss was observed at 2 mA even for largest emission spot size on the cathode.

2.2. 405 nm Laser system

For experiments with unpolarized beam a 150 mW GaN Laser-diode was used which produced 405 nm light (3.06 eV photon-energy). We have tested this laser also in r.f. synchronized mode, which resulted in a 2.5 GHz pulse train with < 70 ps (FWHM) long pulses. Such a laser diode is an extremely simple means of injecting r.f. synchronized electron beams in c.w. accelerators with (unpolarized) average currents in the mA range. In spite of the small average power this is possible with NEA-GaAs since photosensitivities at 405 nm are > 30mA/Watt. The same holds for the potentially more stable *KCsSb* cathodes where we have recently achieved 20mA/Watt.

3. Corrections to observed lifetime

The observed lifetime τ in an experiment may be expressed as

$$\tau = \left(\frac{1}{\tau_{sum}} + \frac{1}{\tau_{IBB}} \right)^{-1}. \quad (2)$$

The term τ_{sum} stands for sum of all other effects which tend to deteriorate the photocathode globally, i.e. on the whole active surface. In order to obtain a result for τ_{IBB} one has to correct for τ_{sum} . We therefore discuss the effects which determine τ_{sum} .

Vacuum lifetime and field emission: In figure 1 we present the q.e. as a function of time in 'armed and ready condition' when the 100 kV accelerating voltage is applied continuously and the valves in the beam line are open. The resulting average current from periodic q.e. measurements is so small that it has no influence on the lifetime. The so measured decay constant characterizes the parallel interaction of field emission produced gases and ions and of the residual gas with the cathode surface. Starting with a period of almost constant q.e. an exponential decay sets in after about three weeks. Depending on weather one defines the lifetime as the time constant of the exponential fit or as the overall reduction to 1/e from the beginning we find $\tau_{sum} = 26 - 50$ days.

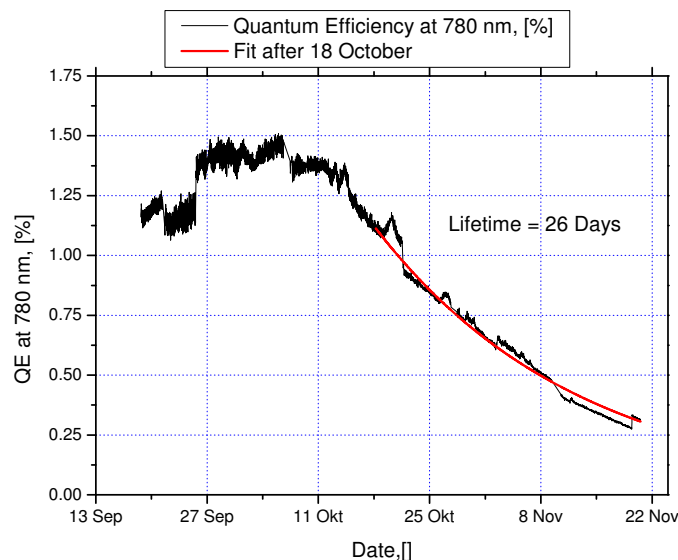


Figure 1. Quantum efficiency as a function of time with HV switched on and open valves in the beam line towards the beam dump but with negligible average current

Thermal effects: The value for τ_{sum} presented above is only an upper limit, since additional effects further diminish it in high current operation. For instance, our investigations of the dependence of τ_{sum} on cathode temperature [3] yield an exponential reduction:

$$\tau_{sum}(T) = \tau_{sum}(T_0 = 20^\circ C) e^{-(T-T_0/50)}. \quad (3)$$

Because the cathode holders in our experiments may show thermal coefficients as low as $2mW/K$ (due to the low thermal conductivity of the interfaces between the semiconductor and its holder) we have to reduce laser intensities to below 100 mW to avoid excessive heating. This allowed for currents between 1 and 3 mA. The upper value is already limited by the capability of the 100 kV supply of the source. The measurements were performed with constant laser intensity to avoid a shortening of τ_{sum} because of increasing temperature.

Transmission losses: We have observed [4] that $\tau_{loss}[h] = 1000/I_{loss}[nA]$ gives an estimation for the effect of losses directly behind the anode. Hence, in our case, such losses must be reduced to about one nA - or a relative loss of $\approx 10^{-6}$. This requires to restrict the active surface of the cathode to a somewhat smaller circular diameter than the cathode itself - 3 mm vs. 10 mm - since emission from cathode regions close to its edge leads to losses which may reach $5 \cdot 10^{-4}$ if the whole cathode area is used. The restriction of the photo-active area is provided by the mask activation technique [5]. Under this condition we do not expect further reduction of τ_{sum} by beam losses. However, a factor that is difficult to quantify is the backstreaming of gas from the beam dump. In our set-up the beam dump is about three meters away from the source, it is separated from it by a 90 degree bend and backstreaming is suppressed by a three fold differential pumping stage. Pressure increase in the vicinity of the beam dump was $\approx 1 \cdot 10^{-9} mbar/mA$. If we assume a 10^3 -fold reduction due to differential pumping, we get a 20% pressure-rise in the acceleration stage at 2 mA. This will reduce Q_τ directly via τ_{IBB} and will also reduce τ_{sum} due to the increased global interaction with residual gas.

Measurement of τ_{sum} : In order to avoid the uncertainties introduced by estimating the reduction of τ_{sum} due to increased temperature in operation and backstreaming we have tried to measure τ_{sum} by analyzing the q.e. distribution after operation. This resulted in a value of $\tau_{sum} = 15d$, which is in reasonable agreement with the expectation of a reduced τ_{sum} due to the increased temperature of the cathode during the experiment.

4. Results with NEA GaAs

Bulk GaAs cathodes were used at 780 nm (IR-light, 'polarized' operation) and 405 nm (blue light, 'unpolarized' operation). In polarized operation the source has roughly reproduced the values reported in table 1. With the blue laser we have performed two lifetime experiments at laser spot diameters of 0.3 and 1.5 mm respectively. The spot sizes are defined by the $1/e^2$ - values of the laser intensity distribution. The 1.5 mm result is presented in figure 2, both measurements yielded a nearly exponential decay, as indicated by the solid line in the figure which has the time constant $\tau = 5.5$ days with an initial current $I_0 = 2.3$ mA. The charge that is extracted during one lifetime under the condition of fixed laser intensity is $Q = I_0\tau(1 - 1/e)$, resulting in $Q(0.3mm) = 150C$ and $Q(1.5mm) = 700C$. The charge lifetime Q_τ (as defined in eq.1) is somewhat higher, since the value of τ_{IBB} instead of τ should be used. Extracting τ_{IBB} from equation 2 yields $Q_\tau(0.3mm) = 160 - 240C^1$ and $Q_\tau(1.5mm) = 1100C$. These results are in contradiction with area scaling since Q_τ is increased by a factor of only 4.5 - 6.9 whereas the ratio of emission areas is 25. This outcome is similar to an experiment which was published by

¹ The experiment at 0.3 mm was performed at lower laserpower and current (0.8 mA) which should yield a higher value of τ_{sum} if compared to the larger beam diameter. Unfortunately we have not been able to measure τ_{sum} in this case. We therefore assume: $15d < \tau_{sum} < 47d$, which leads to the variation in Q_τ after correction.

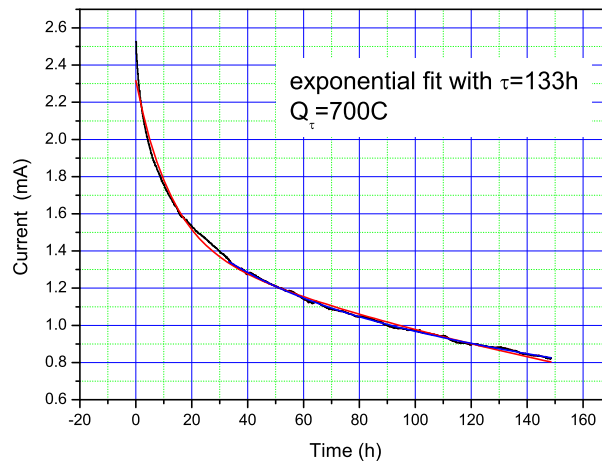


Figure 2. Current versus time at high intensity produced from 1.5 mm diameter laser spot.

Grames et al. from JLAB [6]. Larger absolute values of Q_τ - by about a factor of $\approx 2-3$ - were observed. However, the discrepancy in the ratios of Q_τ and the emission areas was similar.

A part of the discrepancy may be explained by an analysis of the local q.e.-distribution after the experiment. Figures 3 and 4 present a map of q.e. before and after the production of 700 C of charge with 1.5 mm emission site diameter. A first interesting feature is the fringe of higher remaining q.e. in figure 4 where about 2/3 of the initial q.e. can still be found. Since these regions have only small overlap with the emission site, we may attribute the reduction in the fringe to global damage, i.e. τ_{sum} , resulting in $\tau_{sum} = 15d$.

Second, the region of maximum damage is not coinciding with the position of the laser spot (Cross in the right figure.). This feature is usually observed and is believed to be the result of a small displacement of the beam by about 1 mm from its starting position, maybe caused by magnetic stray fields in the acceleration stage or by the focusing effect of the conically shaped cathode holder. In contrast to the situation in a strictly homogeneous electrostatic field the electrons now follow a curved trajectory. The high energy ions which are produced towards the end of the acceleration are therefore projected back towards a position which is not exactly the same as the emitting spot. As a consequence there exists an area of about 1.5 mm diameter where the damage is very large. It seems that the size of this 'central damage area' is quite independent from the laser spot size. In regular accelerator operation beams of small diameter are started at a somewhat excentric location in order to avoid the central damage area. Unfortunately, due to the smallness of the total active area - this restriction is necessary in order to avoid beam loss (section 3) - it is not possible to avoid an overlap of the emission site with this heavily damaged area in the case of the 1.5 mm beam, whereas it may well have been the case for 0.3 mm. This effect points in the right direction to remove some of the discrepancy. Furthermore, the high current density at small sizes - surpassing $2A/cm^2$ for the 0.3 mm experiment - may lead to a widening of the beam directly in front of the cathode. In consequence the increased effective beam area may also reduce the discrepancy.

5. Outlook

As a possible reason for the deviation from area-scaling we have identified the overlap of emission sites with $> 1mm$ diameters with the heavily damaged areas on the cathode. Since observations

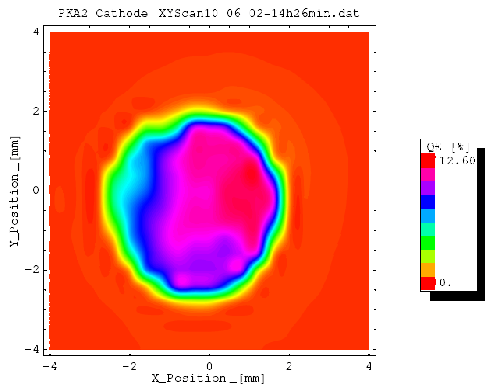


Figure 3. Quantum efficiency distribution before run

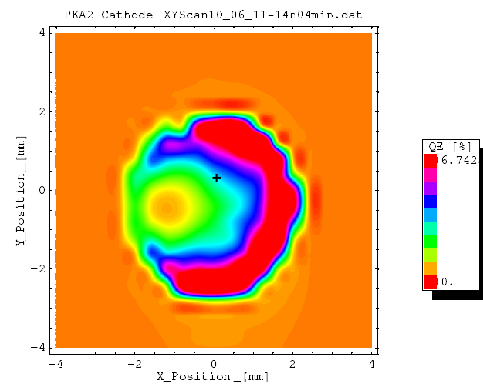


Figure 4. Same measurement after production of 700 C in the run.

so far support the assumption that the area of heavy damage is independent from the laser (emission-) size this effect can be mitigated by creating a somewhat larger activated area of ≈ 5 mm diameter. The larger size could allow to avoid the heavily damaged region for emission spot sizes of ≈ 2 mm diameter. It is desirable to produce the expected charges of about 5 kC within a time $\ll \tau_{sum}$ in order to avoid uncertainties due to the corrections for τ_{sum} . Therefore it will be necessary to use currents of the order 20 mA. Before we can attempt such an experiment we have to solve two main problems: Most importantly the thermal conductivity of the mechanical interfaces in the cathode holder must be increased by about an order of magnitude. This is feasible by soldering the cathodes to the cathode holder and by pressing the holder with more force into the electrode structure. Second, the gas desorption in the beam dump must be further reduced. Probably the best way to achieve this is to replace the present faraday cup by the 'suppressed collector' of an electron cooler. Such devices achieve differential pressures of $< 10^{-11} \text{ mbar/mA}$ which gives the one order of magnitude improvement necessary [7].

The more robust KCsSb photocathode will be tested in the near future. First cathodes with a sufficiently high quantum efficiency at 405 nm were successfully produced. They will be transported to the 100 kV source in UHV transport vessels. We expect to perform similar measurements as presented in this paper with KCsSb cathodes during 2011.

Acknowledgments

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