Multi-Alkali Photocathodes Performance in a DC 300 kV Inverted Geometry electron gun

ADRIANA CANALES-RAMOS

(Universidad Nacional Autónoma de México at Mexico City, Mexico, C.P. 04510)

Mentor: CARLOS HERNÁNDEZ-GARCÍA

(Thomas Jefferson National Accelerator Facility, Newport News, VA 23606).

Abstract

The electron-ion collider (EIC) proposed by Jefferson Laboratory requires unprecedented hundreds of mA of un-polarized electron beam at MHz repetition rates (Continuous Wave, CW) to cool down the ion beam. As a viable alternative to Cs:GaAs photocathodes (in ~100 kV DC electron guns) for generating an electron beam that meets those stringent requirements we are studying multi-alkali photocathodes in a High Voltage Direct Current (HV-DC) inverted-geometry insulator electron gun. The performance of our in-house fabricated CsK_2Sb photocathodes is characterized with the 1/e QE lifetime, showing great robustness in a 300 kV DC inverted-geometry electron gun. Even severe damage at the photocathode electrostatic center caused by arcing did not affect QE in the laser-illuminated area; moreover no QE decay was detected while measuring lifetime at 0.1 and 0.5 mA sustained in each case for several hours. We present the highest electron beam current (1.0 mA DC) generated at the highest voltage (300 kV) in an inverted-geometry electron gun with multi-alkali photocathodes. The next step towards higher current needed for the EIC is to run stable 5.0 mA electron beam with the same electron gun configuration.

Introduction

At the moment high-energy nuclear physics experiments at Jefferson Lab rely on polarized electron beams generated at 0.1 mA CW with Cs:GaAs photocathodes in ~100 kV DC electron guns. These photocathodes are very sensitive to vacuum conditions and ion-back bombardment that limit their 1/e quantum efficiency lifetime to about 500 Coulombs at a few mA CW. Extrapolating to 100 mA the lifetime would be only around 5 Coulombs, or about one minute before the photocathode needs replenishing, which is impractical.

In this work we study CsK_2Sb photocathodes as an alternative to generate high current un-polarized electron beam (EB) needed for the EIC. GaAs photocathodes can be purchased, but CsK_2Sb photocathodes are usually fabricated near the gun. The main advantage of multi-alkali photocathodes is that they can survive under worse vacuum conditions than GaAs photocathodes [1].

The EB is generated by photoemission**.** Therefore, it is necessary to illuminate a photocathode to obtain photoelectrons. The quantum efficiency (QE) of the photocathode (PC) is a ratio between the photoelectrons generated and the incident photons (eq. 1).

$$QE(\%) = \frac{N_{e^-}}{N_\gamma} \times 100 = \frac{Ihc}{\lambda Pe} \times 100 = \frac{124 I(\mu A)}{\lambda(nm)P(mW)} \quad (1)$$

Where I is the photocurrent measured, λ the wavelength of the laser and P the laser power at the photocathode. QE measured over time describes for how long we can obtain a good amount of electrons (current) from the photocathode with a fixed laser power [2].
Lifetime, τ, is the time by which the QE has decreased to $1/eQE_0$ (eq. 2).

$$QE(t) = QE_0 e^{-t/\tau} \quad (2)$$

Photocathodes of large 1/e QE lifetime are particularly interesting to obtain as much charge as possible from the same photocathode.

Our goal is to run a stable 5 mA electron beam at the Gun Test Stand (GTS), with a CsK_2Sb photocathode to evaluate its QE lifetime.

Methods

In order to produce EB, a 532 nm $Nd:YVO_4$ laser (Coherent Verdi-10) illuminates an in-house fabricated CsK_2Sb photocathode (Fig. 1(a)). The recipe to fabricate the photocathode has been studied and optimized before [2]. It consists of a layer of alkali (Cs-K), a few nm thick, deposited over a layer of Sb (from a few nm to hundreds of nm thick, different thicknesses can produce different QE) which is deposited over a GaAs substrate.

Laser power at the photocathode was controlled via computer by a motorized attenuator which consists of two crossed linear polarizers and a motorized ½ waveplate in between them. Laser beam transport is needed to illuminate the photocathode with a circular beam of ~1 mm FWHM diameter.

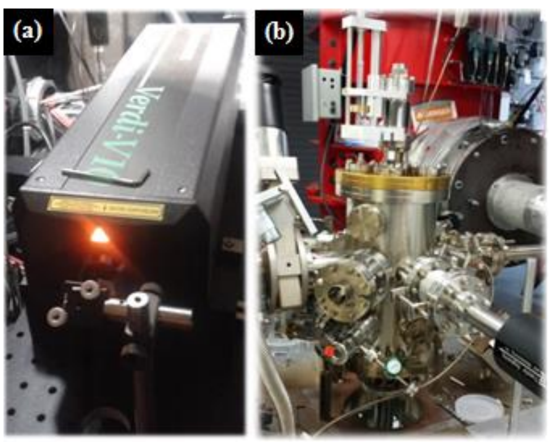

Fig. 1. (a) 10 W Coherent Verdi laser, (b) photocathode preparation chamber and (in red) the High Voltage Power Supply for the electron gun.

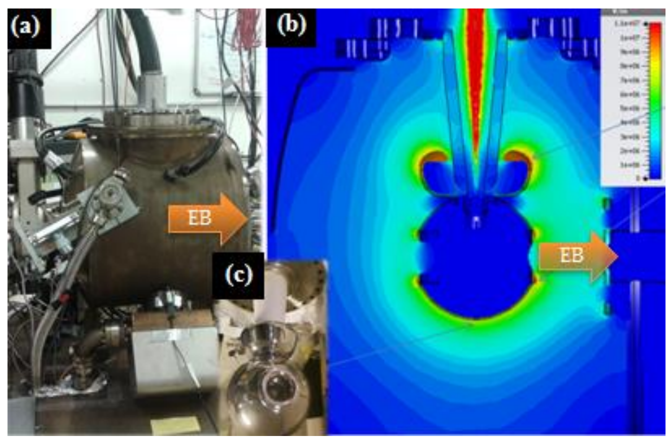

Fig. 2. (a) Inverted-geometry DC electron gun picture, the arrow shows the EB direction. (b) Interior of the electron gun, the color represents the voltage, the electrode is the sphere in the center and the anode is at the end of the arrow. (c) Electrode picture.

The inverted-geometry electron gun consists of an electrode at 300 kV (where the photocathode is placed) and an anode, usually grounded. It is designed to focus the beam at the anode [3]. The electrode has a spherical shape and it is carefully polished to avoid field emission.

GTS beamline, where the photocathodes are tested, is shown at Fig. 3. Photocathodes are fabricated at the preparation chamber (Fig. 1(b) and Fig. 3(i)). Then they are transferred to the High Voltage DC electron gun (ii). The photocathode is placed in an electrode where it is maintained at a negative 300 kV. High voltage at the electrode of the electron gun is provided by the high voltage power supply (HV-PS) (Fig. 1(b)).

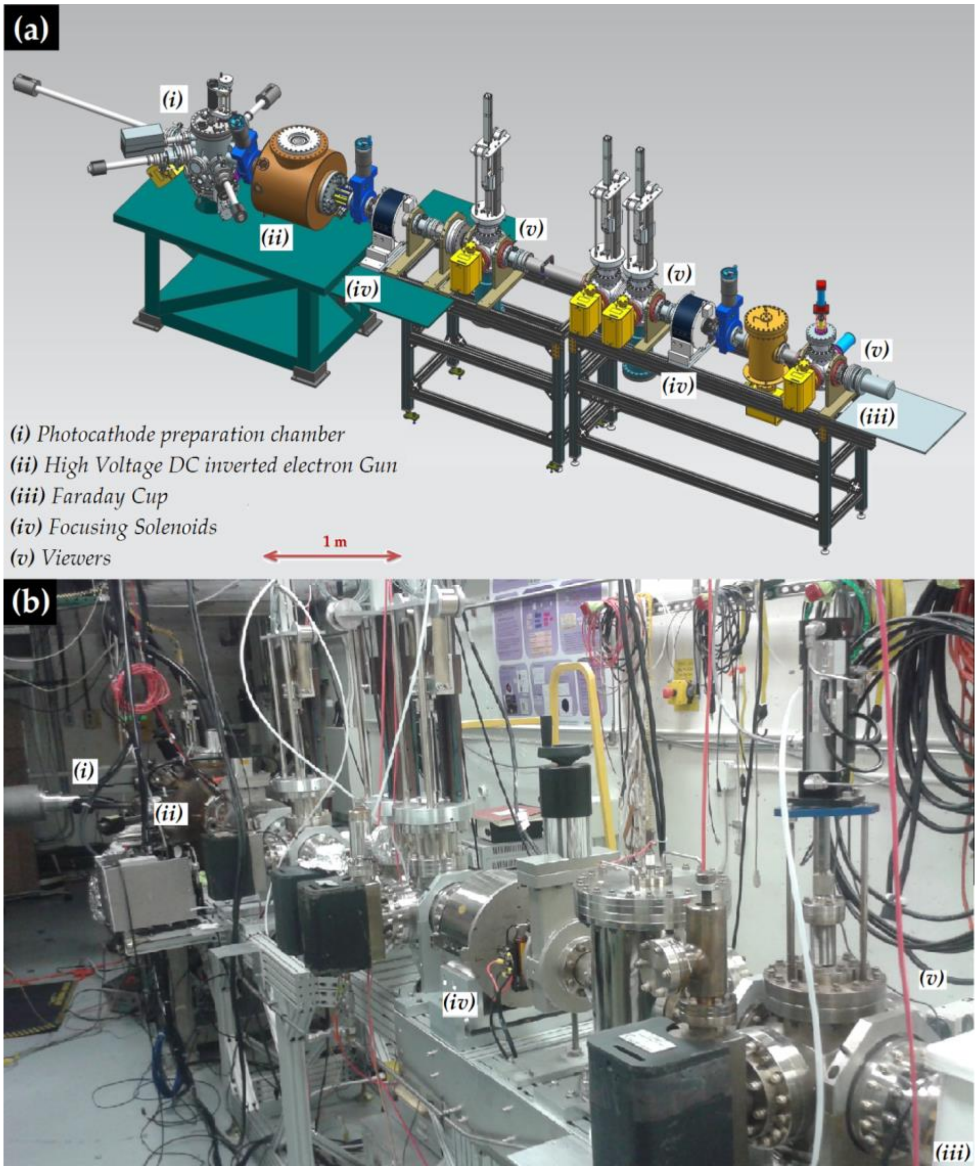

Fig. 3. (a) Beamline schematic. (b) Gun Test Stand (GTS) beamline picture. Our PC is fabricated at the preparation chamber (i), and then it is introduced to the HV-DC electron Gun (ii). The EB is produced by shinning green laser light on it. Then it is focused (iv) and steered with magnets to the Faraday cup (iii) at the dump of the beamline. The Faraday cup collects beam current. The beam shape can be observed through the viewers (v).

The produced EB can be steered and focused, by a series of magnets, to the Faraday cup at the beam dump. The Faraday cup collects the beam current and it is measured in time. The shape of the EB can be monitored at low current with three viewers located along the beamline. Viewers allow to steer the EB to the Faraday cup and to maintain it centered along the beamline. It is really important to steer the beam properly, because if it hits the beam gas and ions might be generated; ions might travel to the photocathode and induce serious damage in it.

Beam current is controlled with laser power, since the amount of electrons produced depends directly on laser power at the photocathode. In order to achieve high current EB it is necessary to condition the beamline. This means that the laser power should be increased gradually while the vacuum and radiation levels are monitored to make sure they are low.

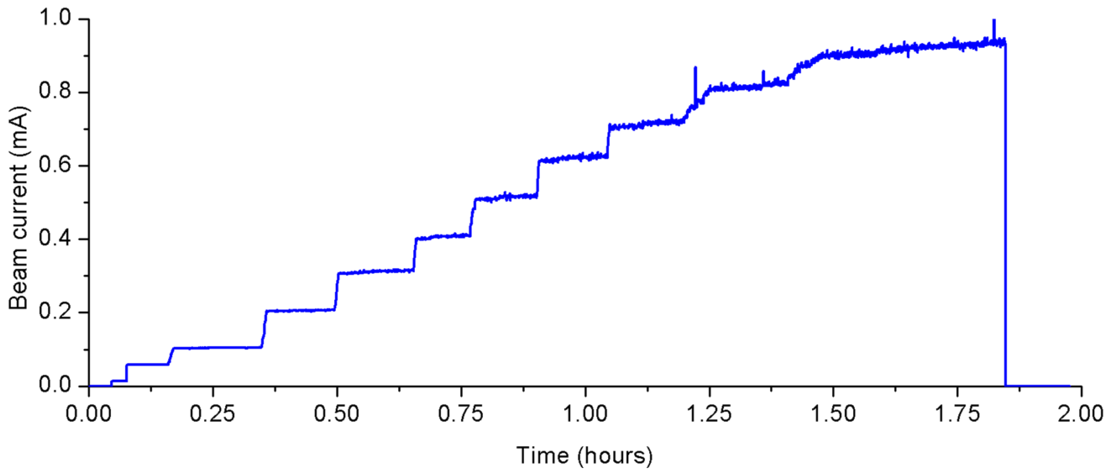

Fig. 4. Typical signal of current in time while raising the laser power to obtain 1 mA.

As showed in Fig. 4 to maintain vacuum and radiation signals low, laser power is kept fixed several minutes at different currents (usually every 100 μA). If vacuum levels are high more gas can be ionized; therefore, more ions might travel downstream and hit the photocathode. Moreover, if there are enough ions in the anode-cathode gap they might create an arcing. Each arcing event damages the photocathode.

Since ions generate arcing events in the anode-cathode gap, it is important to prevent ions created downstream from entering to it. A way of doing it is biasing the anode to a fixed voltage (0-1500V in our case) [4]. Then a positive potential is created at the anode-cathode entry that repels the ions back to downstream.

Also, the higher the gun voltage is the fewer the ions yield at the anode-cathode gap [4]. Therefore, the amount of ions yield at ~100 kV (Continuous Electron Beam Accelerator Facility electron gun voltage) is almost the triple than at 300 kV.

On the other hand, at high voltage it is more probable to induce field emission from the electrode of the gun to ground. Field emission between the anode and the cathode might desorb gas that can react with the photocathode's surface and can also create ions. High radiation levels mean that there a strong field emission or that the EB is hitting the beam pipe.

To avoid field emission from the electrode it is necessary to polish it very well and to do some Kr conditioning. It means that Kr is introduced in the electron gun and, while raising the voltage, field emitters will be hit by Kr; this results on a smother surface [5].

Results

We studied the current behavior in time for different beam runs with a CsK_2Sb photocathode, as shown in Fig. 4. This figure shows an interesting event: current drops suddenly from 1 mA to 0 mA. The current drop is caused by a HV-PS trip; which is a result from arcing events (AE). Each AE raises the current measured by the HV-PS, if the current is higher than the security limits, the HV-PS it will automatically turn off to protect itself from a big discharge.

An excess of ions can cause the HV-PS to trip many times during a run. It is important to avoid HV-PS trips because each AE also damages the photocathode.

Remarkably, we have not observed QE decay up to 1 mA when running beam without any arcing event (Fig. 5). As stated in eq. 2, an exponential QE decay is expected for each photocathode. The longer the photocathode can produce current the better it is. Also, it seems that QE improves after illuminating the photocathode for a while, maybe because the temperature of the photocathode increases while the laser beam hits it.

Graph in Fig. 5 also emphasizes the importance of avoiding arcing events, since as far as they are not produced the current is stable (and even rising a little bit) when the laser power is fixed. This means that QE is stable or getting better during the beam run. Nevertheless, when running at 0.6 mA (Fig. 5) there was an arcing event that produced a

QE loss (current dropped to 0.5 mA). Therefore, arcing events must be prevented in order to increase to 5 mA (maximum of the HV Power Supply).

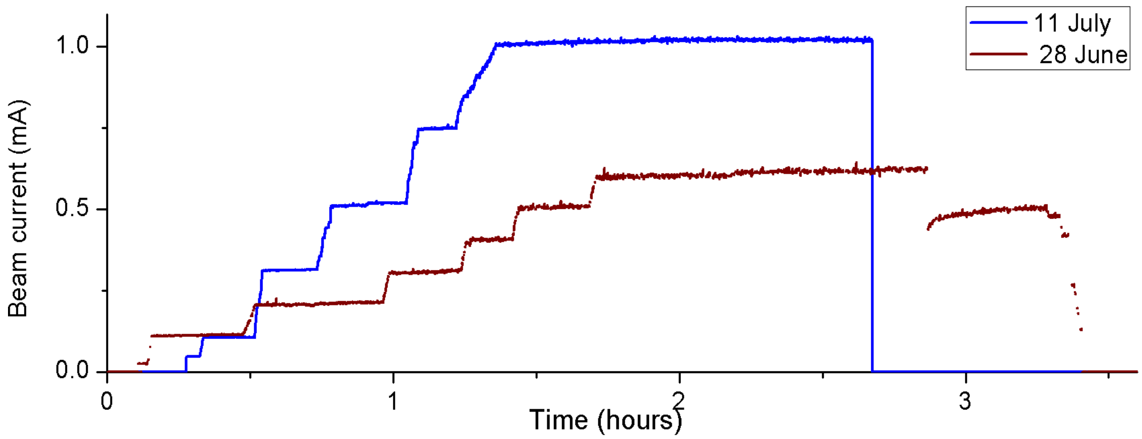

Fig. 5. EB run at 0.6 mA and 1 mA for more than 1 hr. The runs were stopped due to HV-Power Supply (PS) trips. There is no observable QE decay with time. The QE decay for the 0.6 mA run was caused by an arcing event.

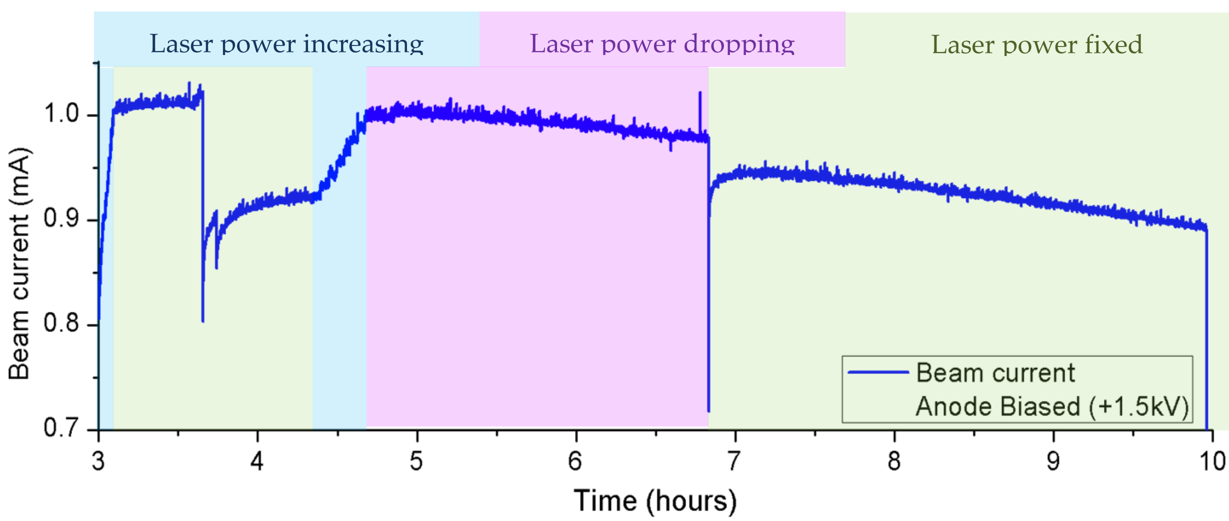

Fig. 6. EB run at 1 mA for ~ 6 hours. Each current drop was caused by an arcing event. Background colors indicate the laser power status: blue– laser power (LP) increase; green – LP fixed; purple– LP drop.

After several HV-PS trips, the anode was biased at a voltage between 0-1500 V to prevent arcing events. Graph of Fig. 6 shows a 6 hours run at 1 mA with QE decays caused by AE. Each AE causes a QE drop followed by a slight QE recover. The colors represent laser power status. During blue time lapses the laser power was increasing to get 1 mA of beam current. Laser power remained fixed for the green time lapses and there was a loss of laser power during the purple one. It is important to report the laser drop because beam current also fell down during this time. Since they were both coming down it is not accurate to think QE was decaying.

On the other hand, each sudden current drop in Fig. 6 represents an arcing event and it is related to a current spike measured by the HV-PS is showed in Fig. 7(a). Every current spike is an AE. Arcs do not affect directly the EB current, hence only the HV-PS is able to detect AE because it is closer to the electron gun.

Impressively, after several AE the photocathode still provides beam current, it is clearer in Fig. 7 where many AE took place during a reduced time. This is directly related to the robustness of the photocathode, even after several damages the photocathode can continue running beam.

The damages can be induced by field emission or by an excess of ions in the anode-cathode gap. Of course, after the measurements showed at Fig. 7 where done we proceed with a Kr conditioning to prevent field emitters.

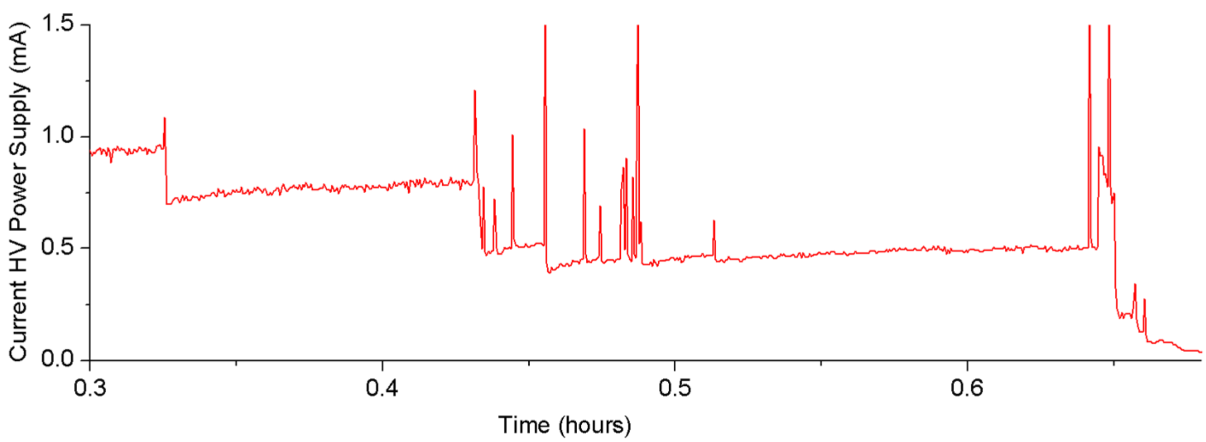

Fig. 7. (a) Current at the HV-PS during a series of arcing events. Each spike represents an arcing event. Even after several AE the photocathode still provides beam current.

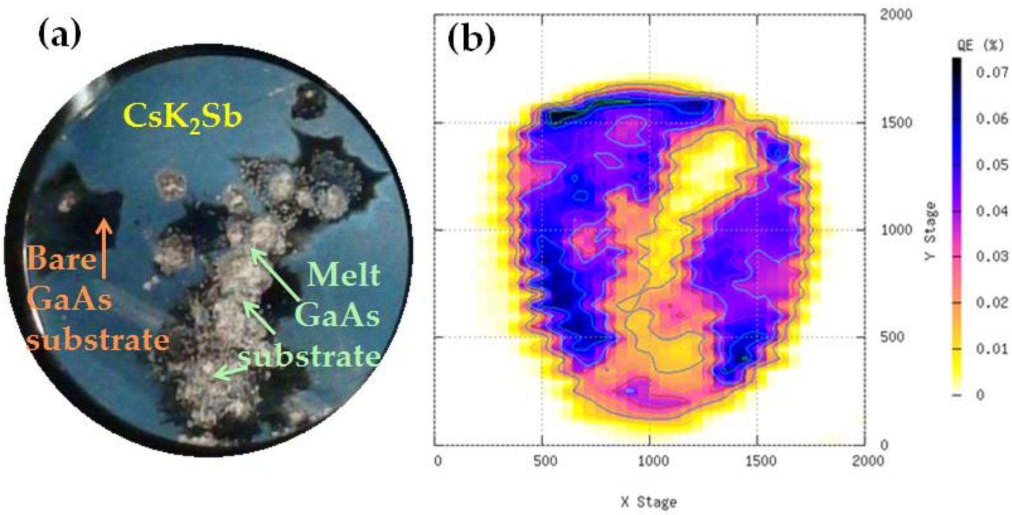

Fig. 8. (a) Damage at the electrostatic center of the PC caused by a series of arcing events. With anode biased from 0 to +1500 V. (b) QE map of the PC shown in (a).

Each AE induces damage at the electrostatic center of the photocathode (Fig. 5(b)) because the electric field is stronger in that point [4]. The electrostatic center depends on the geometry of the electron gun and on the anode's voltage; both variables might change the potential between the anode and the cathode. The location of the electrostatic center can be calculated and needs to be avoided by the laser beam in order to always illuminate a non-damaged spot at the photocathode.

The anode was biased to different voltages in order to reduce arcing events, therefore the electrostatic center changed to different spots. After several arcing events the photocathode is shown at Fig. 8(a). Every crater was created by an arcing event; some of them are deeper than the others because of the amount of AE that took place when that was the electrostatic center. A QE scan of the photocathode allows us to understand the QE at different locations at the PC (Fig. 8(b)). We can see that the QE is very low at the craters spots, but it is still good at non damaged spots.

Also QE curves where obtained at high current. QE curves are obtained by measuring the current for different laser power: it is a linear relation (eq. 1), and higher slope means higher current. Fig. 9 shows the QE curves for the PC after several arcing events. After the firsts AE the QE drop from 8% to 3%. Nevertheless, after the first drop, the QE obtained with the laser beam at a non-damaged spot remained constant at 2-3%.

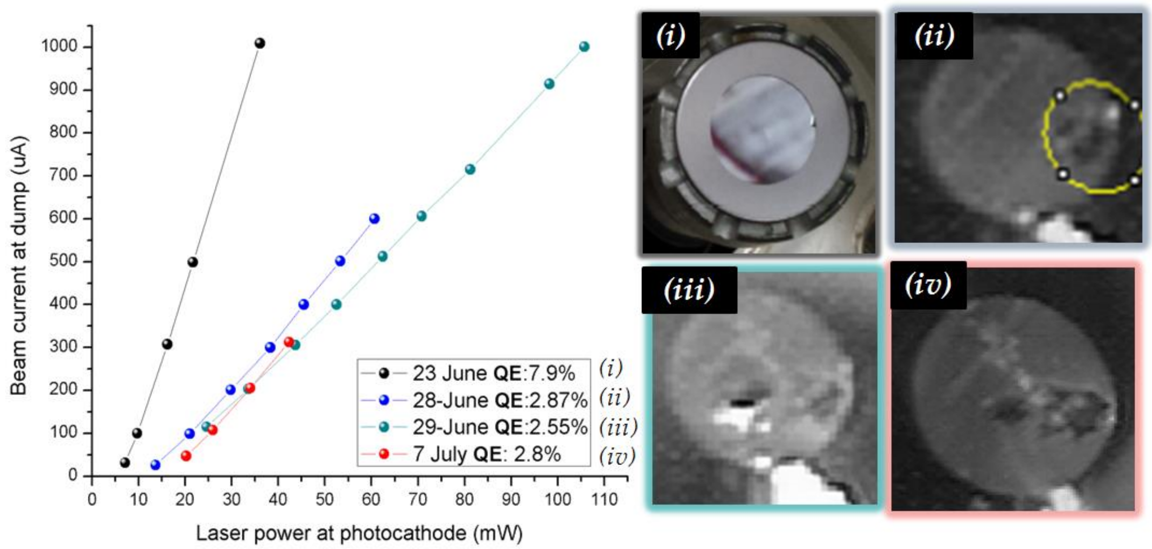

Fig. 9.QE curves for different EB runs (left). Laser spot was located at a non-damaged area to obtain the curves. Each QE curve is related to a PC image where the different damages are visible (right). QE barely changes after arcing damage at non-damaged spots.

On the other hand, biasing the anode did not reduce arcing events as expected. Even at different voltages the HV-PS kept tripping. Maybe the energy of the ions created is high enough to ignore the positive voltage at the anode. For that reason, it is necessary to implement different techniques to prevent ions from entering the anode-cathode gap. For example, changing beam dump position might help to decrease the number of ions that strike the photocathode.

At the moment the beam dump is in front of the electron gun (just separated by about 3 m) and most of the ions are yield downstream. Therefore, putting the dump at an angle, with respect to the electron gun, will decrease the amount of ions able to make their way through the PC.

Another way to avoid ions created downstream can be adding clearing electrodes before the Faraday cup [6]. These electrodes will deflect the ions created before they strike the PC.

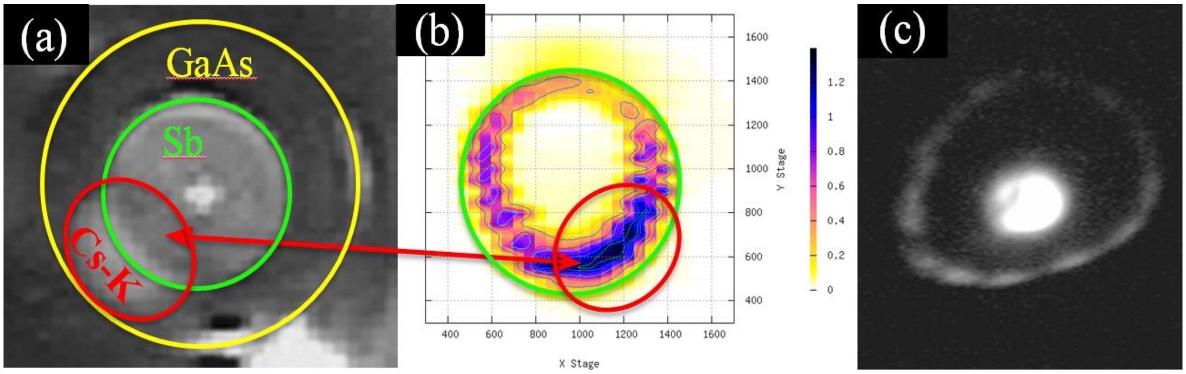

Fig. 10. (a) Picture of a masked photocathode fabricated to reduce EB halo by limiting the active area. The bright point in the center is the laser beam. (b) QE scan of the masked photocathode. (c) Picture of the EB generated by locating the laser spot at the center of the masked PC.

It is also important to focus the beam correctly, because by hitting the beam pipe it is possible to create more ions. A problem that arises when trying to focus the beam is beam halo. Beam halo is a group of electrons surrounding the EB that are not part of the EB and that are hardly focused. Halo is usually due to laser beam reflections in the electron gun. A way to avoid halo is to decrease laser beam reflections. To decrease them it is possible to add Brewster windows to the electron gun (at the entrance and exit of laser beam). But in order to add them it is necessary to open the vacuum chamber and it would be necessary to condition vacuum again, which would take several weeks.

Then, another solution is to make a photocathode with a smaller active area. In order to make the active area smaller it is necessary to add Sb and alkali only in a certain part of the photocathode. Therefore, even if light strikes the whole photocathode we would only obtain electron from the active area. To make that PC, a mask is used in front of the PC at the Sb and alkali deposit moment. By limiting the active area, even if there are many reflections out the active area no electron beam will be crated. Beam halo will be less if electrons are only emitted from the masked area.

However, making a masked photocathode in the current photocathode preparation chamber is really difficult, because there is little control over the Sb thickness layer and the amount of alkali introduced (Cs-K). It is called a masked PC, since a mask with a hole is used to cover the GaAs substrate during the deposition of Cs-K and Sb. Then, only the GaAs situated in the hole of the masked is activated by the Sb and Cs-K.

A first masked photocathode was fabricated to eliminate EB halo by limiting the active area (Fig. 7). Nevertheless, due to the lack of control while fabricating the photocathode, the Sb layer and the Cs-K layer were not completely overlapped. Fig. 7(b) shows a QE map of the masked photocathode. It is interesting to notice that the intersection between the Sb and the Cs-K shows the highest QE while in the center QE is really low.

A second masked photocathode was fabricated using the mask only to deposit Sb then the Cs-K where deposited without the mask to improve the homogeneity. This photocathode showed lower QE in the center, which probably indicates the Sb layer is not uniform and that the amount of Cs-K was not enough to activate the thicker Sb location. The next step is to work on the uniformity of the masked photocathode by depositing Sb layer without mask and activating it with Cs-K with the mask.

Conclusion and future work

The present work shows the great robustness of the in-house fabricated CsK_2Sb photocathodes. Even with severe damage the PC produced photoelectrons. On the other hand, opposite to expectations, biasing the anode did not seem to reduce arcing events.

In addition, there was not an observable QE decay for hours up to 1 mA. Moreover, it is important to mention that we have achieved 1 mA DC at 300 kV in an inverted electron gun. This represents the highest current at the highest voltage with this type of gun.

In order to go to 5 mA (the limit of the HV power supply) to evaluate QE lifetime, it is necessary to avoid arcing events. Therefore, it is important to create fewer ions that can reach the anode-cathode gap. To do it we can implement several techniques, such as clearing electrodes in the end of the beamline [6], relocate the dump at an angle with respect to the gun, and improve beam focusing and transport. Also, it is necessary to work on a better procedure to limit the active area of the photocathode, since currently it is difficult to fabricate a masked photocathode with good QE at the GTS preparation chamber.

Acknowledgements

This project was partially supported by the JSA Initiatives Fund Program, a commitment from the JSA owners, SURA and PAE Applied Technologies. Initiatives Funds support programs, initiatives, and activities that further the scientific outreach, promote the science, education and technology of the Jefferson Lab and benefit the Lab's extended user community in ways that complement the Lab's basic and applied research missions. Additional support was provided by Mexican Physical Society program *Veranos científicos en el extranjero* and the Universidad Nacional Autónoma de México (UNAM). The authors gratefully appreciate discussions with the JLab Injector Group, and guidance from Shukui Zhang and Riad Suleiman.

References

[1] R. Mammei, R. Suleiman, J. Feingold, P. Adderley, J. Clark, S. Covert, J. Grames, J. Hansknecht, D. Machie, M. Poelker, Physical Review Special Topics-Accelerators and Beams 16 (2013) 033401.

[2] M.A.A. Mamun, A.A. Elmustafa, C. Hernandez-Garcia, R. Mammei, M. Poelker, Journal of Vacuum Science & Technology A 34 (2016) 021509.

[3] C. Hernandez-Garcia, M. Poelker, J. Hansknecht, IEEE Transactions on Dielectrics and Electrical Insulation 23 (2016) 418.

[4] J. Grames, R. Suleiman, P. Adderley, J. Clark, J. Hansknecht, D. Machie, M. Poelker, M. Stutzman, Physical Review Special Topics-Accelerators and Beams 14 (2011) 043501.

[5] M. BastaniNejad, M.A. Mohamed, A. Elmustafa, P. Adderley, J. Clark, S. Covert, J. Hansknecht, C. Hernandez-Garcia, M. Poelker, R. Mammei, Physical Review Special Topics-Accelerators and Beams 15 (2012) 083502.

[6] S. Full, A. Bartnik, I. Bazarov, J. Dobbins, B. Dunham, G. Hoffstaetter, Physical Review Accelerators and Beams 19 (2016) 034201.