ALKALI CATHODE TESTING FOR LCLS-II AT APEX*

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Abstract

Electron sources of high brightness and high bunch charge (~ 300 pC) with MHz repetition rate are one of the key technologies for next generation X-FEL facilities such as the LCLS-II at SLAC and the Euro XFEL at DESY. The Advanced Photoinjector EXperiment (APEX) at the Lawrence Berkeley National Laboratory (LBNL) is developing such an electron source based on high quantum efficiency (QE) alkali photocathodes and the VHF-Gun, a new scheme normal conducting RF gun developed at LBNL. The VHF-Gun already demonstrated stable CW operation with high gradient (20 MV/m), high gun voltage (~ 750 kV) and low vacuum pressure (~ 3×10^{-10} torr) laying the foundation for the generation of high brightness electron beams. In this paper, we report the test and characterization of two different alkali cathodes in high average current (several hundreds of pC per bunch with MHz repetition rate) operation at APEX. Measurements include cathode life time, QE map evolution and thermal emittance characterization, to investigate the compatibility of such cathodes with APEX gun for the challenging requirements of LCLS-II.

INTRODUCTION

Next revolutionary FEL light source facilities, such as the LCLS-II at SLAC [1], requires MHz beam repetition rate with similar peak brightness as the state of the art ~ 100 Hz FEL drivers [2]. From the perspective of electron source, such a requirement translates to an electron gun of both high electric field and high duty cycle, and a photocathode of high quantum efficiency(~ 1%), low thermal emittance (< 1 mm.mrad/mm) and long life time (> 1 week) [3].

R&D on innovative electron gun technologies addressing the need of simultaneous high peak field and high duty cycle, from DC sources to Superconducting Radiofrequency Guns has made a lot of progress [3]. Though normal conducting high frequency (~ GHz) RF guns have provided beams of tremendous high peak brightness with 100 Hz repetition rate, they are criticized for not being able to reach higher duty cycle due to thermal load. Our group at Lawrence Berkeley National Laboratory has focused the effort on the new type of normal conducting RF gun resonating in the VHF frequency range (APEX, [4]), which has achieved reliable operation in continuous wave mode (CW) with accelerating fields (in excess of 20 MV/m) required to produce low emittance-high charge electron beams with high peak current needed to drive the next generation of Free Electron Lasers [5]. The basic gun parameters for cathode testing are shown in Table 1.

Table 1: Nominal APEX VHF Gun Parameters

Parameter	Value	Unit
$E_{cathode}$ in CW mode	20	MV/m
f_{rf}	185.71	MHz
E_k	758	keV
Base Pres. rf off	4×10^{-11}	Torr
Base Pres. rf on	3×10^{-10}	Torr

High brightness, high-yield photocathode materials are essential for high repetition rate electron sources. Unfortunately, such materials are usually very reactive semiconductors and their performances tend to degrade very fast with time and extracted charge, which can be a serious limitation to the operation of a future facility like LCLS-II and has been subject of intense studies in recent years [6]. The degradation of high QE semiconductor photocathodes are mainly due to three reasons, first is reaction with residual gases in vacuum, second is back bombardment of ionized residual gases or field emitted electrons, third is laser heating. Two categories of alkali photocathodes are tested at APEX gun to characterize its feasibility to host high QE semiconductor cathodes. First is UV sensitive Cs_2Te cathode, and second is the green sensitive antimonide cathodes (Cs_3Sb and K_2CsSb). The Cs_2Te cathode testing inside APEX gun has finished [7], and testing of antimonide cathodes just started, both are presented in this paper.

APEX BEAMLINE AND LASER SYSTEM

Cathode testing is done using the APEX phase I beamline, as shown in Fig. 1. It starts with the core part, the VHF gun and cathode loadlock system, and a set of beam diagnostics follows, such as ICT, YAG screen, Farady cup, emittance slits, deflecting cavity and energy spectrometer magnet, which are used to characterize both cathode and beam transverse and longitudinal phase space.

The Cs_2Te cathode is tested with a home made Yb-doped fiber laser system [8]. The 37.14 MHz oscillator seed a chain of Yb-doped fiber amplifiers. The repetition rate is reduced down to 1 MHz during amplification. The total IR beam is about 1 W, and after two second harmonic generations, both green and UV laser are available for the cathode testing. Recently, a similar commercial laser with 2 W IR power is installed, and will be used for antimonide cathode testing and APEX phase II commissioning.

* Work supported by the Director of the Office of Science of the US Department of Energy under Contract no. DEAC02-05CH11231
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ISBN 978-3-95450-134-2

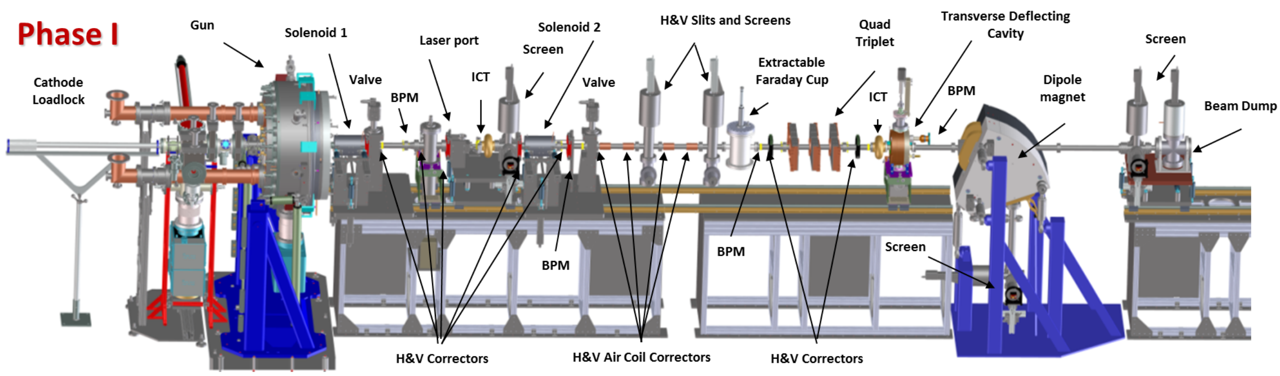

Figure 1: Cathode tested at APEX phase I beamline.

CESIUM TELLURIDE

The photoemission threshold of Cs_2Te is in UV, and with QE above 1%, it's a good candidate to produce high bunch charge (~ 300 pC) beam at 1 MHz required by LCLS-II. Besides, it has been tested in pulsed normal conducting RF guns [9, 10], and has shown both good QE and good life time with vacuum above 10^{-9} torr, but whether Cs_2Te cathode can survive the CW normal conducting gun is still an open question.

APEX Cs_2Te cathodes are purchased from INFN-LASA [11], which are round thin film of Cs_2Te deposited at the top of the polycrystalline molybdenum plug [12] on a region of 5 mm diameter. The cathodes were shipped to Berkeley in a vacuum suitcase, and stored for more than a year before installation in the experimental apparatus. During the entire period the total pressure in the chamber was kept below 10^{-9} Torr via Non Evaporable Getter pumps (NEGs). A map of the quantum efficiency of the fresh cathode is reported on the left side of Fig. 2, together with a picture of the deposited area on top of the plug.

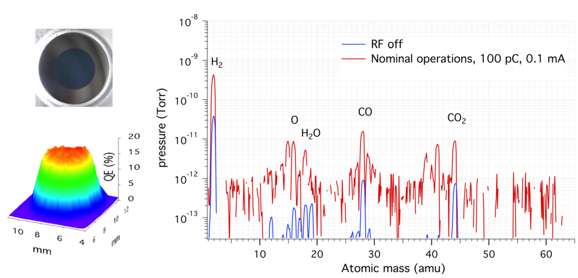

Figure 2: Left: image and QE map of the Cs_2Te cathode before operations (Courtesy of D. Sertore, INFN/LASA). Right: residual gas analysis in the APEX gun without RF power (blue) and during 0.1mA operations (red) (from [7]).

Gun Vacuum

As already mentioned, low gas pressure in the gun is of paramount importance for cathode lifetime: the total pressure determines the rate of ion production, causing cathode bombardment, while the presence of specific elements and compounds leads to chemical contamination. In the case of Cs_2Te, it has been demonstrated its receptivity to O and CO_2, while it has shown to be fairly insensitive to CO, N_2, and CH_4 [13]. The right plot of Fig. 2 reports residual gas analysis traces in the VHF gun in absence of electric field and during operations, with nominal CW power and 0.1 mA average current. In both cases, the total pressure is dominated by the partial pressure of hydrogen, with the other chemical species down by about two decades. The gas pressure is fairly insensitive to the value of extracted average current, while directly dependent on the average RF power feeding the cavity.

QE Degradation

In order to characterize and understand the dependencies of the cathode performance on the specific operating conditions, we performed continuous measurements of the same cathode plug for a period of a week, changing the average current extracted. The measurements were done on the same cathode plug, characterized by QE values and QE maps.

According to the previous findings [13], the main cause of contamination is caused by reaction of cesium with oxygen and carbon dioxide, with the poisoning effect of oxygen being about 100 times faster. Therefore, to a good approximation, only oxygen pressure can be considered in assessing the degradation by contamination. Residual gas analysis of the APEX gun volume (Fig. 2) shows an increase of the oxygen line by about 2 orders of magnitude when the RF power is feeding the cavity. Oxygen is desorbed by the cavity walls during operations, due to RF heating and X-rays absorption by the cavity surface. Most of the contamination will therefore happen during operations. Figure 3 reports QE evolution during operations. The horizontal axis reports the hours of operation of the electron gun, with RF power feeding the cavity, both with and without electron beam extraction. The top-axis shows the total exposure to oxygen, expressed in Langmuirs (10^{-6}torr·s). A fit of the measurements reveals a $1/e$ lifetime of about 14.5 Langmuirs which, in our case, corresponds to about 402 h of operations, consistent with the previous measurements at low fields and low currents [13], and fulfils the baseline requirement of LCLS-II.

ISBN 978-3-95450-134-2

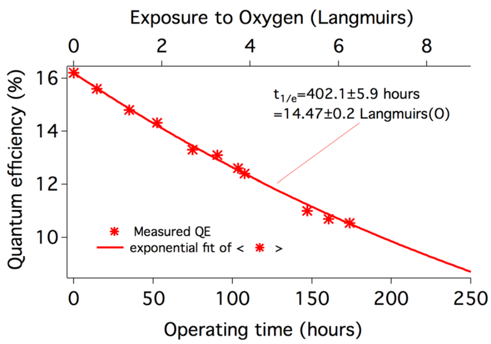

Figure 3: Exponential fit of QE as function of operational time and exposure to oxygen (from [7]).

Besides, cathode sputtering by ion and electrons bombardment is a major concern when running at high average currents. Such effect is generally very large in DC guns, as the static accelerating field captures all the positively charged ions and accelerate them back to the cathode creating dips in QE at the center of the cathode [14]. In our case the accelerating field is oscillating at a frequency of about 186 MHz, and only a small fraction of ions are captured by the field and find their way back to the cathode [15]. The damage rate of ion back-bombardment is proportional to the total pressure in the gun and to the average beam current. We measured cathode lifetime against different average beam currents, and no correlation between QE lifetime and average current was detected within the experimental accuracy upon variation of average current by more than one order of magnitude (from 0.02 mA to 0.3 mA), implying negligible contribution to the degradation by the back-bombardment at such currents and vacuum levels. In particular there was no evidence of locally enhanced degradation due to either bombardment or laser heating, enabling beam operations at the rf center of the cathode. The right plot of Fig.4 gives an example of QE map, taken at the end of the measurement campaign, which shows quasi-uniform QE degradation of the cathode.

RF assisted QE Rejuvenation

It has already been shown [13] that QE degradation can be partially recovered. Such rejuvenation requires heating and illumination with UV light for breaking the strong ionic bonds formed between oxygen and cesium. Consistently with such previous findings we observed a slight increase of QE at the beginning of each run.

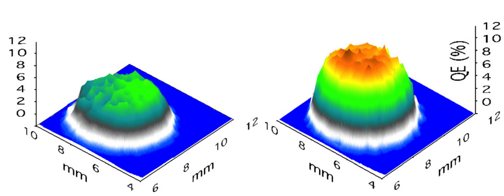

Figure 4: QE degradation after the 3-week shutdown and QE rejuvenation after few hours of gun operation at full power (from [7]).

Quantum efficiency degrades also during machine shutdowns. Without rf power in the cavity oxygen levels are too low for explaining the measured rate of degradation with cathode oxidation. One possible alternative is the formation of weak bonds (Van der Walls-like) between the cathode surface elements and the residual gas molecules in the cavity (expecially water). Such bonds are very weak, with characteristic distances in the range of 0.3-0.6 nm and energies in the 0.2-20 meV range, and an externally applied field of 20MV/m is sufficient to break them apart. QE rejuvenations at the beginning of each restart of APEX gun running were routinely observed, and one example is shown in Fig. 4. The QE at the cathode center before the 3-week shutdown was 11%, while it dropped down to about 5.5% at the restart (left map of Fig. 4). After few hours of operation following the shutdown, it recovered 11% QE as well as the flat QE distribution before the shutdown (right plot of Fig. 4).

Thermal Emittance

Thermal emittance was characterized, by measuring the electron beam size at the first viewscreen as function of the solenoidal lens strength. The emittance of 500 fC beam was measured for different laser spot sizes at the cathode, and a linear regression of the results lead to a value of respectively 0.72 ± 0.07 and 0.79 ± 0.05 $\mu m/mm$ RMS for horizontal and vertical emittances, in line with previous results on the same type of cathode [16].

Cathode Surface Analysis

We have demonstrated negligible correlation of cathode lifetime with average current, and indicated the surface oxidation during operations as the main mechanism of QE degradation. In fact, we experienced another deterioration mechanism: field-emitted electron sputtering.

Some fied emission electrons can be directed toward the cathode plug causing erosion and ejection of atoms from the active film. Others hit the anode walls producing secondary electrons that are then accelerated back at the opposite phase of the field, hitting the cathode [12]. Figure 5-A shows the evolution of iso-QE lines (12%) of a fresh cathode at constant time intervals (5.5 hours) during operations. After a quick degradation of the right side of the cathode the QE stabilizes. The inset of Fig.5-A shows the imaging on a downstream screen of field-emitted distribution at the cathode, after compensation for the solenoid rotation. The field emitters are distributed along the edges of the circular gap between cathode plug and cavity wall, and are concentrated on the right side of the cathode.

Post-mortem analysis of the cathode confirms the cause of asymmetric degradation. Figure 5-B shows interferometric measurements done on the plug. The white inner circle delimits the active region of the plug (deposition area). The macroscopic features of the area include a peak and a valley corresponding to the high and low QE areas of the cathode. The difference in height is on the order of the initial Cs_2Te coating, suggesting reduction of deposited material.

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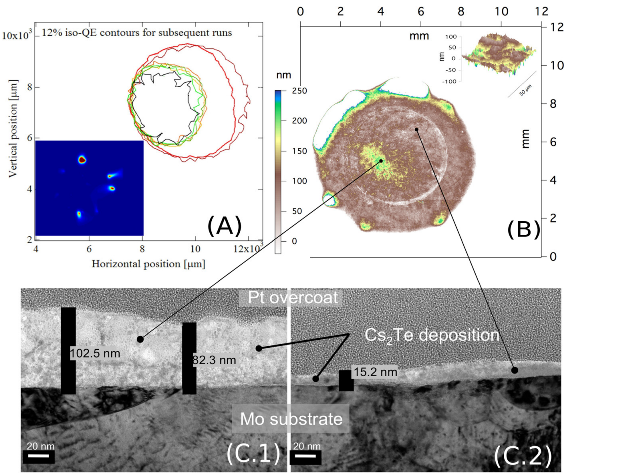

Figure 5: (A) Iso-QE lines during operations. The inset shows the asymmetric distribution of field-emitted particles, imaged at the beamline viewscreen. (B) Post-mortem interferometry on the cathode surface showing asymmetric erosion. The difference between peaks and valleys is at the level of film deposition thickness. (C.1-C.2) Post-mortem TEM measurements of the Cs_2Te layer in the peak and valley as shown in figure (from [7]).

Such hypothesis is confirmed by TEM measurements in Fig. 5-C.1(C.2). Two $5\mu m$-wide samples, chosen from the peak and the valley as shown in the figure, were prepared by Focused Ion Beam lift-out technique and exposed to 200 kV electron beam for imaging. Platinum were deposited on the region of interest to protect from ion implantation and damage of the surface of interest. The large thickness difference of active deposition measured between the two areas explains the difference in quantum efficiency [17]. Such cathodes are grown by deposition of 10 nm of Tellurium and consequent deposition of Cesium by evaporation. About 70 nm of Cesium have been experimentally found to be the optimum for QE, with an atomic ratio between Cs and Te of about 2.5 [13]. We have performed Energy dispersive X-ray spectroscopy on the film to measure the element composition. Nine different point spectra at different locations around the film were measured with 10 and 20 kV beam energies, and an overall mapping using 8 kV beam was performed. Traces of molybdenum (substrate) have been found on all the measurements, as well as small amounts of oxygen and carbon. The atomic percent of Te and Cs varies along the cathode and, while in the high-QE region (lower-right side of the film) the atomic percent ratio Cs/Te is close to 1.5, it rapidly decreases well below 1 moving toward the low-QE region (upper-left side). Such decrease of Cesium on the surface explains the difference in QE between different areas [13], while the asymmetric distribution of field emitted electrons matching the cathode QE map suggests the cause of the degradation speed between different areas of the film to be electron sputtering.

GUN IMPROVEMENTS BENEFIT CATHODE OPERATION

After the Cs_2Te cathode testing, the APEX gun went through a full refurbishment. The mating surface between cathode and anode halves of the cavity showed signs of degradations. In particular the rf spring was damaged in some points due to poor RF contacts. The mating surface was polished and machined again, and the RF spring was substituted with a new one of thicker gold coating, which improved the unloaded Q and thus reduced the RF heat load by 15%. The highest temperature of the anode cavity wall dropped from lim 100°C to ~ 70°C, and the vacuum pressure at nominal gun voltage went from 8×10^{-10} torr to 3×10^{-10} torr. Besides, the cathode/anode region were processed with dry ice cleaning and mirror-like hand polishing, which reduced the transported dark current downstream the APEX beamline from 350 nA to < 0.1 nA at nominal gun voltage, more than 3 orders of magnitude reduction. With the above improvements of the gun, life time of the Cs_2Te cathode is expected to be even longer than the one reported in Fig. 3.

ALKALI ANTIMONIDE CATHODES

Alkali antimonide cathodes are sensitive to green laser, which could simplify the photoinjector driving laser system in terms of power, transverse profile quality, feedback control and diagnostics. Besides, alkali antimonide cathodes have smaller thermal emittance compared with Cs_2Te cathodes [18], which can help in further improving LCLS-II beam emittance. APEX is collaborating with ALS photocathode lab on alkali anotimonide cathode preparation, and antimonide cathode testing results inside APEX gun will help optimize cathode preparation recipe, such as deposition sequence, thickness, roughness et al. Initial testing results have shown QE above 1% for CsK_2Sb inside the APEX gun, and further alkali antimonide cathode testing is still to be done.

CONCLUSION

We have tested two categories of alkali cathodes for continuous operations in high average current electron injectors for the next generation of Free Electron Lasers. The UV sensitive Cs_2Te cathode has been characterized for the first time in a normal conducting CW system providing simultaneous high accelerating fields and mA-scale current. The results demonstrate that such cathodes are robust enough to withstand continuos operations in the APEX-like operating conditions. The green sensitive alkali antimonide cathodes testing is still in progress. The successful blending between the normal conducting APEX VHF gun and semiconductor cathodes opens the doors to a new generation of scientific instruments, as high repetition rate Free Electron Lasers, where peak brightness meets high flux.

ISBN 978-3-95450-134-2

ACKNOWLEDGMENT

The authors would like to thank M. Zolotorev for useful discussions, Russell Wells for the coordination of all mechanical activities that allowed to perform the presented measurements, and D. Sertore for providing the cathodes. The authors acknowledge support from DOE grants No. DE-AC02-05CH11231.

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ISBN 978-3-95450-134-2