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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{cathode}}$ in CW mode</td>
<td>20</td>
<td>MV/m</td>
</tr>
<tr>
<td>$f_{r f}$</td>
<td>185.71</td>
<td>MHz</td>
</tr>
<tr>
<td>$E_k$</td>
<td>758</td>
<td>keV</td>
</tr>
<tr>
<td>Base Pres. rf off</td>
<td>$4 \times 10^{-11}$</td>
<td>Torr</td>
</tr>
<tr>
<td>Base Pres. rf on</td>
<td>$3 \times 10^{-10}$</td>
<td>Torr</td>
</tr>
</tbody>
</table>

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$_2$Te cathode, and second is the green sensitive antimonide cathodes (Cs$_3$Sb and K$_2$CsSb). The Cs$_2$Te 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$_2$Te 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.

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FEL Technology and HW: Gun, RF, Laser, Cathodes
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 ($\sim 300$ 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 1: Cathode tested at APEX phase I beamline.

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 0.1 mA 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.
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 $0.72 \pm 0.07\,\mu m/\mu m$ and $0.79 \pm 0.05\,\mu m/\mu m$ 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 field 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 $Cs_2Fe$ coating, suggesting reduction of deposited material.

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**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.

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

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

After the $C_s^2Te$ 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 $8 \times 10^{-10}$ torr to $3 \times 10^{-10}$ 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 $C_s^2Te$ 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 $C_s^2Te$ cathodes [18], which can help in further improving LCLS-II beam emittance. APEX is collaborating with ALS photocathode lab on alkali antimonide 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 $C_sK_s^2Sb$ 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 $C_s^2Te$ 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.
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REFERENCES