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COPPER PHOTOCATHODES FOR THE MODIFIED 10 HZ GUN ON THE CLARA ACCELERATOR

T.C.Q. Noakes†, L.B. Jones, F. Jackson, J. Jones, B.L. Militsyn, D. Angal-Kalinin, A. Vick
R. Valizadeh, A.N. Hannah, K.J. Middleman, A. Gilfellon, K. Morrow, M.D. Roper
ASTeC, STFC Daresbury Laboratory, Sci-Tech Daresbury, Warrington, WA4 4AD, UK and
Cockcroft Institute of Accelerator Science, Sci-Tech Daresbury, WA4 4AD, UK

Abstract

From November 2019 to April 2022 the CLARA accelerator at STFC Daresbury Laboratory ran with a 2.5 cell 10 Hz S-band RF gun. Previously this gun used a solid wall back plate that also acted as the photocathode, but it now has a modified back plate compatible with INFN-style photocathode pucks, allowing a greater range of materials and surface preparation techniques to be explored. This paper describes the different photocathodes that were used and the various methods employed to prepare them. An initial cathode, based on a solid Mo puck with a thin film of Cu grown using magnetron sputtering, was seen to give high initial quantum efficiency (QE) but a very fast degradation rate. Subsequent cathodes were hybrids with a Mo body and a solid Cu tip for the active area. Several cathodes were prepared using alternative techniques giving varied initial QE and lifetime. The final cathode had satisfactory QE and a long enough lifetime to deliver a six month period of beam exploitation for external facility users.

INTRODUCTION

The VELA and CLARA front end [1] accelerators have operated at STFC Daresbury Laboratory since 2013 and have employed a 10 Hz 2.5 cell S-band gun which originally had a solid copper back plate acting as the photocathode. A summary of the performance of the variously prepared photocathodes was presented at IPAC18 [2]. In 2018 the gun was modified to include a new back plate with an interchangeable photocathode (Fig. 1) and load-lock system [3] based on the long established INFN/DESY puck design. This paper presents the performance data for the various cathodes that have been used in this modified gun.

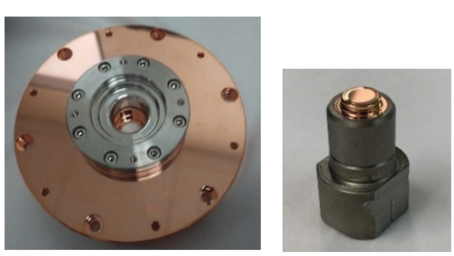

Figure 1: Modified back plate for the 10 Hz gun with INFN-style photocathode puck

PHOTOCATHODES

The various photocathodes used (summarised in Table 1) were characterised in several different ways.

Surface roughness measurements were made using optical interferometric methods [4]. Cathode roughness is an important parameter, since it is likely to be linked to dark current due to field emission from the surface. Typically, the surface roughness achieved is determined by the techniques (such as turning, polishing and chemical treatment) used in surface preparation.

QE is determined through measurement of laser power on a diode close to the end of the optical path that receives a known percentage of the total UV (266 nm) laser flux and the generated beam current measured from a wall current monitor close to the exit from the gun. The normal procedure is to make measurements at a range of laser intensities starting at low beam current and proceeding to higher current and then fitting the linear portion of the plot at the lower end of the beam current range to determine the QE from the slope thus avoiding the space charge limited emission region.

Measurements of QE were made regularly during operations so that the lifetime of the cathodes could be determined. Here a 1/e lifetime has been calculated and whilst this parameter is strictly more appropriate for semiconductor cathodes where degradation is related to contamination from residual gasses, it does provide a useful comparative number. Of course, in the real world the actual lifetime is determined by how long the cathode QE remains high enough to provide the required charge for use (typically 100 nC for CLARA operations) and is generally higher by a factor of 2 to 3.

Dark current measurements are also an important way of characterising photocathode performance and have been made using the wall current monitor in low charge measurement mode. However, even in this mode measurements can become challenging when the current is very low. In addition, these measurements have often been made for different RF power levels giving different fields on the cathode and varied settings of the gun and bucking coil solenoids which makes comparison difficult. Screen images of the dark current on a YAG screen immediately following the wall current monitor have also been collected.

Finally, the tune temperature of the gun has been noted for each cathode (and for different insertions of the same cathode). This temperature is that required to minimise the reflected power from the gun. This parameter is particularly important for the hybrid cathodes where the mounting of the copper insert can give rise to some tip length uncertainty. Where the tip does not protrude into the cavity by the correct amount, this will give rise to incorrect field flatness in the gun and potentially higher fields around the interface between the back plate rim and the insertable photocathode itself.

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Table 1: Summary of Cathodes Used

Cathode number and dates	Cathode Type	Surface Roughness (S_a)	Tune Temperature	Initial QE	1/e Lifetime	Comments
#6 (27/11/2019 to 29/01/2020)	Mo	112.8 nm	31.5˚C			RF conditioning cathode, high dark current
#13 (29/01/2020 to 14/02/2020)	Thin Film Cu	74.5 nm		6×10^{-5}	3.26 days	Good initial QE but decayed rapidly
#13 (12/02/2020)	Thin Film Cu	74.5 nm			0.28 days	Reactivated by heat cleaning to 250˚C, degraded in less than a day
#7 (14/02/2020 to (16/03/2020	Hybrid Mo/Cu	56.9 nm	34.0˚C, 33.6˚C	8×10^{-5}	15.0 days	BPS172 cleaned, high initial QE but still decayed fast
#7 (01/10/2020 to 21/10/2020)	Hybrid Mo/Cu	56.9 nm	34.0˚C	2×10^{-5}		Reinserted after Covid shutdown but only gave low QE
#16 (26/10/2020 to 22/11/2020)	Hybrid Mo/Cu	5.7 nm	33.5˚C	2×10^{-4}	32.7 days	Diamond turned, O plasma treated then centre cleaned with BPS172
#16 13/05/2021 to 01/07/2021)	Hybrid Mo/Cu	5.7 nm		2×10^{-4}	63.7 days	As above but after 6 month shut down for RF waveguide problems
#22 (01/07/2021 to 29/04/2022)	Hybrid Mo/Cu	4.3 nm	31.7˚C	7×10^{-5}	270 days	0.2 mm longer length, off-centre turned, Ar plasma & 250˚C treatment

Molybdenum Conditioning Cathode (#6)

The first solid molybdenum cathode used in the gun was solely intended for RF conditioning. This cathode was seen to have a tune temperature of 31.5˚C, close to the ideal temperature of 30.7˚C. Unfortunately, very high dark current (> 10 nC per pulse) was observed during conditioning potentially as a result of the very rough surface finish which was measured at 112.8 nm (S_a). In future RF conditioning will be carried out with cathodes having a smoother surface finish to try to avoid this problem.

Thin Film Copper Cathode (#13)

The first active photocathode to be used in the modified gun was a thin film copper photocathode that was prepared in the Metal Photocathode Preparation Facility (MPPF) which is based on an ESCALAB-II X-ray Photoelectron Spectroscopy (XPS) instrument with a dedicated deposition chamber attached. Two magnetron sputtering sources are incorporated, one with copper and another with magnesium. Although magnesium thin film photocathodes were also prepared in this facility only copper thin film samples were tested in the CLARA accelerator.

The thin film photocathode was grown on a solid molybdenum puck. Initial growth experiments gave a matt finish that appeared to be very rough but subsequent samples had improved finish, possibly as a result of the sources having less contamination with continued use or through refinement of the growth conditions (for example sputter gas pressure). The sample used in the photoinjector had a roughness of 74.5 nm, which is an improvement on the conditioning cathode. Whilst this cathode gave a good initial QE of 6×10^{-5} it was seen to decay rapidly with a lifetime of only 3.26 days. An attempt was made to reactivate this cathode by heat treating to 250˚C using the new heater stage incorporated into the load lock system of the modified gun. However, whilst this did restore the QE to 4×10^{-5} it decayed even more rapidly with a lifetime of less than a day.

First Hybrid Molybdenum/Copper Photocathode (#7)

Since there were no further copper thin film cathodes prepared a decision was taken to test a two-part hybrid photocathode with a molybdenum body and a copper tip. One potential issue with this type of cathode is the difference in the coefficient of thermal expansion between the two metals. Finite element analysis thermal calculations indicated that any temperature treatment should not exceed 150˚C but tests using spare molybdenum/copper hybrid cathodes suggested that temperatures up to 250˚C might be acceptable with minimum distortion of the copper insert. The hybrid cathodes could therefore be prepared using the same techniques employed for the solid back wall cathodes used before the gun upgrade [2].

The first cathode of this type to be used in the gun had a relatively poor surface finish of 56.9 nm (S_a). It was prepared using a chemical treatment (BPS172) which has been seen to give good QE after only a modest anneal in vacuum (120˚C) [5]. Whilst the initial QE was very good at around 3×10^{-4} again the lifetime was limited losing over 10 % in QE each day. After a long shut down due to the Covid pandemic accelerator operations recommenced and the QE was seen to have dropped to 2×10^{-5}. Throughout its use this cathode exhibited a high dark current of > 2 nC per pulse which could potentially play a role in the degradation process through electron stimulated desorption of gas within the gun cavity.

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On-Axis Turned Hybrid Molybdenum/Copper Photocathode (#16)

To try to reduce dark current, diamond turned copper inserts were prepared using a new capability at STFC Rutherford Appleton Laboratory. The first batch of inserts prepared had very low roughness over the majority of the surface (S_a of 5.7 nm) but unfortunately with a large spike in the centre from on-axis turning. Whilst off-axis turned inserts were requested, they could not be manufactured until a time later than that needed for CLARA operations and so a decision to use an on-axis turned insert was made.

As another potential strategy to reduce dark current a modified treatment procedure was employed where the cathode was initially oxygen plasma treated to leave a high work function oxide surface and then a small area at the centre of the cathode treated with BPS172 which could then be activated by heating to 150˚C without activating the rest of the copper insert, particularly the rim of the cathode where it meets the edge of the modified back plate. This photocathode produced an initial QE of 2×10^{-4} and had a lifetime of 32.7 days.

Following another shut down of several months, this time caused by RF waveguide issues, the cathode was reinserted into the gun and achieved a QE just above 2×10^{-4} which was slightly higher than when the cathode was newly prepared. However, during the shutdown significant amounts of work had been carried out on the laser system including re-steering the beam, so there is a possibility that the apparent improvement in QE was actually caused by using a higher reflectivity part of the in-vacuum light box mirror the performance of which has been seen to degrade during previous runs. The lifetime of the reinserted photocathode also appeared to increase to 63.7 days. However, the amount of dark current seen for this cathode remained high starting at a few nC but falling to about 600 pC by the end of its use. This compares to < 100 pC for the gun with a solid wall back plate photocathode, although the measurements were not necessarily taken under the same conditions.

Figure 2: Oxygen plasma and BPS172 treated cathode with dull ring around the active area.

On removal of the photocathode it was seen that there was a dull ring around the active area of the cathode (Fig. 2). This ring could possibly be a rougher area at the interface between the oxygen plasma treated surface and the central BPS172 treated area but is more likely to be composed of oxalic acid crystallites since this is the main active constituent of BPS172. This dull ring could itself lead to greater dark current.

It had been noticed that the tune temperature of this cathode and the previous hybrid were significantly higher than the ideal with an average discrepancy of 2.8˚C. This corresponds to a frequency shift of 140 kHz which in turn implies that the cathode tip might be around 0.2 mm too short. This would result in a higher field on the cathode and back plate that could also lead to an increase in dark current.

Off-Axis Turned Over-Length Hybrid Molybdenum/Copper Photocathode (#22)

The final cathode used in the CLARA gun during this run was a hybrid molybdenum/copper, off-axis turned and a 0.2 mm longer tip length. This cathode was prepared using argon plasma cleaning, which is essentially a less aggressive version of oxygen plasma treatment [6]. The surface finish of this cathode was excellent at 4.3 nm roughness and the tune temperature was much closer to the ideal temperature. The initial QE from this photocathode was 7×10^{-5} which while lower than the previous cathode was expected from previous studies of the different surface treatments used [5]. The initial dark current from this cathode was significantly reduced (at around 250 pC per pulse) and continued to fall with use. This cathode had a long 1/e lifetime of 270 days and was used to successfully deliver a 6 month period of beam exploitation experiments for external users of the CLARA accelerator.

DISCUSSION AND CONCLUSIONS

Throughout the course of this CLARA run a gradual improvement in photocathode lifetimes was seen. Whilst it is tempting to ascribe to improvements in the preparation techniques used it is also possible that much of this came from the fact that the gun conditioning improved progressively during the run. This would lead to the number and frequency of breakdown events involving spikes in the recorded vacuum system pressure, to decrease which could improve the lifetime. For that reason, it would be unwise to conclude that some of the cathodes with low lifetime evaluated early in the run could not have delivered reasonable performance if used once the gun cavity had become better conditioned. In particular, it would be good to re-evaluate thin film cathodes since this technology offers flexibility in terms of the different materials that could be deposited and then tested.

Attempts to supress dark current by passivation with oxygen plasma treatment and then selective activation with BPS172 and heating were not successful. However, it was clear that this procedure could be repeated in a better way, ensuring the removal of all chemical contamination from the surface, so it might be good to re-evaluate this idea experimentally at some point in the future.

Finally, it is likely that at least some of the improvement seen was due to better surface preparation procedures, in particular the decreasing surface roughness (diamond turning of photocathodes has been previously shown to reduce dark current [7]). Reducing roughness reduces the number of field enhanced breakdown events and with them the number of pressure spikes and hence should lead to improved lifetimes assuming that poor vacuum conditions do negatively affect them.

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REFERENCES

[1] D. Angal-Kalinin *et al.*, "Design specifications, and first beam measurements of the compact linear accelerator for research and applications front end", *Phys. Rev. Accel. Beams*, 23, 044801, Apr 2020. doi:10.1103/PhysRevAccelBeams.23.044801

[2] T. C. Q. Noakes *et al*., "Photocathode preparation and characterisation of the electron source for the VELA/CLARA facility", in *Proc. IPAC'18*, Vancouver, BC, Canada, May 2018, THPMK063. doi:10.18429/JACoW-IPAC2018-THPMK063

[3] B.L. Militsyn *et al.*, "Operation of the CLARA linear accelerator injector with 2.5 cell 10 Hz photocathode gun with interchangeable photocathodes", *in Proc. LINAC2022,* Liverpool, UK, 2022, THPORI15. doi:10.18429/JACoW-LINAC2022-THPORI15

[4] R. Valizadeh *et al*., "Preparation of the Polycrystalline Copper Photocathodes for the VELA RF Photocathode Gun", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper MOPFI069, pp. 440-442.

[5] A. N. Hannah *et al*., "Metal Photocathodes Preparation for Compact Linear Accelerator at Daresbury Laboratory", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 3865-3868. doi:10.18429/JACoW-IPAC2018-THPAL095

[6] T.C.Q. Noakes *et al.*, "Oxygen plasma cleaning of copper for photocathode applications: a MEIS and XPS study" *Vacuum* 205, 111424, Nov 2022. doi:10.1016/j.vacuum.2022.111424

[7] J. Sciffo *et al.*, "Nano-machining, surface analysisand emittance measurements of a copper photocathode at SPARC_LAB" *Nucl. Instrum. Methods Phys. A,* 909, 233, Jan 2018. doi: 10.48550/arXiv.1801.03823