DELIVERY OF CAESIUM TELLURIDE PHOTOCATHODES TO THE CLARA ACCELERATOR AT DARESBURY LABORATORY

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Abstract

High performance electron accelerators require high brightness electron beams. To achieve this a photocathode with a high quantum efficiency (QE) and low intrinsic emittance is required while also being robust with a long lifetime and low dark current. Photocathodes based on alkali metals can fulfil these requirements and, as such, are an important area of research for the accelerator physics community.

The Compact Linear Accelerator for Research and Applications (CLARA) at STFC Daresbury Laboratory has recently been upgraded from a copper photocathode to a caesium telluride photocathode. This has enabled a significant increase in bunch charge for a fraction of the laser power. We discuss the process of manufacturing and polishing molybdenum photocathode plugs and the subsequent deposition of caesium telluride thin films. Three photocathodes have been provided to the CLARA facility with consistent and high quantum efficiency. One of these photocathodes has been successfully operating in CLARA since September 2025 with a stable QE of approximately 11 %.

INTRODUCTION

The Compact Linear Accelerator for Research and Applications (CLARA) at Daresbury Laboratory is a state-of-the-art medium energy electron linear accelerator that has recently been commissioned [1, 2]. CLARA has previously been operated using a copper photocathode; however, in order to achieve its intended design specifications of 250 MeV/c 250 pC bunches at 100 Hz repetition rate CLARA has been upgraded to a caesium telluride photocathode.

Caesium telluride has been a photocathode of choice in the accelerator community for many years and is widely used in accelerators across the world [3]. This is due to its high quantum efficiency (QE) and low intrinsic emittance while simultaneously being robust enough the survive the vacuum conditions of a radio frequency (RF) photoinjector, allowing many months, if not years, of operation using one photocathode.

We detail the manufacturing and polishing of three molybdenum plugs and the subsequent deposition of a caesium telluride thin film on each photocathode, before highlighting some key performance data of one of these photocathodes that has been operating in CLARA since September 2025.

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PHOTOCATHODE PLUG MANUFACTURE

Machining and Polishing

The CLARA accelerator uses a modified 'INFN-style' photocathode plug similar to those used by many accelerators around the world, including the LCLS-II and the EuXFEL [4, 5]. Two pieces of high-purity sintered molybdenum bar (Mo) were supplied to Abelco GmbH, one from Goodfellow (99.9 % purity) and one from WHS Sondermetalle (99.95 % purity, type 361SR). Abelco manufactured three plugs from each piece of material with initial hand polishing carried out by them using Micromesh abrasive pads from 1500 grade up to 12000 grade.

Fine polishing of the photocathode tips was carried out at DESY Hamburg using the process developed for the EuXFEL photocathodes. This involved an initial IPA clean and vacuum bake for outgassing consisting of a 3 hour controlled ramp to 950 °C, a 3 hour soak at 950 °C and finally an uncontrolled 3 hour cool down to ambient temperature. The baking profile only commenced once the pressure inside the oven had fallen to $< 1 \times 10^{-5}$ mbar. The actual pressure through the soaking and cooling stages was $< 1 \times 10^{-6}$ mbar.

Polishing was carried out with a Streurs TegraPol-21. This has a 6-plug carousel, so was loaded with three blanks to separate the polishing of the different photocathode material batches and avoid any cross-contamination. Polishing was achieved in five steps commencing with Buehler MetaDi Mono Suspension 9 micron polishing grit (coarse) and progressing to a Buehler MetaDi Mono Suspension 0.05 micron (super-fine) grit, with the steps repeated as necessary in order to achieve the required level of surface roughness. The acceptable finish criteria was a reflectance of > 57 % at 532 nm. All 6 of the polished photocathodes attained reflectivity levels of ~63 %, but following careful visual inspection using a x6 magnified eyepiece, 3 were rejected due to the presence of surface defects assumed to be pits linked to the sintered nature of the original source material manufacture. The 3 plugs which were judged to be acceptable for use in the CLARA photoinjector were numbered 033 which originated from the Goodfellow batch, and 034 & 036 which originated from the WHS Sondermetalle batch.

Surface Imaging and Roughness

Upon receipt at Daresbury laboratory, high resolution surface images of the photocathode surfaces were taken using a Keyence VHX-7000 microscope. Figure 1 shows an example image of photocathode 034 at 50x magnification

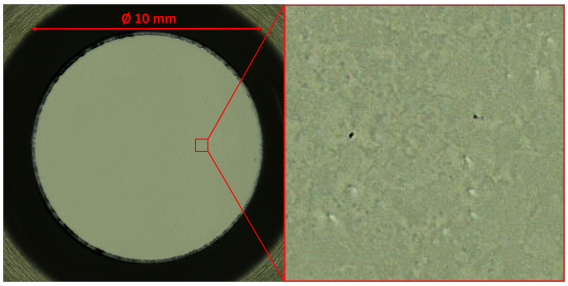


Figure 1: 50x magnification image of the photocathode 034 plug highlighting the presence of pit-like features.

with full coaxial lighting. These images reveal that every plug had very small surface features assumed to be pits that could not be seen using the x6 magnified eyepiece.

Surface roughness measurements were taken using a SmartWLI white light interferometer with a 50x objective lens. For each photocathode thirty 8750 µm^2 images were taken across the plug diameter and average root mean square (RMS) and arithmetic roughness values for each photocathode were computed. These are summarised in Table 1 and an example image for photocathode 034 is shown in Fig. 2. The SmartWLI measurements also showed evidence of pitting, validating our interpretation of the Keyence images.

Table 1: RMS (S_q) and Arithmetic (S_a) Surface Roughness of the Polished Photocathode Plug Surfaces

Photo-cathode	S_q [nm]		S_a [nm]	
	Average	Std. Dev.	Average	Std. Dev.
033	30.5	8.2	23.8	6.1
034	31.2	18.5	22.3	12.5
036	26.5	11.0	21.0	9.0

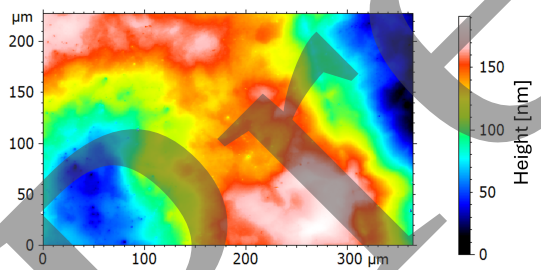


Figure 2: A SmartWLI image for photocathode 034.

PHOTOCATHODE DEPOSITION

Alkali-metal Photocathode Preparation Facility

Caesium telluride was deposited in the Alkali-metal Photocathode Preparation Facility (APPF) at Daresbury Laboratory [6]. The base pressure was ~3 × 10^{-10} mbar with pressures typically rising to the low 10^{-9} mbar regime during depositions. Resistive heating and argon ion bombardment provided sample cleaning. Tellurium with 5N purity was deposited from a 235 °C Knudsen cell with a 300 °C hotlip and caesium was deposited from a 615 °C Knudsen cell loaded with SAES Alkamax pills. Tellurium flux was monitored using a Inficon quartz crystal microbalance (QCM). The sample was biased at −18 V and illuminated using a modulated 265 nm Roithner LaserTechnik LED driven at a constant 20.06 mA. Sample photocurrent was measured using a RBD Instruments 9103 picoammeter. The LED was slowly pulsed during the caesium deposition then ran continuously once the deposition stopped. Images before, during and after the deposition were taken using a Ximea XiQ USB camera with internal lighting from two 20 W halogen bulbs.

Photocathode Growth

The three photocathodes were ultrasonic IPA cleaned and dried with dry nitrogen before being loaded into a vacuum suitcase. The suitcase was pumped and baked, achieving a pressure in the XHV range (< 2 × 10^{-11} mbar). Three caesium telluride films were deposited onto photocathodes 033, 036 and 034, in that order. Prior to deposition each cathode was resistively heated at ~39 W for 75 minutes. A thermocouple temperature of ~370 °C was reached although it is important to note that the true photocathode temperature will be different. During the cool down each photocathode underwent a 20 minute 500 eV 12.5 µA argon ion bombardment to remove any residual contaminants.

The cathodes were kept at room temperature throughout the tellurium and caesium depositions. 10 nm of tellurium, according to the QCM, was deposited at ~0.035 Å s^{-1}. The rate was checked before and after the deposition and timings were adjusted accordingly to reach 10 nm.

Caesium was deposited for between 4 and 6 hours until the photocurrent peaked and started to noticeably decrease. As the caesium cell temperature was not adjusted from growth to growth, the caesium flux slowly decreased and, as such, the deposition time increased for each subsequent photocathode. Figure 3 shows the measured photocurrent from each photocathode during the caesium deposition and its subsequent evolution over the following 10 to 15 hours once the deposition was stopped - marked as ‘a’ on the curve. ‘b’ denotes when the LED was switched from a pulsed to continuous mode resulting in a drop in power and photocurrent. The shape of the photocurrent response was consistent across all three photocathodes, including the early growth stage, which is highlighted in the insert of Fig. 3. The peak photocurrent reached was broadly similar for each photocathode with any discrepancy likely due to a combination of fine variations in composition and differing alignment with the LED spot. After 20 hours the final photocurrent readings were 348 nA, 340 nA, and 338 nA, for photocathodes 033, 034, and 036 respectively. Figure 4 shows post deposition images taken under similar lighting, position and camera settings. All three photocathodes exhibit the same blue colour. The consistent growth profile, and similar final photocurrent and colours, points to three highly similar Cs-Te films being deposited. The exact chemical composition, surface roughness, and QE of the Cs-Te films was not analysed due to time and equipment constraints.

Post growth each photocathode was transferred to the vacuum suitcase and stored under XHV conditions.

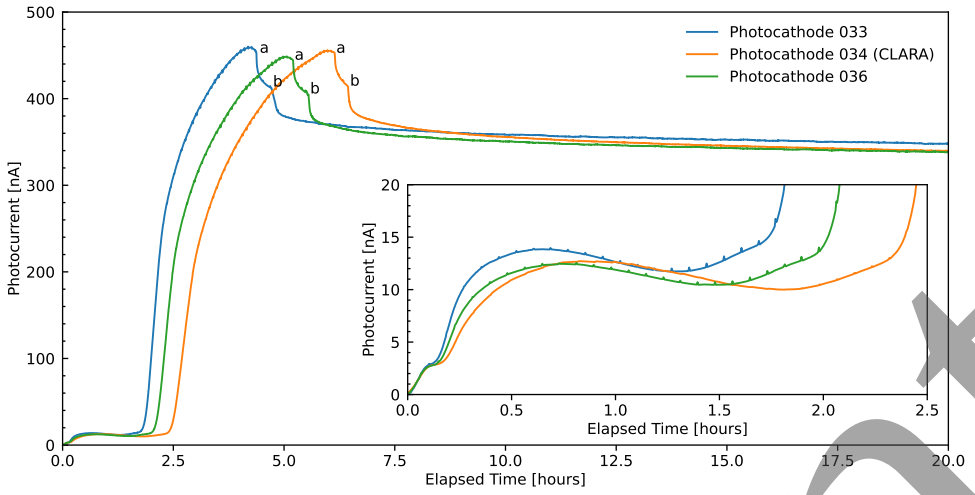
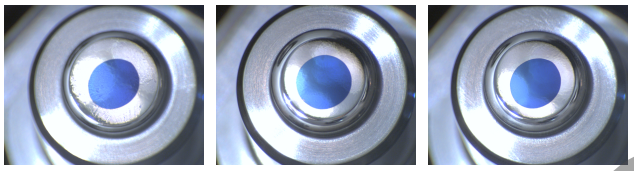


Figure 3: Evolution of the photocathode photocurrent during the caesium deposition for photocathodes 033, 034, and 036. 'a' denotes the end of the caesium deposition and 'b' denotes the switching of the incident LED from pulsed to continuous operation. Insert: A close-up of the first 2.5 hours of deposition.



(a) Photocathode 033 (b) Photocathode 034 (c) Photocathode 036

Figure 4: Post deposition images under similar lighting conditions and camera settings.

OPERATION IN CLARA

In September 2025, photocathode 034 was loaded into CLARA. During RF conditioning, surface defects were seen to appear on the photocathode surface. These are discussed in more detail in Ref. [7]. Despite this, the QE of the photocathode has remained high allowing the 266 nm CLARA drive laser to be modified to deliver ~0.009 µJ per pulse, down from ~2.268 µJ when operating with the previous copper photocathode. This increased headroom opens the door to implementing laser pulse shaping techniques in future. The effective QE after RF conditioning, as measured on the first Faraday cup, is shown in Fig. 5. It has remained stable at approximately 11 % with the observed variations likely a result of non-optimal beam transport. The evolution of the QE will be closely monitored in future. Dark current levels are acceptable; ~100 pC with a 1.25 µs RF pulse and a 87 MV/m field at the photocathode using standard gun solenoid settings [8]. A 0.7 µm rad normalised emittance with a 250 pC 35 MeV/c beam after the first linac has been consistently measured [2].

CONCLUSION

We have successfully provided a caesium telluride photocathode to the CLARA accelerator at Daresbury laboratory. Three photocathode plugs were manufactured and polished to a good RMS surface roughness of ~30 nm, although very small pits were noticed across all the photocathode plugs. A caesium telluride film was deposited onto each photocathode plug using a room temperature sequential deposition method. The final photocurrent achieved, the film colour and the growth profile was consistent across all three depositions. Photocathode 034 has been operating successfully in CLARA since September 2025 maintaining a consistent and stable QE of approximately 11 %.

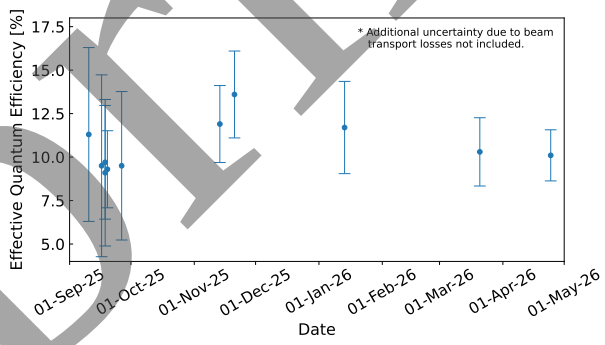


Figure 5: Effective quantum efficiency of photocathode 034 over time inside the CLARA photoinjector showing a stable quantum efficiency of approximately 11 %.

The performance of the photocathode 034 will continue to be monitored. Meanwhile, further R&D work is planned to improve the the quality of the Cs-Te film deposited. These techniques may include heated depositions, multilayer depositions and co-deposition recipes.

ACKNOWLEDGMENTS

The authors would like to acknowledge and thank DESY Hamburg, and in particular, Mario Lengkeit for sharing their knowledge and extending the use of their facilities for the polishing of the CLARA photocathode plugs.

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