

EVIDENCE FOR RF BREAKDOWNS CAUSING SURFACE ANOMALIES ON CAESIUM TELLURIDE CATHODES AT CLARA

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Abstract

The Compact Linear Accelerator for Research and Applications (CLARA) at Daresbury Laboratory has recently undertaken an upgrade of its photocathodes from using a copper emission surface to using caesium telluride (Cs_2Te). During the conditioning of the first Cs_2Te cathode a significant number of RF breakdowns were detected, and so that cathode was replaced; subsequent inspection of the cathode identified a number of surface defects. To better study the second cathode, a diagnostic camera was used to collect images of the surface *in situ* during RF conditioning; the frequent formation over time of surface defects was observed. In this paper we present a statistical analysis of the breakdown events and surface image data, utilizing cross-correlation of the signal derivatives to account for cumulative trends. The analysis reveals a correlation between the rate of defect formation and the incidence of RF breakdowns, with a Pearson coefficient of $r = 0.59$ at zero time lag. These results provide quantitative evidence that RF breakdown events are the likely driver of surface morphology changes on Cs_2Te cathodes.

INTRODUCTION

Caesium Telluride Cathodes at CLARA

Copper is a simple yet robust photocathode with limited quantum efficiency (QE) of approximately 2×10^{-4} under illumination at 266 nm, while Cs_2Te is somewhat less robust but offers QE typically in the region of 10–20% at 266 nm; Cs_2Te is therefore commonly used in high-brightness electron sources to deliver electron bunch charges in the nC range, for example in photoinjectors for free-electron lasers (FELs). The CLARA [1] photoinjector [2] is a test-bed for novel high-brightness applications, and its electron source was recently upgraded from using a Cu emitting surface [3,4] to using Cs_2Te . The Cs_2Te photocathodes developed for CLARA were manufactured by sequential Cs and Te deposition onto polished molybdenum (Mo) substrates (INFN-style photocathode plugs), carried out at room temperature using our dedicated offline Alkali metal Photocathode Preparation Facility (APPF) deposition system [5]. Early photocathode plugs obtained QE around 5%, increasing to typically ~15% as the deposition process was refined [6]. Transitioning CLARA to regular use of Cs_2Te allows the drive laser power to be reduced, due to the much-increased QE of Cs_2Te compared to Cu. Prior to the use of Cs_2Te , CLARA

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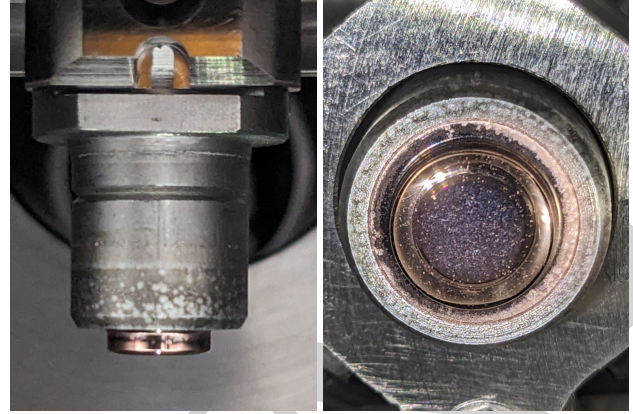


Figure 1: Photocathode #020 (Cu) on removal from the CLARA photoinjector.

operated for 2 years using a similar Cu-tipped hybrid Mo/Cu photocathode plug (reference #020 in our series of production). Upon its removal it was noted that the Cu cathode surface was significantly marked and pitted as shown in Fig. 1 (when photographed under white light with the cathode located in the gun load-lock storage chamber), with additional marking and discolouration evident on the edge of the plug between the tip and RF spring contact area. This morphology is somewhat similar to cathodes examined elsewhere, and is perhaps caused by breakdowns occurring on the cathode surface over extended periods of operation.

For Cs_2Te deposition, nine Mo plugs were manufactured by Abelco GmbH from a variety of sintered Mo stock material, then polished with the assistance of DESY (Hamburg) to attain surface finishes with measured reflectivity of $> 57\%$ at 532 nm. All plugs met this surface finish criteria, though several plugs retained very-small visible surface feature, believed to be pits associated with the sintered nature of

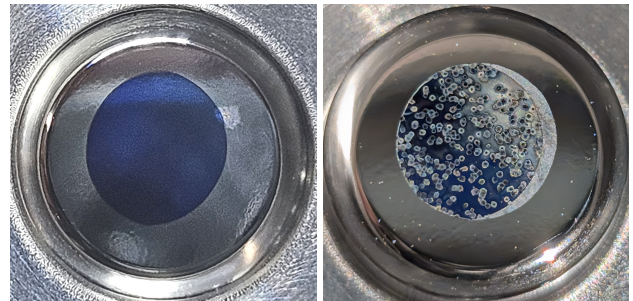


Figure 2: Photocathode #036 (Cs_2Te) as-deposited (left) and on removal from the CLARA photoinjector after 3 days of RF conditioning (right).

the source material. Two plugs utilising Mo sourced from WHS Sondermetalle were selected as having suitable surface quality (determined by areal surface roughness, see [6] for details) for Cs₂Te deposition (plug serial #034 and #036). After Cs₂Te deposition both cathodes #034 and #036 exhibited similar low-field QE around 18 % at 266 nm. These cathodes were transferred using a UHV vacuum suitcase into the CLARA photoinjector gun load-lock system. After RF conditioning for many hours at 10 Hz and 100 Hz pulse repetition rates at RF pulse lengths up to 1.25 μ s, both cathodes exhibited nearly-constant high-field QE of around 11 %. This is consistent with the QE loss that might be expected from photocathode plug transfer handling, but a precise comparison is not possible since the QE measured in the CLARA gun occurs at a high surface electric field around 90 MV/m, and therefore will be augmented by Schottky barrier lowering [7].

Cathode Degradation

Several accelerator facilities have reported the emergence of surface patterning after long-term photocathode operation in an RF gun. Argonne National Laboratory employ a different cathode plug design to the INFN variant in their AWA driver and apply a somewhat lower peak electric field gradient at the cathode surface (85 MV/m as compared to 90 - 120 MV/m in CLARA). Following replacement, post-mortem analysis of an AWA photocathode indicated that the photoemissive layer may be damaged or even completely removed back to the molybdenum plug substrate [8]. At CLARA, similar morphology changes were observed on cathode #036 after an abbreviated run in September 2025 that was characterized by frequent RF breakdowns, as can be seen in Fig. 2. Following this, cathode #034 was installed and a camera used to monitor the formation of surface changes under the application of RF (using LED illumination reflected from a nearby YAG diagnostic screen to illuminate the cathode surface), whilst also recording the occurrence of vacuum events and RF trace violations; vacuum events are often associated with RF breakdowns at or near the cathode. Successive images were captured of the evolving cathode surface, which were then image-processed to identify and count the emergence of surface defect features. While it has been hypothesized [8] that the appearance of cathode surface defects is linked to breakdown events, empirical evidence is scarce. Chemical analysis suggests that Cs₂Te may degrade into elemental tellurium clusters over time during operation in high-gradient RF guns [9]. Given that this degradation is energetically favourable, it is suggested that the localized energy deposition from an RF breakdown provides the necessary activation energy to trigger either phase transition or material migration. Below we argue that there is a temporal correlation between breakdown events and defect formation which, in combination with a proposed mechanism of cathode material change, offers an explanation for the degradation in QE observed across various Cs₂Te installations.

IMAGING METHODOLOGY

Imaging of the CLARA cathode was performed using a diagnostic camera originally intended to assist cathode insertion. To illuminate the cathode surface an additional LED was mounted on a YAG screen stage around 1m from the cathode, giving just sufficient lighting for surface details to be observed. To compensate for the non-ideal lighting conditions, batches of 19 images were taken whilst the stage providing the lighting was moved. Image collection took 5 minutes and was performed hourly for the first week of RF conditioning, and then daily for the following week. This series of images was then cropped, masked, and normalised as shown in Fig. 3. To identify the defects from the cathode under varying lighting conditions, we apply Robust Principal Component Analysis (RPCA) [10]. RPCA decomposes a matrix M into low-rank (L) and high-rank (S) components such that $M = L + S$. Unlike traditional PCA, which is sensitive to large outliers because it minimizes the L_2 norm, RPCA achieves robustness by solving the convex optimization problem Principal Component Pursuit (PCP). This involves minimizing a weighted combination of the nuclear norm of L (to enforce low rank) and the L_1 norm of S (to enforce sparsity), expressed as

$$\min_{L,S} \|L\|_* + \lambda \|S\|_1 \text{ subject to } L + S = M. \quad (1)$$

Applied to a set of images I , L_n contains the background element contribution common to all images for image I_n , and S_n contains the changing elements of image I_n . Applied to the collection of cathode images under varying lighting, the L matrix contains the cathode features (including defects) while the S matrix contains the noise and lighting features as in Fig. 3. This pipeline results in an array of low-rank cathode images for each sample time of gun operation, which we take the mean of to produce a final image for that sample.

Computer Vision (CV) approaches to identify and count the number of defects in an image, including the use of OpenCV-based Hough Circle Transforms, proved unreliable due to the poor and varied lighting and complex reflections in the images. Instead, manual counting was used: via a simple web application, users identified defects on a given processed cathode image, marking the position of each defect. Cathode images were presented to users in random time order to avoid bias, and results were associated with each user to allow later analysis of bias differences between the users. The data set here comprised 96 images, with several users typically analysing a given image. To analyse the relationship between breakdowns and defects, we compared the cumulative count of RF breakdowns (detected by a trace violation detected by breakdown detector) against the count of surface surface defects. Because both datasets are naturally monotonic and cumulative, a simple correlation analysis is meaningless. Instead, to extract the underlying relationship we calculated the first difference of each dataset, representing the rate of change, and performed a cross-correlation analysis.

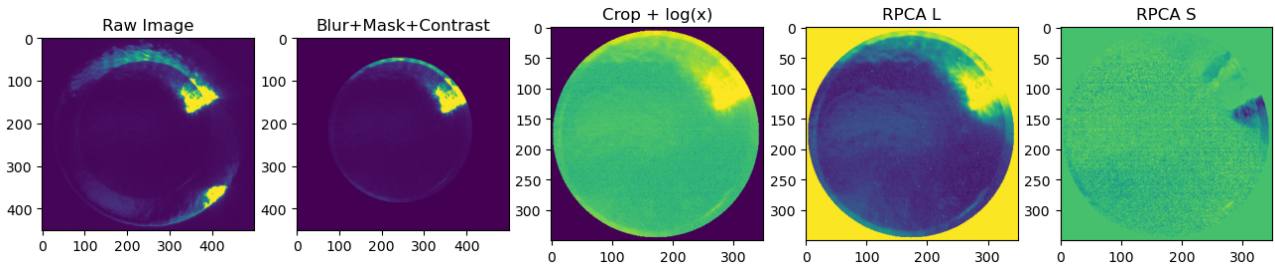


Figure 3: Steps of the image processing pipeline, progressing from left to right. Images were captured in batches of 19 each with varying lighting position. Each image is then Gaussian blurred to reduce pixel-level noise, masked to include only the surface of the cathode, and then contrast stretched. The image is then further cropped, and the logarithm of the non-zero values is taken to enhance variations. Finally, RPCA is applied to each batch, and the mean of the low-rank components is taken as the final image for defect identification, while the high-rank components are discarded.

RESULTS AND DISCUSSION

The cross-correlation analysis is shown in Fig. 4. The data indicates a moderate correlation ($r = 0.59$) between the rate of RF breakdowns and the appearance of surface defects. We did not observe the creation of defects during periods without RF applied to the gun, which is indicative that the defect mechanism is not purely a vacuum or laser phenomenon. Whilst there are a larger number of breakdowns than defects, it appears that every defect is accompanied by a breakdown (within a small time window). We speculate that a breakdown that occurs on the deposited Cs_2Te causes sufficient energy deposition to give rise to either localized heating or to chemical change within the Cs_2Te . There is some indication in Fig. 2 that material has migrated from the deposited Cs_2Te layer onto the surrounding uncoated area. While we do not have an image of cathode #034 which shows the same outcome, we speculate that material has migrated on that cathode too. However, it is notable that the dark current from the Cs_2Te cathodes in CLARA is lower or comparable to that measured for the previous Cu cathode #020 [11]. This may be because the origin of the dark current is not from the cathode itself but from the rim of the backplate (essentially an annulus around the cathode). It is surprising that what appear to be defects created in a low work function photoemissive surface, and the non-uniformities created by extracted material from the Cs_2Te layer, do not act as a significant dark current source under the application of RF.

CONCLUSION

We have demonstrated that, even with limited diagnostic hardware, systematic image analysis can provide insights into cathode degradation. The formation of surface defects on Cs_2Te is quantitatively linked to RF breakdown events. Future work will examine whether these defects reduce the QE at the defect site, and whether similar "invisible" damage occurs on metallic cathodes like copper.

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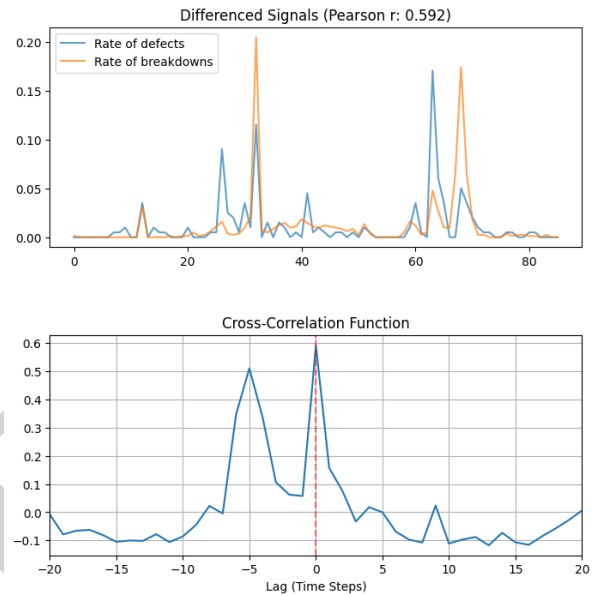


Figure 4: Plots of the analysis of breakdowns against surface defect formation. In the top plot, the first difference of the normalised counts of breakdowns detected and cathode surface defects are plotted and the Pearson correlation is calculated. In the bottom plot, the cross-correlation function is plotted on the differenced signals, showing a strong peak at $t = 0$, indicating simultaneity.

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