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PHOTOCATHODE PREPARATION AND CHARACTERISTICS OF THE ELECTRON SOURCE FOR THE VELA/CLARA FACILITY

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Abstract

The VELA and CLARA accelerators at Daresbury are test facilities with a focus on FEL research and industrial applications of electron beams. Recently the CLARA front-end has been commissioned with acceleration of beam to 50 MeV. A normal conducting 2.5 cell S-band RF photoelectron source operated at up to 70 MV/m has been used as the injector for both VELA and CLARA front-end. Several different copper cathodes have been used throughout its operational life, employing different preparation techniques. Oxygen plasma treatment is a well-known procedure for removing hydrocarbon contamination from surfaces whereas Argon plasma treatment also removes contaminants and typically leaves a thinner oxide at the surface. In this work we compare photoemitted and dark current, as measured directly after the gun, for these alternate surface preparations and also present results from post-use optical and electron microscopic analysis of the photocathodes. Electromagnetic simulations are used to help explain the results.

INTRODUCTION

The VELA and more recently CLARA front-end (FE) accelerators [1] have been dependent on a 2.5 cell S-band 10 Hz RF photocathode electron source. This source uses a solid copper back plate in the first half-cell of the cavity which acts as the photocathode to produce the necessary electrons. Since the back plate is an integral part of the vacuum system, the cavity must be vented to atmosphere to change the photocathode. From the inception of the VELA/CLARA FE, cathodes have been prepared ex-situ using a combination of solvent degreasing and plasma cleaning. Both O and Ar plasma treatments have been used. Because of a perceived difference in the dark current performance of the two treatments, a detailed investigation of these procedures has been carried out.

VELA/CLARA FE PHOTOCATHODES

Table 1 lists the various photocathodes used over the lifetime of the VELA/CLARA FE accelerators. In the very first run (cathode ‘-1’) the level of dark current was extremely high, but this was thought to have been caused by a very rough surface where sub-millimetre scale machined grooves were easily observable by eye [2]. These asperities are likely to have provided sites for RF breakdown and subsequent field emission. For this reason the next photocathode installed (cathode ‘0’) had a diamond polished surface with a greatly reduce level of roughness (typically 30 nm rms). However, scanning electron microscope (SEM) analysis showed that there were significant numbers of ‘dark features’, which have been attributed to diamond inclusions. Whilst it was concerning that these inclusions might also give rise to significant dark current by providing sites for field emission, in fact this cathode gave significantly reduced dark current and when the cathode was reused for the next run (summer 2015), the dark current was even lower, presumably as a result of further RF conditioning during operation.

Table 1: Summary of Cathodes Used

Number and date	**Dark charge per pulse**	**Laser pulse**	**Photoemitted charge**	**Comments**
Cathode ‘-1’ 2013	1200 pC @ 60-70 MV/m, 3 μS pulse	180 fs, 0.3 mm	>250 pC	Machined grooves visible on surface, O plasma cleaned
Cathode ‘0’ Autumn 2014	380 pC @ 70 MV/m, 3 μS pulse	180 fs, 0.3 mm	>250 pC	Diamond polished, O plasma cleaned. SEM shows ~10 μm diamond inclusions
Cathode ‘0’ Summer 2015	130 pC @ 70 MV/m, 3 μS pulse	180 fs, 0.3 mm	>250 pC off-centre	As above
Cathode ‘2’ Spring 2017	>1500 pC† @ 70 MV/m, 2.5 μS pulse	180 fs, 0.3 mm	Low but not quantified	Diamond turned, Ar plasma cleaned
Cathode ‘3’ Autumn 2017	< 100 pC† @ ~70 MV/m, 2.5 μS pulse	3-20 ps, 1.0 mm	40 pC (75 pC off-centre)	As cathode ‘2’, but O plasma cleaned. Conditioned using bespoke script
Cathode ‘0’ Winter 2018	>120 pC† @ ~70 MV/m, 2.5 μS pulse	3 ps, 1.0 mm	>250 pC	Re-prepared using diamond turning and Ar plasma cleaning. Conditioned using script

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† Solenoid and bucking coil settings not scanned.

Subsequent photocathodes have been produced using diamond turning instead of polishing, since this is known to give rise to low roughness (< 100 nm rms) surfaces without diamond inclusions [3]. For the fourth run in Spring 2017 (after the source had been moved from VELA to the CLARA FE), Ar plasma cleaning was substituted for O plasma cleaning. However, significant issues were experienced with the dark current from this cathode, which gave even higher values than the first very rough cathode. Because there was a suspicion that this was due to the Ar plasma treatment, this cathode was replaced with cathode '3', which was prepared with the O plasma treatment instead. At the same time, the PI laser was upgraded with a pulse stretcher that gave pulses with durations between 2 and 20ps. The imaging of the laser was also changed so that the beam spot on the cathode was increased to 1 mm diameter. The laser intensity on the cathode was therefore reduced by a factor of at least 375. With this cathode very little dark current was observed (below the noise level), but also very little actual charge could be generated even with a laser power of up to 72 µJ per pulse. For the most recent operation, cathode '0' was re-installed after refinishing the surface by diamond turning. This cathode was Ar plasma cleaned and gave a charge above 250 pC.

Plasma Cleaning

Plasma treatment was carried out using a Henniker HPT-200 plasma cleaner. In the case of O plasma cleaning, the plasma is a mixture of ions, electrons and O free radicals with some UV radiation also produced. Cleaning is thought to be via a combination of mild ion bombardment plus more aggressive chemical treatment from O radicals. For Ar treatment, clearly ion bombardment is still happening, but there is still a contribution from O radicals coming from residual O in the chamber.

X-ray photoelectron spectroscopy (XPS) and medium energy ion scattering (MEIS) analysis of samples prepared in the same way as the photocathodes showed significant oxide film generation for the O plasma treatment, where the film thickness was dependent on both the power setting and the treatment time. Even for short treatment times at low power a film thickness of 5 nm was seen, which could not be removed using a 250˚C anneal (representing the highest temperature achievable while the photocathode is baked in-situ in the RF source). The Ar plasma treatment also left an oxide, but of about 1 nm, which again was not entirely removed by annealing but might provide a lower work function than the thicker oxide seen with O plasma treatment. Full details of the analysis of these films are provided elsewhere [4,5].

Optical and Interferometric Measurements of Cathode '0'

In the first three operational periods with the RF gun it was found to be possible to generate over 250 pC of charge per bunch, which is the nominal highest charge required for the intended operational modes. During these runs a very short laser pulse was used (180 fs FWHM) which coupled to the high intensity required for the low QE Cu photocathode could have had a significant cleaning effect either by heating, or by ablation of the surface to remove any residual oxide layer. During the third run, in which cathode '0' was reused, the maximum obtainable charge in the centre of the cathode dropped significantly and it was necessary to move the laser to an off-centre position to achieve higher charge bunches.

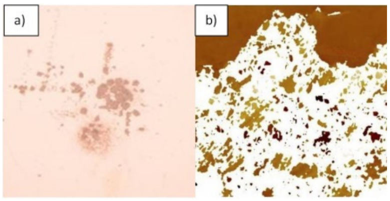

Figure 1: a) A photograph of the centre of cathode '0' showing the damage spots where the laser was incident. b) An interferometric image of the heavily damage region where the roughness is greater than instrument range.

Figure 1 shows optical images of the surface of cathode '0' after its second period of use. In Fig.1a a wide area (~5 x 5 mm) image is presented which clearly shows the large amount of damage on the cathode. Figure 1b is an interferometric measurement of a heavily damaged area (130 x 130 µm) the white regions of the image are where the height difference is greater than the range of the instrument (~ 5 µm). It is possible that the heavily damaged area is the product of either surface melting from the high laser flux density or a number of laser induced ablation events occurring in the near vicinity of each other. In either case the influence of the strong electric field present during the RF pulse may have helped to increase the amplitude of the roughness seen.

Dark Current

In an attempt to explain the dark charge data presented in Table 1, simulations were carried out using CST Microwave Studio EM solver to model the electric field, a Fowler-Nordheim empirical model of field emission and OPERA simulations of the solenoid fields. At the nominal operational parameters it was found that only dark current which originates at the surface of the back plate (which acts as the photocathode) can escape. Further tracking of these electrons using ASTRA demonstrated that much of this dark current does not propagate down the beam line, particularly if collimation is used. However, up to 5% can be transported and so an understanding of the origins of this dark current is important from both a practical perspective and for academic interest. Further details of the dark current simulations are given in Ref. [6].

SEM Analysis of Cathode '2'

Because of the high dark current seen on cathode '2' during the Spring 2017 run, post analysis of this cathode using scanning electron microscopy (SEM) was carried out. Figure 2 shows two images, the first of an untreated and unused cathode surface and the second of a crater in the surface of the used cathode. It should be noted that the two images have different magnifications, so the domains visible in image b) are at least 10x larger than those in image a). Growth in domain size during heating is well known and the used sample has been Ar plasma treated, heated to 250˚C (as part of the RF cavity baking procedure) and then conditioned using RF power before use in beam generation.

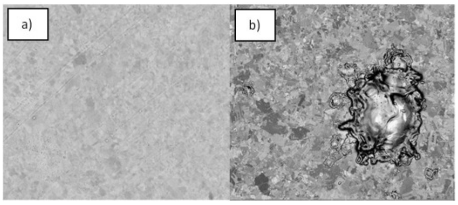

Figure 2: SEM images of Cu photocathode surfaces, a) An unused cathode (15 × 15 µm), b) Cathode '2' after removal from the gun (150 × 150 µm).

The crater seen in Fig. 2b is not caused by ablation from the laser, since the image is taken from a region of the back plate surface which cannot be illuminated by the laser. The origin of this feature is thought to be due to an RF breakdown event either during conditioning or when generating accelerated beam. Similar features have also been seen in the optical microscopy images. Such features could easily act as sites for field emission and contribute to the dark current seen. A series of SEM images was taken every 0.9 mm across the back plate to investigate the spatial distribution of these features. In Fig. 3, the number of features is plotted as a function of radial position across the cathode with the mid-point, where the electrons are extracted, at 42 mm. This data is compared to the distribution of the RF fields present on the back plate during the RF cycle which have been generated using CST Microwave Studio.

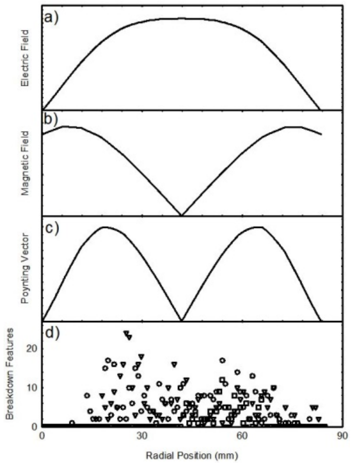

Figure 3: A plot of breakdown features against distance across the back plate compared to the RF fields present. a) Electric Field. b) Magnetic field, c) Poynting vector, d) distribution of breakdown features.

There is some limited evidence of a bimodal distribution of breakdown events across the back plate, with the largest number of events occurring in a ring at about 20 mm radius. This may point to a correlation with the fields present on the cathode during the RF pulse, specifically the Poynting vector which is a measure of the power dissipation on the back plate.

DISCUSSION AND CONCLUSIONS

The O plasma treatment used to prepare photocathodes for the early runs on the VELA/CLARA FE accelerator produced a contamination free surface, but with a thick oxide layer that could not be removed during baking of the cavity. During these runs the intense laser pulse led to either surface melting or ablation effectively producing metallic Cu, which was then able to produce electrons. However, over time the effective quantum efficiency went down and although part of this effect may have been an observable degradation of the final mirror in the laser transport system, the extreme roughening of the cathode surface most likely also contributed. The oxide coating on the rest of the back plate provided high work function, which may have contributed to the low dark current seen.

When a longer laser pulse with a larger spot size was used no cleaning effect occurred and the O plasma treated cathode could not produce sufficient electrons due to the high work function and thus low QE. The combination of Ar plasma treatment and 250˚C annealing did allow sufficient QE to be obtained, but gave rise to much higher dark current. A simple explanation could be that this treatment led to lower work function across the whole back plate. However, SEM post-analysis of cathode '2' showed a large number of features which are likely to be caused by RF breakdown. These features show some evidence of correlation with the RF power dissipation and may arise due to additional localised heating at the surface during RF conditioning and operations. Recent work on RF conditioning has suggested that breakdown features of this type can occur at dislocations, possibly associated with domain boundaries [7] and indeed larger domains were seen in the SEM images. It is possible that O plasma treatment may partially supress domain migration by diffusing into the Cu, pinning the boundaries and this might have a beneficial effect in reducing break down and hence dark current. Further investigation of the effects of O and Ar plasma cleaning and heat treatment using SEM are planned in the near future.

For the most recent cathode Ar plasma treatment has been used, but now also employing an improved automated RF conditioning procedure that appears to reduce the amount of dark current seen. Full details of this procedure are given elsewhere in these proceedings [8]. Other approaches that could give rise to low dark current photocathodes are a) using Ar plasma treatment followed by O plasma where the central section of the photocathode is masked to prevent oxide growth in that region, and b) developing a proper laser cleaning procedure that will be effective with the O plasma treated cathodes.

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