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OPERATION OF THE CLARA LINEAR ACCELERATOR INJECTOR WITH 2.5 CELL 10 Hz PHOTOCATHODE GUN WITH INTERCHANGEBLE PHOTOCATHODES

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Abstract

During the commissioning and operation run in 2021-2022 the photoinjector of the CLARA facility, a 2.5 cell cavity S-band photocathode gun originally developed for the ALPHA-X experiment [1] was used. The copper back wall of the cavity served as the gun photocathode during operation until 2019. In order to reduce the significant time required for replacement and/or reactivation of the photocathode, and to improve the flexibility of the injector the gun has been upgraded for operation with DESY/INFN style interchangeable photocathodes. This upgrade included a new design of the cavity back wall to accommodate the photocathode socket and equipping the gun with a load-lock system. Modification of the gun also required replacement of the bucking coil, which zeros field in the photocathode emission plane. After the upgrade, the gun was commissioned and then operated with a hybrid Cu/Mo photocathode during the last two years. During the winter 2021 - spring 2022 experimental run, the gun steadily operated with a cathode field of 60-70 MV/m (limited by the available RF power) and with an off-centre diamond turned photocathode which delivered stable bunches with a charge of 100 pC.

INTRODUCTION

Compact Linear Accelerator for Research and Application (CLARA) [2] is an S-band RF electron accelerator which is under development at STFC Daresbury Laboratory. Phase I of the machine is now in operation and delivers 35 MeV/c electron bunches with a charge of 100 pC at a repetition rate of 10 Hz. In 2019 the photoinjector of CLARA was upgraded for operation with interchangeable photocathodes with a final goal to improve beam quality, increase duty factor, reduce the dark current and eventually allow for operation with different type of photocathodes including high quantum efficiency Cs_2Te. This paper gives overview of the injector upgrade and its performance during the recent user run. The performance of the whole machine and achieved beam parameters are described in [3].

UPGRADE OF THE CLARA INJECTOR

The injector upgrade included three main tasks: the redesign of the cavity back wall to equip it with a photocathode socket, construction of a photocathode load-lock system and replacement of the bucking coil. In addition, design of the cavity cooling jacket was revised to improve thermal contact of the cavity with the jacket. Final scheme of the upgraded injector is shown in Fig. 1.

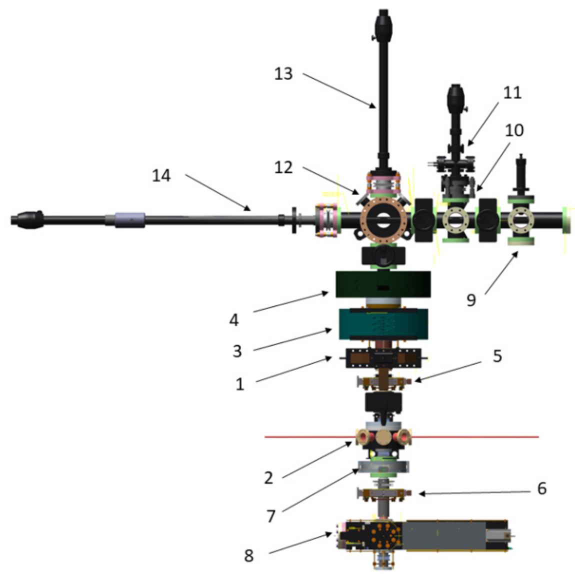

Figure 1: Layout of the CLARA photoinjector upgrade (top view). 1-photocathode gun, 2-light box, 3-main focusing solenoid, 4-bucking coil, 5, 6 H-V steering coils, 7-Wall Current Monitor, 8-YAG beam viewer-collimator, 9-photocathode transport vessel, 10- heating chamber, 11-heating stage, 12-interchange chamber, 13, 14-magnetic manipulators.

The original design of the gun, with a replaceable cavity back wall which also served as a photocathode, allowed the upgrade to be implemented without significant intervention into original construction. The cavity back wall, which was just bolted to the first cell, was redesigned and equipped with a photocathode socket. Special attention was paid to profile of the photocathode socket rim. Its elliptical profile was optimised to prevent surface field excess which may be potential source of field emission. RF contact between the photocathode and the socket is provided by a gold coated spring. The back wall has been diamond turned from oxygen free copper with final roughness of about 10 nm. A detailed description of the RF design and RF commissioning of the upgrade is described in [4].

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The photocathode puck used in the gun upgrade is based on the FLAB/INFN/DESY design which is also now used by the LBNL-SLAC collaboration in the injector of LCLS-II. The difference in the design of the VELA/CLARA facility design from these other photocathodes is its hybrid scheme, where electrons are emitted from a copper tip which is attached to Mo puck (see Fig. 2b). The tip is manufactured with off-centre diamond turning technology which gives a surface roughness of less than 10 nm.

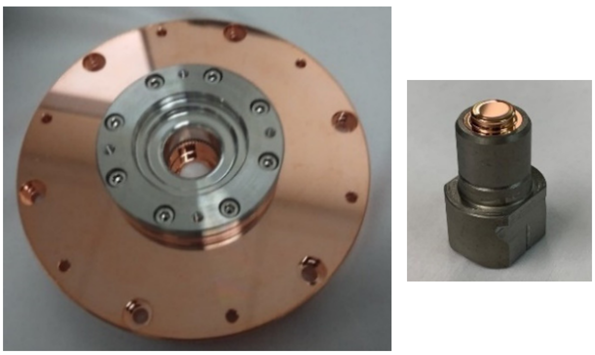
(a) (b)

Figure 2: Back wall of the gun cavity with photocathode socket (a) and Mo photocathode puck with diamond turned tip (b).

OPERATION OF THE PHOTOINJECTOR WITH HYBRID PHOTOCATHODES

Initial RF conditioning of the modified gun was carried out using a solid Mo cathode puck with a machined surface finish that had a roughness which was much higher than the intended run cathodes

After several experiments with different types of photocathode the design chosen for beam delivery was a hybrid puck with a Mo body and a smaller Cu insert at the tip (Fig. 2b). The first of these samples was a Cu insert with a machined finish that had been chemically treated with BPS172. The tip had been then heated to 150 °C before insertion to activate it. This cathode exhibited a high initial quantum efficiency (QE) of $3{\cdot}10^{-4}$ but degraded quite rapidly with a 1/e lifetime of 15 days (although its operational life was about twice this before there was insufficient QE to generate a 100 pC bunch charge).

The subsequent photocathode used in the modified gun was produced using a new ‘in-house’ diamond tuning capability. The surface finish was very good (around 5.7 nm S_q) but the cathode was on-axis turned so that there was a large spike in the centre (more than 400 nm). To try to minimise the dark current from this cathode a more elaborate preparation scheme was used. The puck with Cu insert was first Oxygen plasma cleaned which should leave an oxidised surface with relatively high work function and then chemically treated in the central emitting section. The sample was then heated to 110 °C in the load-lock. By carrying out this procedure it was hoped that the central section where the laser will hit the cathode should have low work function and thus high QE. However, the section around the edge of the cathode would have high work function supressing any dark current coming from this area where the field is higher. The cathode was seen to have an initial QE of $2.0{\cdot}10^{-4}$ and a 1/e lifetime of 32.7 days. Unfortunately, the dark current was seen to be relatively high and so it was planned to replace this photocathode with one that had been off-axis diamond turned to avoid the centre pip (Fig. 3). On removal it was also seen that a ring that looked like small crystallites or possibly just very high roughness had appeared at the junction between the O plasma treated region and that subsequently chemically treated. This could also have contributed to the dark current.

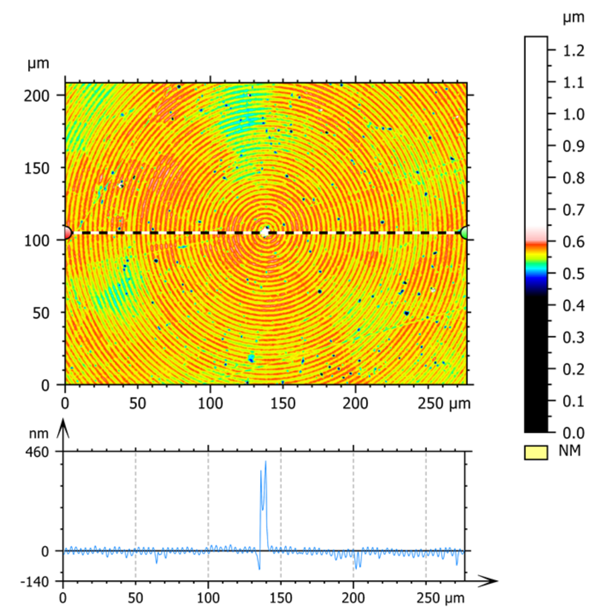

Figure 3: Surface roughness of on-centre diamond turned photocathode Cu insert.

The final photocathode prepared for this run has an off-centre diamond turned Cu insert which was treated using Ar plasma instead of the chemical treatment, since there were concerns about whether this treatment might lead to greater roughness or cause higher dark current in some other way. The Ar plasma treated cathode was initially heated to 150 °C but had to be heated to 250 °C (as expected from previous laboratory studies [5]) to achieve significant QE ($8{\cdot}10^{-5}$). The 1/e lifetime of this cathode was 270 days with a potential operational lifetime before being unable to achieve 100 pC even longer.

DARK CURENT CHARACTERISATION

One of critical parameters of an electron injector is the so-called dark current, defined as the charge generated during an RF pulse without any laser illumination. As some CLARA experiments are very sensitive to dark current special attention was taken to investigate this process. Dark current measurements were taken throughout commissioning and operation of the upgraded gun using a wall current monitor and screen approximately 1 m from the gun exit

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(item 8 on Fig. 1). During initial high power RF conditioning with the Mo puck, dark current of over 10 nC per RF pulse (2.5 us at the maximum gun field/klystron power) were measured (with gun solenoids off), but was significantly lower after the replacement of a faulty gun Klystron with a lower power one and several weeks of conditioning.

Subsequent dark current measurements were taken during commissioning with different cathodes. The dark current data taking and analysis methods were being developed during commissioning and measurements were not always taken at consistent gun parameters, so it was difficult to assess/compare the dark current performance of each cathode in great detail. However, some common features emerged: a reduction in dark current during RF conditioning of a given cathode was observed; and stronger solenoid focussing reduced the amount of dark current emitted from the gun.

It became clearer the "photocathode socket rim" (curved edge of the opening in which the cathode sits) was a significant source of dark current. This was confirmed by both comparison of CST dark current simulations with screen images, and observations of screen images before/after cathode retraction/reinsertion, especially when the cathode was rotated in the process. For certain solenoid and gun power settings, the dark current from the socket rim dominated the dark current emitted from the photocathode puck, however at typical operating gun parameters for normal beam transport, it was usually defocussed before the first screen (Fig. 1). It also emerged that cathode size/shape, and their position after insertion, could have a significant effect on the gun field flatness and field on the cathode surface and thus significantly affect the amount of dark current produced, again making it difficult to compare dark current from different cathodes.

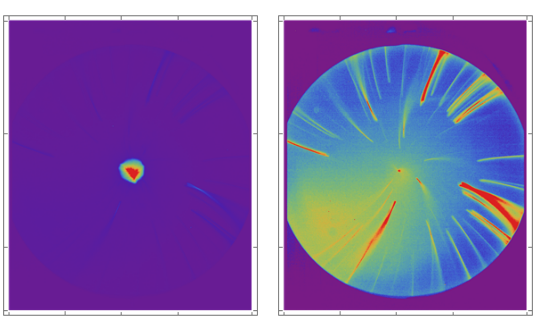

Figure 4: Dark current on the YAG screen approximately 1 m from the gun, for nominal CLARA operating gun settings. Left; beam and dark current. Right; dark current only. The colour maps are adjusted to emphasise the beam/dark current in each image. The maximum pixel values/brightness from the left (beam) image is are around 20 times of the right (dark current) image.

During CLARA exploitation at an RF power of 4.5-4.7 MW (at the gun) using the final photocathode, the dark current was around 1-1.5 nC per RF pulse with the solenoids off, and around the WCM noise level - 100-200 pC - with the solenoids at nominal beam transport setting. This dark current level stayed stable over the several months of CLARA exploitation. Figure 4 shows the first YAG screen image with beam and dark current for typical CLARA operation, with the cathode used in user exploitation.

AMPLITUDE AND PHASE STABILITY OF THE GUN RF FIELD

As the beam delivered by CLARA is transported down to experimental area in 20 m with a beamline which includes an S-bend, high requirements are imposed on beam energy stability. Energy and phase stability of the injected beam has a significant impact on overall energy stability. Dependence of beam energy (E_b) on RF power (P) and emission phase (φ) can be simply described as,

$$E_b = \sqrt{PZ}\,[1 - a(\varphi - \varphi_0)^2], \quad (1)$$

where, Z, φ_0 and a are equivalent cavity impedance, crest phase and fitting parameter respectively. The impact of RF amplitude and phase jitter on the beam can be calculated by measuring beam energy jitter σ_E observing horizontal beam position and its jitter in the spectrometer beamline at various phases around crest phase and fitting to,

$$\sigma_E^2 = \frac{Z}{4P}[1 - a(\varphi - \varphi_0)^2]^2\sigma_P^2 + 4a^2PZ\,(\varphi - \varphi_0)^2\sigma_\varphi^2, \quad (2)$$

where σ_E, σ_p and σ_φ are standard deviations of beam energy, RF power and phase respectively. Variation in beam energy jitter with phase is shown in Fig. 5. The measured phase jitter was 0.037 degree compared to 0.08 degree obtained from the fit, attributing 66 fs to laser-RF locking. RF power showed a jitter of 0.07% at 4.6 MW.

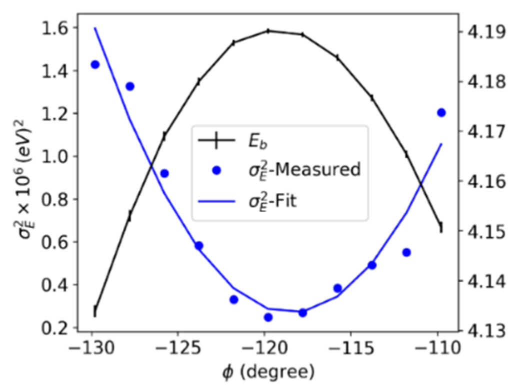

Figure 5: Beam energy and variance at different phases around crest, fitted to the above error equation.

CONCLUSION

The upgrade of the 2.5 cell 10 Hz photocathode gun for operation with interchangeable photocathodes allowed for significantly improving operational performance of CLARA. It reduced the downtime required for photocathode replacement and following high power RF conditioning and opened perspectives for operation with Cs_2Te material in the nearest future. It also allows the photocathode infrastructure for future replacement of CLARA injector for 400 Hz gun to be optimised. However, this upgrade has minor negative effects such as a slight change of the field

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profile in the gun with every new photocathode and some increase of dark current. The reasons for the increased dark current are currently under investigation.

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