RECENT DARK CURRENT MEASUREMENTS ON THE CLARA S-BAND RF ELECTRON GUNS

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Abstract

The CLARA accelerator at Daresbury Laboratory has recently commissioned a new electron gun as part of a larger upgrade to the facility. The new gun (‘HRRG’) is a high repetition rate (400 Hz) 1.5 cell S-band cavity (3 GHz fundamental frequency) designed to produce low emittance beams with momenta up to 5 MeV/c, with field gradients at the cathode surface up to 120 MV/m and RF pulse lengths of up to 3 μs. The previous CLARA gun (‘LRRG’) was a similar 2.5 cell device but of low repetition rate (10 Hz). Dark current emitted from the gun is an important issue for several reasons, so is monitored and managed throughout CLARA commissioning and user operation. We present dark current measurements from the new HRRG gun through its commissioning phase and early stage operation, and make a comparison to those taken from previous LRRG gun.

INTRODUCTION

The CLARA (Compact Linear Accelerator for Research and Applications) accelerator, operating since 2013 at Daresbury Laboratory, is a medium energy electron accelerator providing low emittance, moderate charge beams of high quality for various applications [1]. The original CLARA design was intended to generate a beam with short bunches for free electron laser development, but this has evolved more general range of exploitation. The CLARA electron sources were designed to generate an electron beam with energies up to 5 MeV using a photocathode in an S-band RF gun with up to 400 Hz single-bunch repetition rate. As is the case with many guns of this type, field emission from the gun, or dark current, is of interest and concern. Dark current has negative effects such as the irradiation and damage of machine components, but may also serve as an indication of gun and cathode performance. Dark current behaviour and characteristics are complex due to many convolved factors including its very large temporal and energy spread in comparison to the core electron beam, macroscopic surface geometry and microscopic surface details, and has been the subject of several studies in similar electron guns [2,3].The LRRG (Low Rep Rate Gun) CLARA gun was a 2.5 cell copper RF cavity operated at a maximum rate of 10 Hz in which the cavity backplane served as photocathode. This was later upgraded with a new backplane which facilitated photocathode exchange supported by a ‘load-lock’ system. This enabled beam operation with cathodes of different preparation and composition. More recently, a new HRRG (High Rep Rate Gun) 1.5 cell RF cavity gun with capability to run up to 400 Hz was commissioned and used at CLARA, which again uses a load-lock system, and for the first time Cs$_2$Te cathodes are being used in CLARA.

CLARA GUN, INJECTOR, AND DARK CURRENT DIAGNOSTICS

For the work in this paper we examined the dark current near to the gun exit, using the first diagnostic screen after the gun and the wall current monitor located immediately upstream of this screen. The injector beamline (gun and beamline with diagnostics upstream of the first main linac) is shown in Fig. 1. A beam focussing solenoid surrounds the gun and a bucking solenoid exists so that the magnetic field at the cathode surface can be set to zero. There are apertures which may affect the transport of the dark current from the source including the gun RF coupler and the light box.

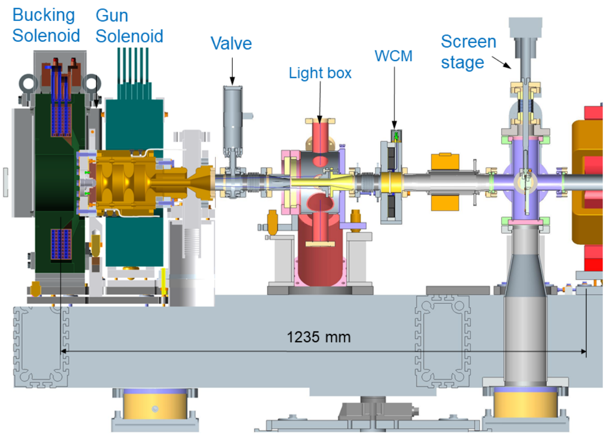

Figure 1: CLARA injector schematic.

The cathode region of the gun is illustrated in Fig. 2 which strongly influences certain features of the dark current, as described below. Based on a design elsewhere [4] the cathode insert or ‘plug’ incorporates a rounded elliptical edge profile or ‘rim’ and is positioned in an opening in the gun backplate, which itself has deeper elliptical rim. These rounded rim profiles are designed to optimise the shape the gun electric field in the cathode region, and to limit the electric field strength in certain locations and thus suppress generation of dark current.

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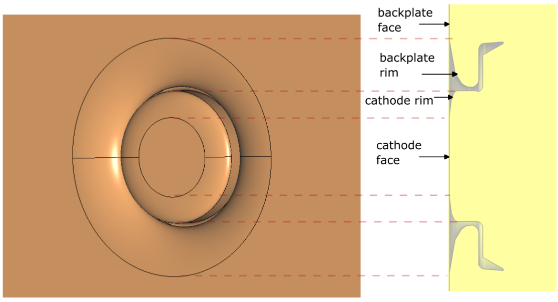

Figure 2: CLARA cathode and its features. Left - 3D view. Right - 2D profile.

DARK CURRENT MEASUREMENTS AND SIMULATION

CLARA Low Repetition Rate Gun 'LRRG'

Initial dark current measurements and simulations with the 2.5 cell LRRG and its back-plate cathode were presented in [5] so are not included here. When the LRRG gun was upgraded with a removable cathode plug and load-lock system, our simulations were developed further to investigate the contributions of these additional cathode elements to the dark current footprint. Dark current measurements were taken throughout the commissioning of the LRRG and its cathode and dark current was simulated using the CST (Computer Simulation Technology) code [6], which performs a full 3-D simulation of the gun electromagnetic field, its solenoids, and the generation and transport of field emission from the various gun surfaces. This work is described in detail in [7]. In the period of the commissioning and operation of the upgraded LRRG gun, several different copper(Cu)-tipped molybdenum(Mo) photocathodes were used which involved different preparation methods [8], observations and measurements were made at different stages of gun/cathode conditioning and operation. In early conditioning, substantial dark current in the order of several nC per RF pulse was observed, this fell as conditioning progressed; we assume this is due to the conditioning of the cathode region surfaces which dominates the measured dark current. Even after reducing, the dark current remained significant and easily measurable during the CLARA user programme. Despite this, there was no machine damage other than discoloured vacuum windows. The user programme ran successfully with gun parameters achieving approximatately 70 MV/m and 2.5 μs pulse length (two experiments including [9] operated with a reduced gun gradient to mitigate the dark current). First beam operations used photocathode # 013 which was a copper thin film deposited onto a molybdenum puck, as described in [8]. On the appearance of dark current on the first diagnostic screen, we sought to model and reproduce this in a simulation. Screen images were taken at three different solenoid settings and the conditions replicated in a CST simulation which involved using the CST electromagnetic (EM) field solver to predict the 3D field and a PIC (Particle-In-Cell) solver to simulate the dark current. The PIC solver used triangulation to distribute emission points over the internal surfaces of the gun and a macroscopic application of the Fowler-Nordheim [10] model to calculate the field emission current from each point based on the electric field at that point predicted by the EM solver.

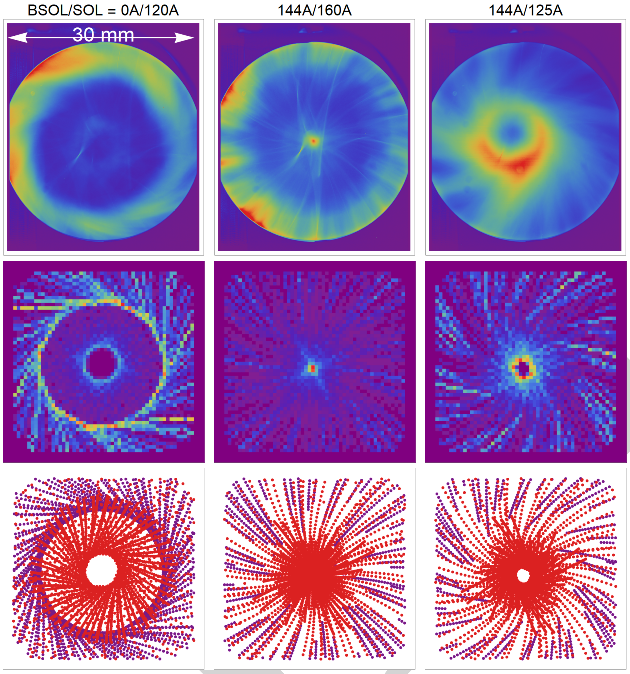

Figure 3: LRRG dark current measurement and simulation. Top row measured, middle and bottom rows simulated. In the middle row the colour map represents the density of electrons (red most intense, violet least intense). In the bottom row the colour map indicates the source of emission (red cathode rim, purple backplate rim).

Figure 3 shows a qualitative level of agreement between the measured and simulated data which allowed identification of the likely emission sources of the dark current features. This was supported by further screen observations of the dark current with the different cathodes subsequently used in the LRRG (see Fig. 4). The results show that a significant 'halo' of dark current on the screen originates from the backplate rim, and does not vary with cathode type or position. The central bright feature of dark current may not necessarily be due to field emitters in the centre of the cathode (as one might naively expect), but from the edge of the cathode and focussed to the centre of the screen.The simulations had convergence issues which did not significantly affect the 2-D pattern of the dark current, but did affect the relative and absolute amount of charge extracted at any point in the simulation. Despite using finer mesh and implementing sub-meshing, these problems were not fully resolved. Despite this issue it is possible to conclude that for gun parameters within the normal operating range, dark current entering the main beamlines is dominated by the cathode region (including the rims) while emission from the gun cell irises and much of the gun backplate does not escape the gun.

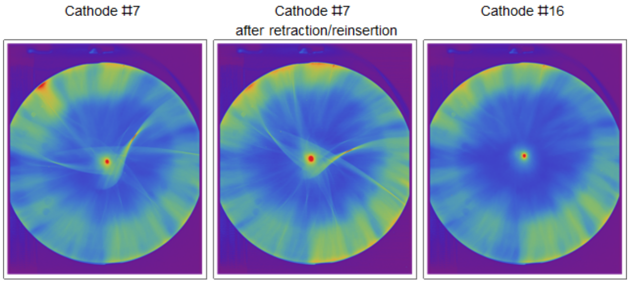

Figure 4: LRRG dark current on first beamline screen, with different cathode configurations.

CLARA High Repetition Rate Gun 'HRRG'

The 1.5 cell HRRG gun at Daresbury was developed and conditioned in parallel with the LRRG. In 2024/25 the HRRG gun was prioritised for conditioning and first beam was extracted in April 2025. During the conditioning process, dark current measurements similar to those made on the LRRG were made, again with several different cathodes. Initial work used a hybrid Mo plug which featured a diamond-turned Cu tip (named cathode # 020) . Later, and for the first time in the UK, a Cs_2Te cathode was utilised with a quantum efficiency (QE) around 18 % at 266 nm measured under low field conditions [11]. The solenoid configuration was the same as that for the LRRG. CST simulations were not performed at the same level of detail for the HRRG. The HRRG gun reached a higher field than the LRRG but had generally operated with shorter pulse length, generating beam for exploitation at 1.25 μs (although longer pulse lengths were used in the conditioning process). The estimated field strength is approximately 80 MV/m at present parameters. We applied the same approach developed for the LRRG to detect dark current emission on the first diagnostic screen and the observations from then to understand the emission sources. Dark current images are shown in Fig. 5 which compares the dark current from the first cathode used in the gun during its initial conditioning (cathode # 020) with that from the Cs_2Te (cathode # 034). The images, for a solenoid configuration which cancelled the field on the cathode, show a central contribution from each cathode with a outer contribution the source of which we identify as the back plate rim, as in the LRRG studies.

Similarly to the LRRG, we saw high measured levels of dark current (several nC per pulse) during early stages of conditioning, which decreased and stabilised over time. After stabilisation of the dark current, the amount was measured as a function of solenoid field strength, repeated over a longer time scale. This is shown in Fig. 6 which shows a very similar level of dark current for cathode # 034 compared to # 020 and an overall dependence on the solenoid which gives a maximum dark current extraction at intermediate solenoid values (typically for beam the main solenoid is operated at greater than 200 A). Cu cathode # 020 had a QE (measured in-situ) around 1E-4 % at the time of these dark current measurements, while Cs_2Te cathode # 034 was substantially higher at around 10-13 % . However we see little difference in the total dark current which suggests that in the injector, the dark current is dominated by emission from the backplate rim.

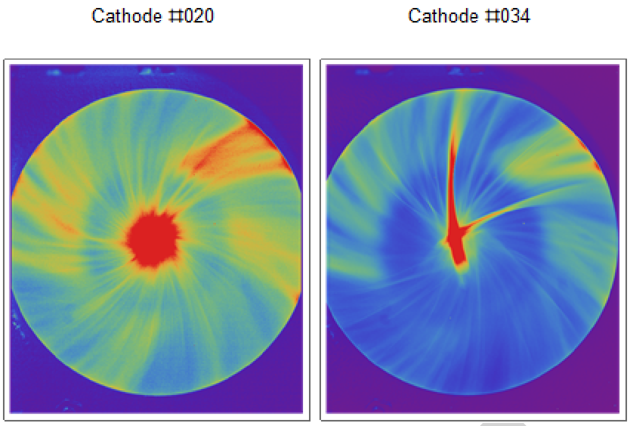

Figure 5: HRRG dark current on first beamline screen, for different cathodes.

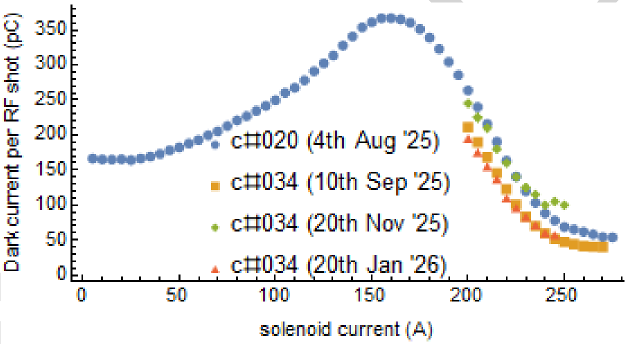

Figure 6: HRRG dark current measurement vs. solenoid field strength for different cathodes at different stages over the accelerator commissioning period. The gun power/gradient was set to the same value for all sets of data.

CONCLUSIONS

The main features of the dark current from the CLARA LRRG and HRRG guns have been deduced from measurement and simulation. Some subtleties on how to separate dark current from cathode vs back plate rim have been clarified. Dark current has not caused major issues in CLARA commissioning and operation, and to-date, understanding its features on a microscopic scale has not been practically necessary. However the macroscopic understanding gained here clearly indicates emission from the backplate rim is significant especially in the early part of the machine. Electron beam collimation throughout CLARA may serve as the most immediate mitigation at present.

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