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LATEST DARK CURRENT STUDIES OF RF PHOTOCATHODE GUN OF DELHI LIGHT SOURCE*

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Abstract

The Delhi Light source is a pre-bunched Free Electron Laser facility to generate coherent THz radiation. The electron beam is generated from a normal conducting 2.6 cell RF photocathode (PC) gun operated at 2860 MHz. The RF gun is powered by a high power RF source for a duration of 4 µs at 10 Hz repetition rate. The dark current during the operation of the RF gun has been found to be substantially high with increasing forward powers (above 3 MW) even after prolonged RF conditioning. Dark current measurements has been done with an in-house developed faraday cup with an objective to understand the possible primary dark current source from locations at the PC that witnesses high accelerating fields. The measurements include the study of solenoid field variation to understand the dark current energies and effect of its steering to understand the possible dark current locations. Simulations to make inference from the measurements has been done assuming different radial position of dark current emitters at the PC surface. The details of the measurements, simulation results and the inference drawn are discussed in the paper.

INTRODUCTION

A compact pre-bunched FEL based THz user facility, the Delhi Light Source (DLS) is at the final stages of commissioning at IUAC, New Delhi [1–4]. The system has a 2.6 cell copper RF photocathode gun operating in pi mode at 2860 MHz. The RF gun is powered by a klystron-modulator system for 4 µs at 10Hz. The gun cavity has underwent over ~ 3000 hrs of RF conditioning and it can now be powered upto 11 MW peak power with stable pick up and rare breakdown events. However at forward power of 3 MW and above, the illumination of YAG screen due to dark current placed at ~1.4 m downstream becomes too bright to distinguish any photo-current. To understand the reason for this high dark current, its measurements were done and based on the emitter parameters obtained from these measurements, ASTRA [5] simulations were performed to trace the possible dark current sources in the photo-cathode.

DARK CURRENT MEASUREMENTS

The dark current was measured at ~ 1.4 m from the PC gun using an in-house built Faraday cup (FC) with a suppressor voltage of 100 V as shown in Fig. 1. The dark current (DC) was measured at forward powers from 3 MW to 9 MW. At

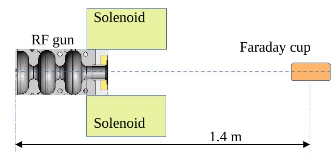

Figure 1: Schematic for dark current measurement.

each power the solenoid placed after the RF gun was scanned to obtain DC plots as shown in Fig. 2(Left). The DC was computed in nC from the FC signal in the scope by taking the area under the curve of the FC signal in Vns and dividing it by 50Ω. The 4μs RF window and the FC signal seen in scope at forward powers 3 MW, 5 MW & 7 MW for the respective solenoid current of 30 A, 45 A & 60 A at which the FC signal was maximum is shown in Fig. 2(Right).

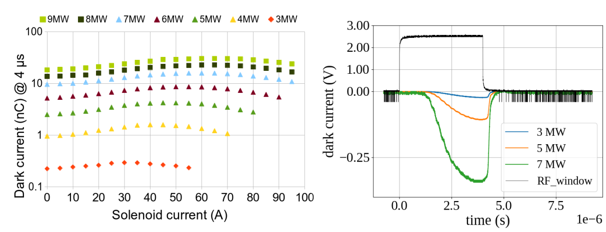

Figure 2: (Left) DC measurements with solenoid scan at different forward powers. (Right) RF window (in black) and the faraday cup signals seen in scope at forward powers 3 MW, 5 MW & 7 MW at respective solenoid currents where DC is maximum.

The dark current data was used to compute the field enhancement factor β using the Fowler Nordheim (FN) equation for field emission [6]. The equation simplified in the linear form for computing β is given below

$$\log_{10}\frac{I}{E^{2.5}} = \log_{10}\frac{5.7^{-12}10^{4.52\phi^{-0.5}}A_0\beta^{2.5}}{\phi^{1.75}} - \frac{2.84^{9}\phi^{1.5}}{\beta E} \quad (1)$$

where, I is the time averaged current in Amp, E the electric field in V/m, ϕ the work function in eV, A_0 the effective emitter area in m^2. With $Y = \log_{10}(I/E^{2.5})$ and $X = (1/E)$, β is computed from the slope and the effective emitter area from the intercept.

The β is computed to be 185 from the FN plot shown in Fig. 3 and the effective area A_0 is computed to be $\sim 7^{-13}$ cm^2. The value of β, emitter area and the dark current charge per RF cycle was thus computed from the measurements and used in the ASTRA simulations discussed in the following sections for locating the emitter sources.

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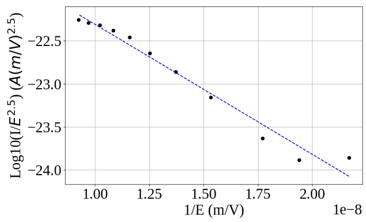


Figure 3: FN plot of measured dark current to compute β.

DARK CURRENT SIMULATIONS

The dark current(DC) sources are usually field emitters due to sharp irregular points or impurity particles on the high field regions of the RF gun. Although the high field regions of the RF gun are located near the photo-cathode and the irises, the field emitters only from the photo-cathode region can travel far downstream and contribute as dark current [7]. The photo-cathode circular edge owing to its small edge area can also contribute to DC.

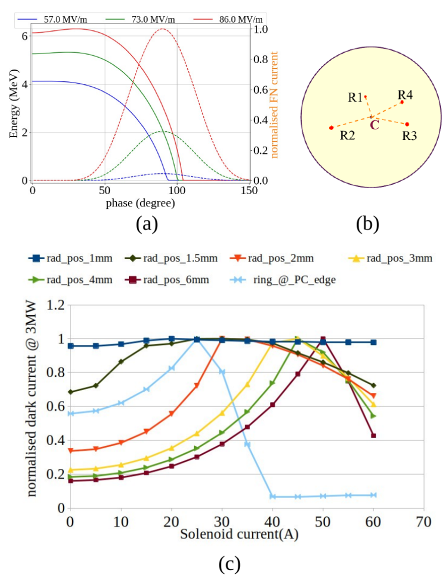
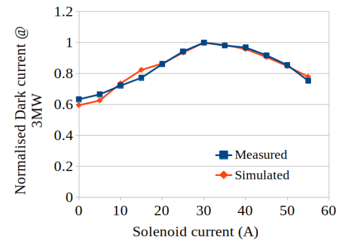


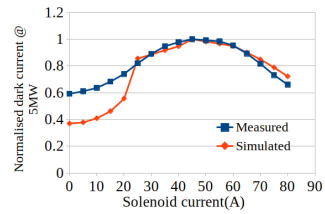
Figure 4: (a) Simulated energy-phase scan and FN plot(dashed lines) showing the overlap of DC over phase with energy distribution at fields 57 MV/m, 73 MV/m & 86 MV/m corresponding to 3 MW, 5 MW & 7 MW resp. (b) Representative emitters on PC at different radial distance from centre. (c) Simulated solenoid scan profiles of normalized dark current for different radial location of an emitter and ring type emitter at PC edge for 3 MW forward power.

Estimation of Dark Current Locations

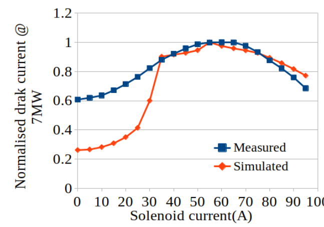
To estimate an idea of the emitter locations using the measurements, field emitters at different radial locations from the PC center has been considered in the simulations as shown in Fig. 4(b). Due to cylindrical symmetry of PC RF gun the DC at FC due to an emitter will only depend on its radial position at a given Cavity & solenoid field.



(a) Results at 3 MW



(b) Results at 5 MW



(c) Results at 7 MW

Figure 5: Sum of solenoid scan profiles of emitters at radial location 1.5 mm, 2 mm, 3 mm and ring type summed in the proportion ~ (a) 35 : 12 : 2 : 2 for 3 MW case (b) 38 : 8 : 5 : 0 for 5 MW case and (c) 45 : 7 : 3 : 0 for 7 MW case, shown against respective measured solenoid scan DC profile.

The dark current charge for a single RF cycle for the simulation was computed from the total charge measured in a RF window divided by the number of RF cycles in the RF window. The A_0 & β computed from the measured data was used to generate the temporal distribution based on the FN model [7, 8] as shown in Fig. 4(a) for three different forward powers. It also shows the overlap in phase of the FN & energy distribution at a given field, thus predicting the possible DC energies and their numbers. Apart from point field emitters a ring emitter representing the PC edge was also considered. First the simulations were done for 3 MW power corresponding to 57 MV/m peak field using the relation $E_{peak} = 32.6\sqrt{P_{forward}}$ specific to DLS RF gun. The solenoid field was varied for different radial locations of the emitters and also for the ring type emitter. The simulations has taken into account the opening area same as FC at 1.4 m to compute the DC. The simulated solenoid scan profiles of normalized dark current for different emitter locations is shown in Fig. 4(c) for 3 MW forward power. Based on the measured solenoid scan profile at 3 MW, the simulated solenoid scan profiles from different emitter locations that could be summed up in varying proportions

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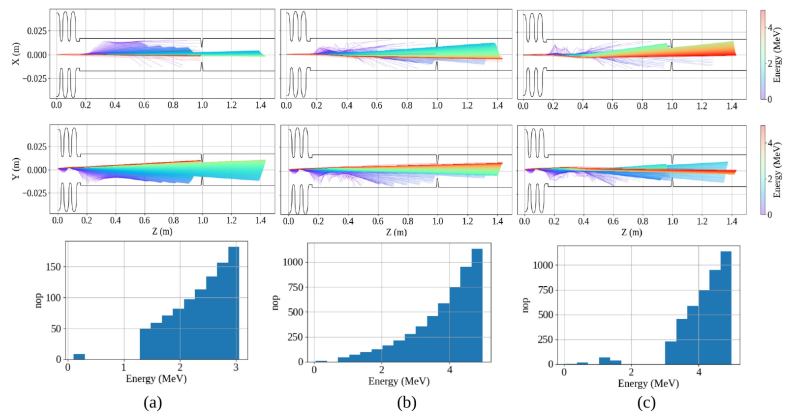

Figure 6: The dark current trajectories from emitter at radial location 1.5 mm color coded with particle energies and energy distribution at screen at 1.4 m for 5 MW forward power at solenoid current of (a) 10 A, (b) 45A and (c) 85 A.

to match the observed profile was tried. It is found that the solenoid scan profiles of emitters at radial location 1.5 mm, 2 mm, 3 mm and ring type when summed in the proportion ~ 35 : 12 : 2 : 2 was close to the observed solenoid scan profile at 3 MW as shown in Fig. 5a. The obtained ratio indicates the DC contribution from the respective emitters with major contribution from emitter at radial position 1.5 mm. The simulations were repeated for 5 MW and 7 MW forward powers having peak fields of 73 MV/m and 86 MV/m respectively. For 5 MW and 7 MW the solenoid scan profiles at radial location 1.5 mm, 2 mm and 3 mm summed in the proportion ~ 38 : 8 : 5 and ~ 45 : 7 : 3 respectively for the two powers was close to the respective observed solenoid scans as shown in Fig. 5b and 5c. For both the cases the contribution from the ring of PC edge is absent due to negligible particles reaching the Faraday cup opening due to higher momentum of the electrons. The above plots suggests that the emitters are located close to the PC center around 1.5 mm to 3 mm and are responsible for major contribution to the DC.

The plots for 5 MW and 7 MW has mismatch in the lower solenoid fields which can be explained from the fact that the simulations are done for a single RF cycle corresponding to the maximum RF field when the cavity pick up signal reaches saturation. Where as measured DC has contribution of all RF cycles within 4 µs window during which the Cavity experience a continuously rising field from zero to steady state. Thus the DC contribution from fields during the cavity rise time is absent in the simulation giving rise to the mismatch. Since the DC energies during rise time will always be lower compared to saturation state the mismatch will always appear at the lower solenoid fields. Moreover at higher powers (5 MW & 7 MW) the amount of field change during the rise time is relatively high to make the mismatch larger.

Estimation of Distribution of Dark Current Energies

With the estimation of probable location of DC emitters, to understand the reason for photo-current getting shadowed by the DC background on YAG, the trajectories of DC energies was plotted for 5 MW case with emitter location at radial position of 1.5 mm (as Y offset). The energy trajectories and distribution of DC at the screen position 1.4 m is shown in Fig. 6 for three different solenoid current of (a) 10 A, (b) 45 A and (c) 85 A. Although lower energy electrons of DC is more in number due to nature of FN distribution over phase (see Fig.4(a)), the trend of lower energies reaching the screen even at low solenoid fields as in case (a) is less as they are easily deflected with even small solenoid field. The higher energies are again less in number as dictated by FN distribution but may not be insignificant depending upon β and they mostly do reach the screen as in case (c). At moderate solenoid fields of 45 A as in case (b) most of the electrons reach the screen as these are intermediate energies with sufficient number as governed by overlap of FN distribution and energy phase scan. Thus for a photo-current energy ~ 5 MeV at 5 MW requiring an intermediate solenoid current (~ 50 A) for screen at 1.4 m, the dark current electrons will also accompany the photo-current as evident in the trajectory plot of case(b).

CONCLUSION

The dark current measurements were done by scanning the solenoid field at different forward powers to investigate the dark current sources with the help of simulations. The simulations with different radial position of emitters indicates the presence of field emitters at around ~ 1.5 mm to 3 mm measured from the PC center. The estimated presence of emitters close to the PC center is assumed to be the main cause of large dark current background that shadows the photo-current as concluded from the dark current trajectory data. Efforts will be made to identify and confirm the emitter locations by thermal imaging of the PC surface. Further the Cu PC will be replaced by semiconductor PC to increase the photo-current very soon.

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