DARK CURRENT STUDIES AT THE APEX PHOTOINJECTOR*

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Abstract

The increasing scientific demand for a high repetition rate FEL light source is driving the development of electron sources with high beam quality, delivering electron bunches at rates in the MHz range. An ongoing project to develop such a source is the Advanced Photoinjector Experiment (APEX) at LBNL. High brightness electron beams require high fields at the cathode during the electron emission. Such high fields associated with imperfections on the cathode surface area can induce undesired electron field emission (dark current). Excessive dark current can generate quenching of SRF structures and undesired radiation doses activating accelerator components and damaging undulator structures. In the present paper, we discuss the dark current studies performed at APEX. Field emitters in the cathode area have been localized and characterized, and techniques for minimizing dark current emission and to passively remove it have been investigated.

INTRODUCTION

APEX aims to demonstrate the capability of a new concept RF gun, the CW 186 MHz VHF-Gun [1, 2], of delivering electron beams with quality required by X-ray FEL applications at MHz-class repetition rates. Figure 1 shows a cross section of the VHF-Gun. The requirements of CW operation and high accelerating field cause many technical challenges, and dark current control is one of them. Here we report on the dark current studies at APEX, with experimental measurements and simulation results. Based on the specific position of dark current emitters, a scheme for a passive collimation is proposed which could significantly reduce the dark current amount transported downstream.

DARK CURRENT MEASUREMENTS AND SIMULATIONS

Dark current measurements in APEX included the imaging of field emission sources located in the cathode area, and the measurement of dark current versus accelerating field at the cathode (for a single emitter and integrated over all emitters).

Sources of Dark Current in the VHF-Gun

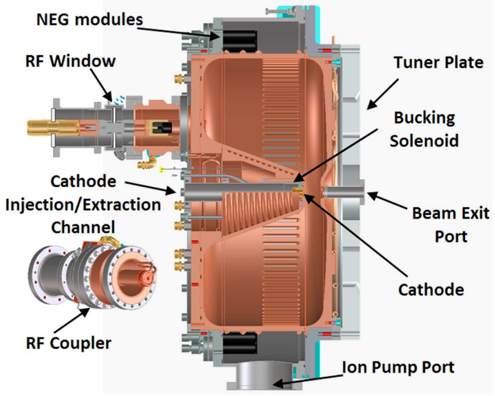

Figure 1: CAD cross-section of the VHF-Gun, with main components in evidence. The gun copper RF cavity resonates at 186 MHz and operates in continuous wave (CW) mode accelerating beams at a nominal energy of 750 keV with a gradient at the cathode of ∼ 19.5 MV/m.

In APEX the photo-emitting material is deposited on a molybdenum plug that can be inserted into the gun by the vacuum loadlock system located in the rear side of the gun. When inserted, see Fig. 2, only the tip part of the plug is exposed to the RF fields in the gun. This part has a radius of 5 mm and is surrounded by the copper of the cavity nose.

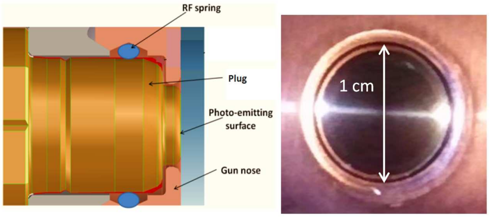

Figure 2: Left: CAD side view of the molybdenum cathode plug inserted in the gun nose. Right: picture showing the plug tip inside the gun viewed from the beam exit pipe.

By properly tuning two solenoids downstream, dark current electrons were used to create an image of the field-emitters at the cathode on a screen located downstream of the second solenoid. In the left side of Fig. 3 one of those images is shown. Several field emitting points are located with good accuracy along a ring are clearly visible. The image magnification was calibrated with the help of ASTRA simulations [3], revealing a ring radius of ~5.3 mm, implying the source to be located just outside the molybdenum plug, on the copper side surrounding the plug itself. The right side of Fig. 3 shows the dark current in the same imaging conditions, but the picture is taken with a much higher dynamic range, unveiling also the weakest sources.

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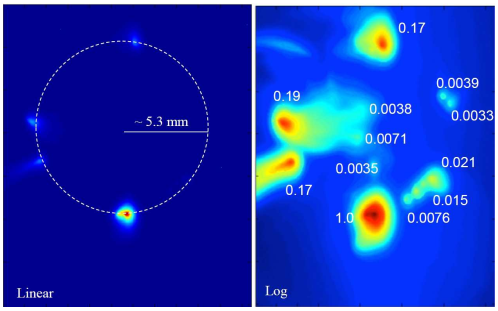

Figure 3: Left: image of the field emitters in the cathode area. Right: the same image with the intensity plotted in logarithmic scale shows the relative intensity of the peaks.

Dark Current Propagation Along the Beamline

Using the information from the experimental observation above, it was possible to simulate the dark current propagation from the emitters downstream the beamline. We represented the dark current source by 4 field emitters laying on the 5.3 mm radius circle, and separated by 90 degrees.

The temporal distribution was retrieved from the Fowler-Nordheim (FN) fit of data taken using a Faraday cup mounted at the exit flange of the gun (see Fig. 4), and the nominal accelerating field of 19.5 MV/m was used. For each gun RF phase the instantaneous dark current was calculated using the value from the fit in the figure. The resulting longitudinal distribution is shown in Fig. 5, together with the Gaussian fit approximation that was used in simulations.

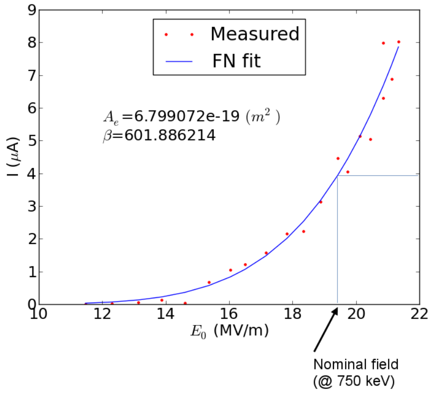

Figure 4: Dark current vs. electric field at the cathode measured by a Faraday cup directly attached to the gun beam exit pipe. A FN fit is also showed. A_e refers to the area of the emitting site and β is a local field enhancement factor that depends on the emitter geometry.

For the longitudinal and transverse momenta, a rectangular distribution with r.m.s. value equal to the momentum equivalent to $E_F / \sqrt{12}$ was used (with E_F the Fermi energy of the metal where the field emitters are located, 7 eV for Cu in our case). Such a choice overestimates the actual energy distribution width, but represents a conservative approximation for our simulations. Simulations showed that, regardless of the emitter size, most particles were lost inside the gun and electrons within such initial distribution are not transported through the beamline to the screen position. This is mostly due to the significant RF defocusing kick that off-axis particles experience at the gun exit.

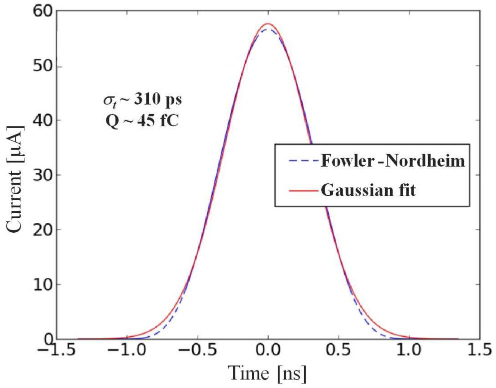

Figure 5: Longitudinal distribution calculated using the FN fit in Fig. 4. Also shown is the Gaussian fit used for the simulations.

Single particle simulations also showed that the only way for the electrons to be transported downstream the beamline, is for them to have a sizeable net transverse momentum radially directed towards the center of the cathode and pre-compensating the RF kick, see Fig. 6. A further investigation of the field configuration in the cathode area showed that the orientation of the electric field in the interface area between the cathode plug and the surrounding copper, see Fig. 7, can indeed generate the radial momentum component required for transporting the electrons. It also appears evident that any field-emitter eventually present on the edge of the cathode plug would imprint on the electrons an opposite net transverse velocity, not allowing them to exit the gun. The net radial momentum value (within the range shown in Fig. 6) that an emitted electron has, depends on the radial position of that particular emitter along the rounded copper edge surrounding the cathode plug. That position is not known and, in order to overcome this uncertainty, multiple simulations with different initial transverse momentum distributions were performed. The initial distributions were assumed to be Gaussian with the same r.m.s. value, equivalent to $E_F / \sqrt{12}$, but with a variable mean value, equi-distributed over the range of transmitted radial momenta defined by the single particle simulations shown in Fig. 6.

By comparing the experimental image in Fig. 3 with the simulated ones, obtained using the same magnet settings, it was possible to significantly reduce the range of possible radial momenta to values between 20 and 40 keV/c.

In addition, the knowledge of the field emitter's locations in the VHF-Gun, allow to develop an effective strategy for reducing dark current. Details of the proposes methods will be presented below.

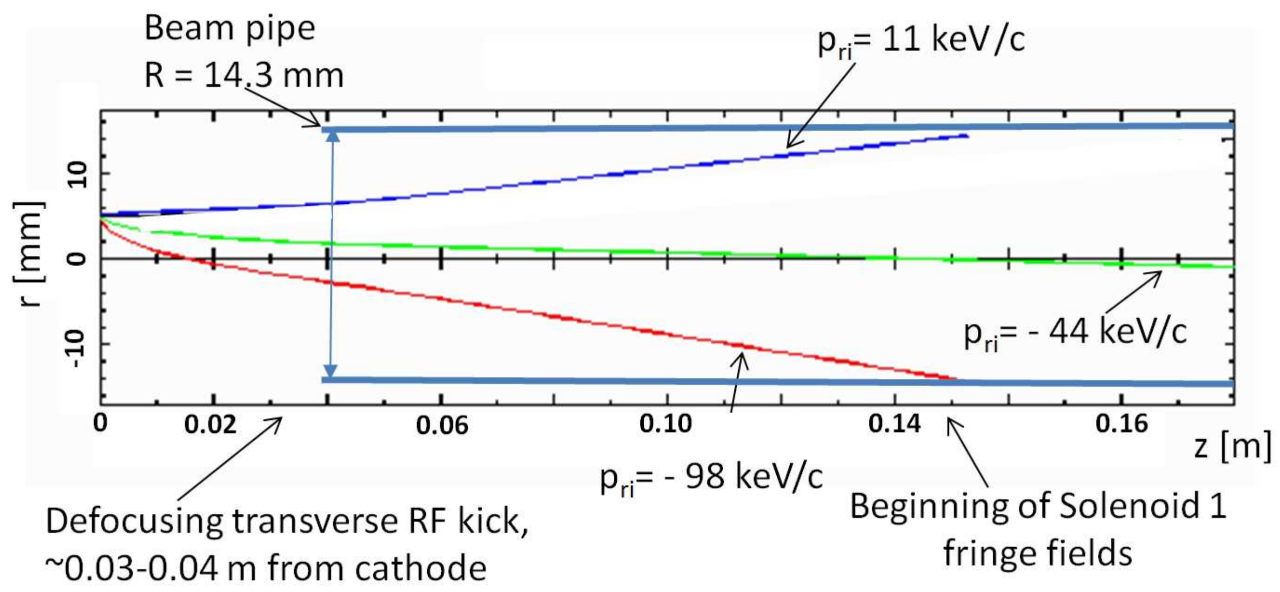

Figure 6: Single particle tracking showing the range of radially oriented transverse momenta required for electrons to be transmitted along the downstream beamline.

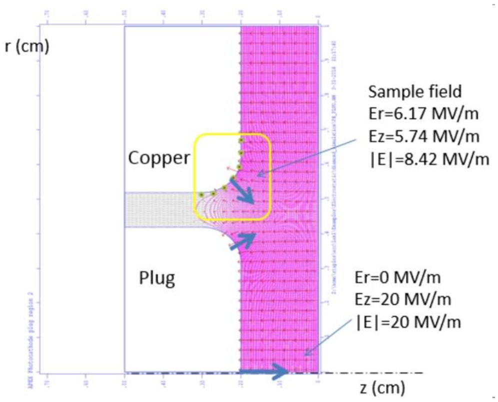

Figure 7: Simulation showing the electric field configuration in the interface area between the cathode plug and the gun cavity nose.

DARK CURRENT MITIGATION METHODS

The use of experimentally tested cleaning techniques such as dry-ice [4] or ethanol rinsing [5] applied to the gun cavity can drastically reduce the number of particulates and hence of potential field emitters. Dry-ice cleaning of the cathode area of the VHF-Gun, where the dark current sources are located, will be tested in APEX in the near future.

The position of the emitters around the VHF-Gun cathode plug can potentially be exploited for a passive collimation, drastically reducing amount of transported dark current. Such a scheme is described in more detail in the next section.

If necessary, by moderately reducing the gun operation energy it is possible to significantly reduce dark current with a minimal impact on the beam brightness performance [6].

An alternative to the passive collimation is represented by an active sweeper system composed by a transverse kicker followed by a collimator. A possible configuration for such a system is presently under study at APEX.

Passive Removal

Based on the experimental and simulation results discussed above, the possibility for a passive collimation scheme system to reduce dark current is studied here. The idea is based on the observation that for a given setting of the solenoids, there could be an optimum position along the beamline where the dark current spots are transversely well separated from the photo-emitted beam, as in the case of Fig. 3. By placing a circular collimator (circular aperture) with the proper diameter in such a position, it is possible in principle to remove most of the dark current without affecting the photo-emitted beam.

In order to evaluate the feasibility of such a scheme in APEX, a number of simulations were performed using the nominal beamline settings for the emittance compensation. The optimal longitudinal position for the collimator along the beamline is the one where the separation between the main beam and the dark current spots is maximum. For each longitudinal position along the beamline, the minimal acceptable radius for the collimator was assumed to be three times the r.m.s. transverse size of the photo-emitted beam in order to minimize losses of such beam. Simulations using the initial distributions described previously allowed to define the position for the collimator that maximizes the reduction in dark current.

Figure 8 shows the simulated dark current transmission vs. the longitudinal position of a collimator of length 1 cm and radius three times the r.m.s. transverse beam size of the photo-emitted beam at that particular longitudinal

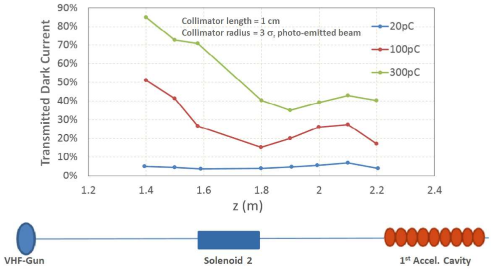

Figure 8: Dark current transmission vs. the longitudinal position of a collimator for three different charges per bunch. The simulations assume a collimator length of 1 cm and a radius three times the r.m.s. transverse beam size of the photo-emitted beam at that particular longitudinal position.

position. The cases for charges per bunch of 20, 100 and 300 pC are shown. It is worth remarking that at any given longitudinal position, the collimator radii used to obtain the results in the figure were not the same between the different charges. Indeed, the photo-emitted beam size depends on the charge per bunch and larger sizes are typically associated with larger charges per bunch. The optimal position for the collimator is the one where the transmitted dark current has a minimum. From Fig. 8, it can be seen that the region right downstream Solenoid 2 represents a good location for a collimator for all the three different charge cases. Additional studies showed that a collimator with 20 cm length inside Solenoid 2 represents a simple and effective solution for all the different charge cases.

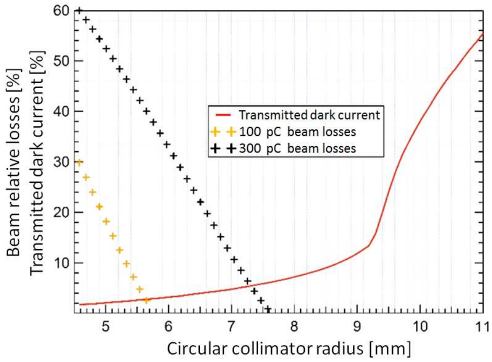

Figure 9: Beam losses vs circular collimator radius. The collimator used in the simulation has a length of 20 cm and is located inside Solenoid 2. It can be seen that with a radius of ~ 8.3 mm no losses are generated in the 100 and 300 pC (20 pC case is not shown in the figure), while ~ 90% of dark current is lost.

A summary of the results is reported in Fig. 9 where the relative dark current transmission and the relative beam losses vs. the radius of the collimator are shown. One can see from the figure that, for example, with a radius of 8.3 mm more than 90% of dark current is suppressed with no losses for the photo-emitted beams for both the 300 and 100 pC case. For the 20 pC case, not shown in the figure, the collimator does not generate losses even for much smaller radii. Figure 9 also shows that in the most challenging case of 300 pC an orbit stability of few hundreds microns is required to avoid photo-emitted beam losses.

The dark current heat load on the collimator is minimal and can be estimated of the order of 1 W. Such a value does not represents a challenge in terms of cooling, but in order to avoid damage to the collimator from the several hundreds of W if the photo-emitted beam is misteered, a proper cooling or a fast machine protection system is required.

A possible issue that needs to be further analyzed and investigated is represented by the effects on vacuum and cathode lifetime that scattered shower products induced by the dark current impinging on the collimator can potentially generate.

An experimental test is planned at APEX in the near future.

CONCLUSION

Dark current in APEX VHF-Gun has been characterized and point-like field emitters were localized in the cathode area. A passive collimation located at the second solenoid along the APEX beam line is proposed to reduce transported dark current by a factor of ten. The collimation system will be tested at APEX.

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