SINGLE PHOTOEMITTER TIPS IN A DC GUN: LIMITING ABERRATION-INDUCED EMITTANCE

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Abstract

Ultrafast electron diffraction (UED) is a rapidly growing field in which there is an increasing need for higher beam brightness, especially for space charge-dominated single-shot applications. We explore the utilization of a cathode field-enhancing micron-scale tip inside a dc gun to obtain brighter sub-pC electron beams using a nominal cathode electric field of 10 MV/m, and peak tip emission fields up to ~ 100 MV/m. As a first step, here we consider the effects of the curvature of the tip geometry on the emittance (without space charge), and determine the conditions for a few simple tip shapes that provide geometry-induced emittance growth smaller than the very low intrinsic emittance of cryogenically cooled multialkali photocathodes.

INTRODUCTION

Brighter electron beams are demanded for single-shot ultrafast electron diffraction and microscopy (UED/UEM), as higher brightness enables the reciprocal space resolution sufficient to resolve diffraction from proteins [1, 2], and allows novel coherent imaging modes in microscopy [3]. For well transported beams, the dependence of the transverse coherence length $L_{c,xy}$ on the normalized rms emittance $\epsilon_{n,xy}$ and beam size σ_{xy} at the sample $L_{c,xy} \propto \sigma_{xy}\epsilon_{n,xy}^{-1}$ shows that, for a given probe beam size, the emittance at the electron source can ultimately limit the transverse coherence [4].

For photocathode sources, this limiting cathode emittance is determined by the initial laser spot size $\sigma_{xy,i}$ and mean transverse energy of the emitted electrons (MTE):

$$\epsilon_{n,xy,i} = \sigma_{xy,i}\sqrt{\frac{\text{MTE}}{m_e c^2}}. \qquad (1)$$

Thus, reducing this limiting emittance requires either reducing the MTE, or minimizing the laser spot size, which is typically limited by the amount of accelerating field at the cathode available to support the necessary charge extraction. It has been demonstrated that the maximum charge density extractable is at least linear in the photocathode accelerating field, and can even have a steeper dependence depending on the beam aspect ratio.

In this work we propose the use of a field enhancing tip coated with a multialkali photocathode material (or other similar low emittance material) to provide higher extraction fields, and therefore a smaller laser spot size, in a dc photogun. Coupled with the extreme low intrinsic emittance provided by operating multialkali photocathodes at threshold (where the MTE is set by the material temperature) [5], sub-nm emittances could be achieved. However, the curvature of the tip must be carefully considered, as it may impart an initial nonlinear transverse position-momentum correlation, and thereby may spoil the cathode emittance.

We take the first steps in determining feasibility of this concept by considering the aberration emittance generated by the curvature of the tip itself without space charge. For simple tip shapes, we determine the conditions for which the this geometry induced emittance growth is much smaller than the intrinsic emittance of cryogenic (20 K) electrons, which are anticipated in next generation dc sources. The two examples of tip geometries considered in this work are shown in Fig. 1.

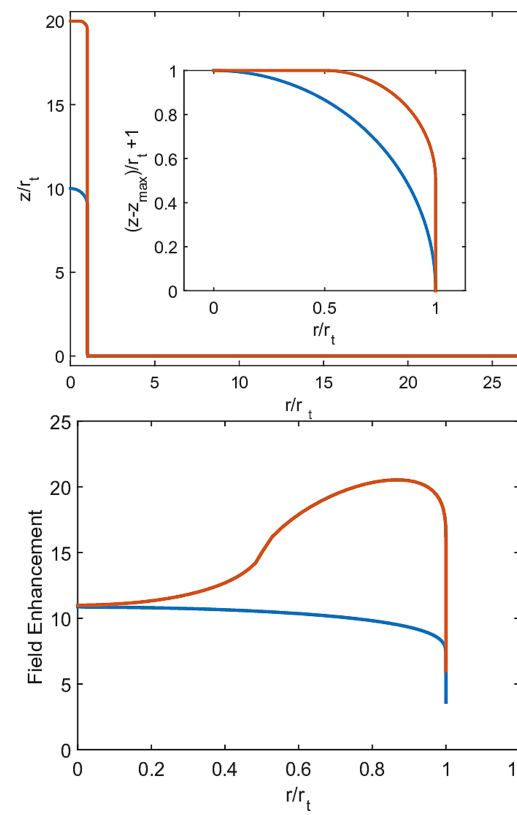

Figure 1: Top: Boundary of the two tip apex geometries considered, which we call “fully round" (blue), or “half round" (orange). Inset: Comparison of tip apex geometries scaled by tip radius r_t. Bottom: Field enhancement vs. radius, showing equal field enhancement at the r=0.

dc guns regularly provide fields on the order of 10 MV/m ([6–8]) at the photocathode plane. In this work we will consider tips with field enhancement $\beta \sim 10$ at $r = 0$, or ~ 100 MV/m extraction fields. For short laser pulses that yield bunches with high aspect ratio σ_{xy}/σ_z, βE_0 =100 MV/m extraction fields have space charge limited source radii between $r_s = (\beta \epsilon_0 E_0 \pi / Ne)^{-1/2} \approx 2 - 8$ micron for $10^5 - 10^6$ electrons per bunch. This sets the spatial scale of the problem. In this regime the field enhancement is roughly given by the aspect ratio of the tip $\beta \sim h/r_t$.

This peak value was chosen to be comparable to those achieved in state of the art normal conducting copper photoinjectors. However, we note at the outset that in practice the highest usable field enhancement will be limited by the onset of unacceptably high values of field emission and any high voltage vacuum breakdown that it prompts. However, high voltage vacuum breakdown is notoriously difficult to predict, and the level of acceptable field emission will vary significantly between applications and downstream optics or collimation. Thus we omit a discussion of these limitations here, but expect that the conclusions drawn below can be generalized to different field enhancements as well.

BOUNDARY ELEMENT FIELD SOLVER AND EMITTANCE CALCULATION

The high aspect ratios of field enhancement structures make the use of traditional volume element field solvers inefficient. Instead, we wrote a boundary element electrostatic solver which discretizes the boundary (rather than the vacuum volume), and solves for the real charge density on each boundary segment (a line in R-Z space) such that the potential boundary conditions are met. Then, in order to calculate the fields at a given point in vacuum, we sum the contribution of each charge density segment. Our solver follows closely the one presented in [9] and was benchmarked in [10], and significantly reduces computation time.

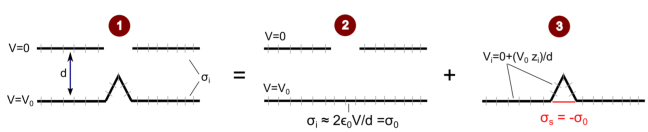

Figure 2: The full field solution (1) is broken down into two pieces. The constant field of an infinite planar diode (2, anode hole ignored), is superimposed on the results of the boundary element solver (3), for the potential shown. Not to scale. Figure taken from Reference [10].

We compute the fields on the tip in the presence of an otherwise uniform electric field of 10 MV/m. We use the superposition principle to separate the problem into two parts: one piece with boundary conditions which provide the uniform electric field far from the tip (an infinite planar diode), and a second piece which corrects the first to provide constant potential on the tip surface. While it is not done here, this separation allows the inclusion of more complicated diode geometries with analytic solutions, such as the inclusion of an anode, without discretizing the anode itself. This process is shown in Fig. 2.

To calculate the emittance generated by the geometry, we track a small number of particles (roughly 20) from the tip with zero initial velocity (no intrinsic emittance). Each particle is tracked to a longitudinal plane (rather than a particular time) such that the radial momentum as a function of the initial position remains constant, i.e. the emiittance saturates. We assume a constant uniform initial radial distribution with maximum emission radius $r_s = 5$ μm, which from the discussion above could yield a space charge limited bunch charge of roughly 10^6 electrons. From this probability distribution, and the final positions and momenta as a function of initial coordinate, we can directly calculate the rms transverse normalized emittance.

GEOMETRY INDUCED EMITTANCE FROM THE CATHODE TIP

We can intuit that for a given emission radius r_s, and fixed aspect ratio (and thus fixed field enhancement), a larger tip will yield smaller emittance, given that the electrons sample less surface and field curvature. This can be seen in an example field ditribution for a fully round apex shape in Fig.3.

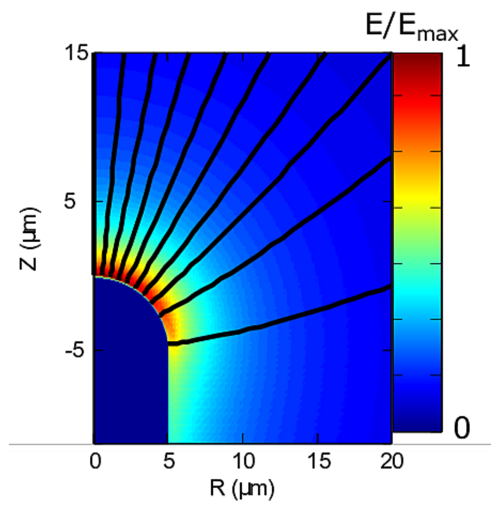

Figure 3: Example electric field distribution from a fully round tip apex shape. Black lines show example electron trajectories.

For a given tip shape (fixing enhancement/aspect ratio) and laser spot size, we seek to determine how large a tip is required to preserve the low emittance of cryogenic scale MTE. In the following, this scale is determined for two practical tip shapes.

Apex Geometry 1: Fully Round

From Fig. 1, it is clear that this tip geometry has the advantage of having the maximum field enhancement located at the tip center, where we expect the transverse fields to be most linear. This tip also very nearly obeys $\beta = h/r_t$. However, the disadvantage to this geometry is its (relatively) large curvature, which leads to a larger emittance signature.

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The final emittance as a function of the tip scale (parameterized by the tip radius) is shown in Fig. 4. These emittances are compared to initial cathode emittances for room temperature and cryogenic (20 K) MTEs, for the both a tip with $r_s = 5\ \mu$m and a flat cathode, which in the pancake limit has a larger spot size by a factor of $\sqrt{\beta}$. Note that in this fully round case a tip radius in excess of $10r_s$ is necessary to preserve the emittance provided by cryogenic MTE, both with field enhancement and without.

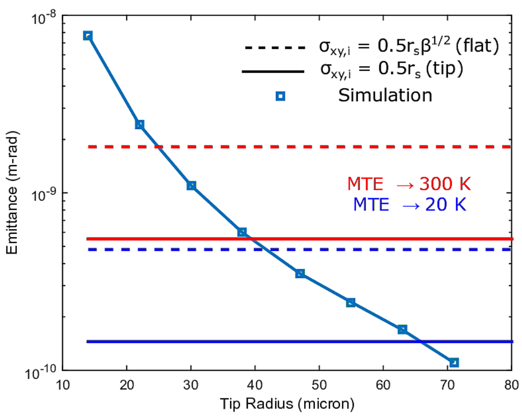

Figure 4: Final simulated emittances as a function of scale, keeping the aspect ratio h/r_t constant. Here and throughout $r_s = 5\ \mu$m. Also shown for comparison are initial emittances for both the tip and a flat cathode case, and for both room and cryogenic temperature MTEs.

Two final transverse phase spaces for different tip radii (14 and 30 μm) is shown in Fig. 5. The reduction of the final emittance arises from a dramatic reduction in nonlinear correlations.

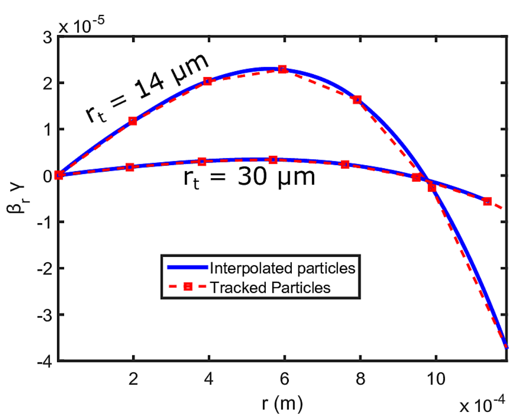

Figure 5: Final transverse phase spaces (with linear correlation removed) for tip radii of 14 μm and 30 μm.

Apex Geometry 2: Half Round

As seen in Fig. 1, this tip does not obey $\beta = h/r$ at the center, but at the edges. Thus to create equal field enhancement as geometry 1 at the center, it must have a larger aspect ratio. Being flatter, we expect this tip to have the advantage of producing lower curvature induced emittance, but at the cost of having a higher field enhancement far off axis. Scaling the tip geometry produces the geometric induced emittances shown in light blue in Fig. 6, where it is again compared to initial emittances in various cases.

In contrast to the fully round case, here having a tip radius of only ~2-3 times the laser spot radius ensures the geometric induced emittance contribution is significantly smaller than the cryogenic intrinsic emittance. Note that the change in slope in the emittance vs tip radius data at $r = 10\ \mu$m is physical, as this indicates the transition from photoemission occurring only on the flat portion of the tip to emission also occurring on the round tip edge.

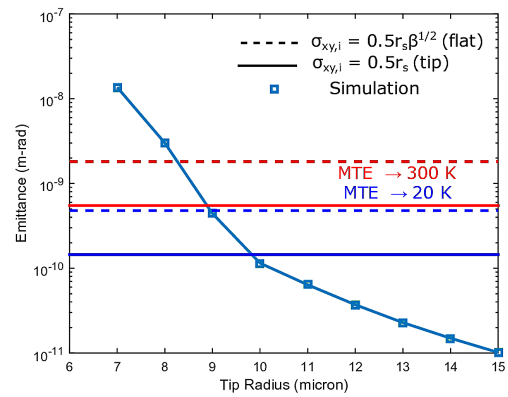

Figure 6: The same as Fig. 4, but for the half round apex geometry.

CONCLUSION AND FUTURE OUTLOOK

In this work we have studied the geometry induced emittance growth of beams photoemitted from a $\beta \sim 10$ field enhancing micron-scale tip placed in a 10 MV/m dc gun. In particular, the emittance from two realistic tip geometries were simulated with a 5 μm laser spot size. For both cases, the geometric induced emittance growth can be made smaller than state of the art cryogenic intrinsic cathode emittances by making the tip radius sufficiently larger than the initial laser spot size. Plans are underway for both manufacturing and proof of principle testing in the Cornell cryogenic dc gun [8].

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