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AN INVESTIGATION OF ELECTRON BEAM DIVERGENCE FROM A SINGLE DFEA EMITTER TIP*

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Abstract

Diamond Field-Emitter Array (DFEA) cathodes are arrays of micron-scale diamond pyramids with nanometer-scale tips. DFEAs can produce high emission currents with small emittance and energy spread. At LANL, we have an ongoing program to test DFEA cathodes for the purpose of using them to generate high-current, low-emittance electron beams for dielectric laser accelerators. We have recently upgraded our cathode test chamber to use a mesh anode in place of a solid luminescent anode. In addition to allowing for downstream beam transport, this arrangement may eliminate earlier problems with reduced cathode performance due to ion back-bombardment. We are measuring divergence of the electron beam past the mesh in an effort to characterize the inherent beam divergence off the diamond tip and divergence contribution from the mesh. We will compare these observations with theoretical and modeled values.

INTRODUCTION

Diamond Field-Emission Array (DFEA) cathodes are arrays of exquisitely sharp diamond pyramids [1]. They are a promising cathode option for a wide range of applications. LANL is currently investigating using DFEAs as the cathode for a dielectric laser accelerator (DLA) [2], which can achieve acceleration gradients of GV/m in a structure where the transverse and longitudinal dimensions of the accelerating field are on the order of the laser wavelength [3]. The promise of DLAs is that they can be orders of magnitude more compact than conventional linacs driven by RF sources. We are currently working to characterize DFEA emission in order to understand how to gate, focus, and collimate beams from a single or few tips. The experimental work presented here is supported by a theoretical modeling effort [4].

DFEAs emit in high or low vacuum, can be transported in air, and have good thermal conductivity that allows for very high per tip current emission without failure. We fabricate DFEAs using standard silicon wafer processes, allowing for the pyramids to be arranged in any array configuration. Individual pyramid base sizes range from 2 micrometers to 25 micrometers, with tips having roughly 50 nm radius of curvature. Overall pyramid height is approximately half the base length. DFEAs were first fabricated at Vanderbilt University, but are now in use at a number of institutions.

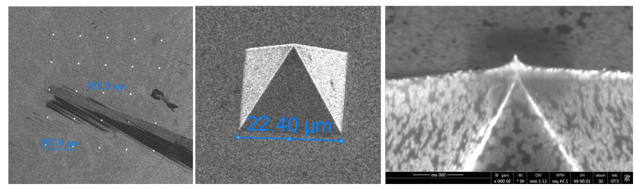

Figure 1: SEM images of DFEA sample Mo-13 at three magnifications. The left frame shows the entire 5x5 array, the middle frame shows the 23 µm base pyramids, and the right frame shows the pyramid tip with about 50 nm radius of curvature.

SEM images of a typical DFEA are shown in Fig. 1. The left frame shows the whole array, 25 pyramids in a 5x5 configuration with about 400 µm pitch. The middle frame shows an individual pyramid with 23 µm base, and the right frame shows a close-up of a pyramid tip. These arrays, which are now fabricated at LANL, are not as exquisitely sharp as some earlier examples, however the emission properties appear to be very similar. The array pictured here is labeled "Mo-13" and produced the data presented in this paper.

EXPERIMENT SET-UP

Our cathode characterization experiments are conducted in a vacuum test stand that is equipped with a number of diagnostics as shown in Figure 2. The test chamber has an ion gauge mounted adjacent to the cathode and anode. The chamber is also equipped with an RGA to analyze constituent gasses. The high-voltage is supplied by a negative 60 kV supply connected to the cathode mount. Experiments are typically conducted at 40 kV, allowing us to operate the DFEAs with an anode-cathode spacing of 3 to 15 millimeters. The cathode is held in a fixed position, and the anode is mounted on a motorized in-vacuum XY actuator stage with a resolution of 25 nm. This stage is used to precisely adjust the field applied to the cathode. We use either an AZO (ZnO:Al2O3) coated sapphire substrate or a stainless-steel plate with a fine mesh welded across a 0.375 inch hole (shown in Fig. 3) as the anode. With the mesh anode we image the beam on the AZO coated substrate (screen). Both the anode and screen are connected to ground through a current-viewing resistor. We operate the experiment in two modes: First, using the set-up in Fig. 2 (set-up A) we test newly fabricated cathodes to determine how many tips emit and whether there is spurious emission from outside the array, and second using the

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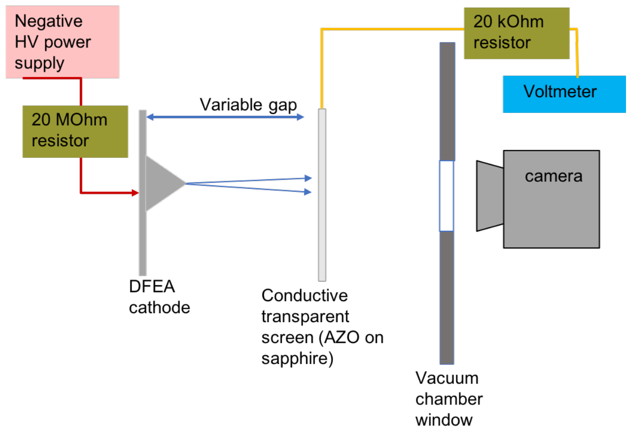

Figure 2: Experimental set-up used for initial cathode testing. Typically we operate the power supply at 40 kV, adjust the cathode-anode gap from 12 mm down to 4 mm, and measure the observed current through a 20 Ohm resistor. We image the emission on an AZO screen.

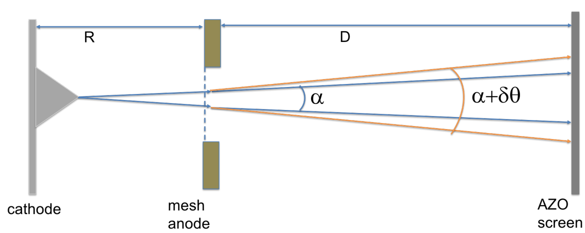

Figure 3: Experimental set-up used for beam divergence measurements. Here we pass the beam through a mesh anode and image the mesh anode on an AZO screen. By changing the distance between the anode and screen we expect to be able to find both the inherent beam divergence as well as the contribution from the mesh.

set-up in Fig. 3 (set-up B) to condition and measure beam divergence. The initial testing experiments typically proceed as follows: with a large anode-cathode gap we turn up the voltage to 40 kV, then slowly bring the cathode closer to the anode. After taking measurements of emission current and pictures of the emission at various gap distances, we bring the cathode away from the anode, continuing to record data. Conditioning and divergence experiments are very similar, except we mount both the mesh anode and screen on the stage, at a fixed separation. We are working to upgrade the system so that both the anode and screen locations can be adjusted separately.

EXPERIMENT RESULTS

Initial Emission from Mo-13

After a cathode is fabricated, we test it for quality. We use the experiment set-up shown in Fig. 2 to determine how many tips emit and if these is emission from defects outside the array. For Mo-13, we observed 20/25 tips emitting. Figure 4 shows the imaged emission from this sample. At maximum we observed 7 μA current per tip, limited by the experimenters. We expect we could have achieved higher currents at closer gaps, however when operating with a screen as the anode we damage the screen, and in doing so damage the cathode by ion back-bombardment.

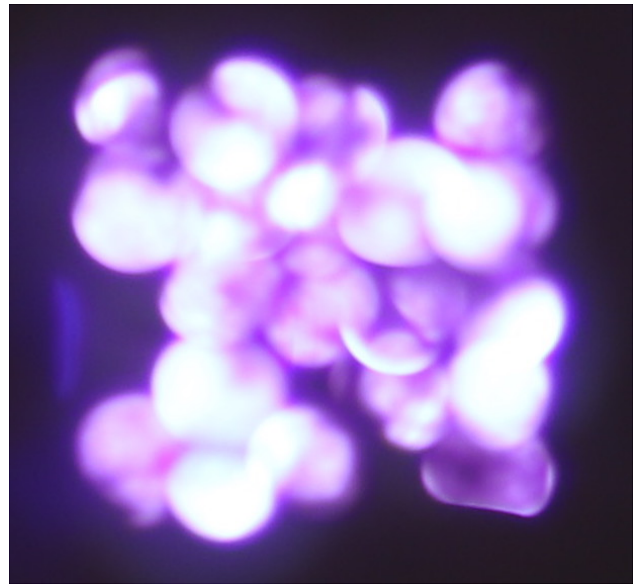

Figure 4: Emission image from sample Mo-13. With this sample nearly 20 tips are emitting and we observed a maximum of 7 μA per tip current.

Figure 5 shows the current emitted by Mo-13 as a function of applied field. Starting around 9 MV/m there are regions where the current increases with constant field. This behavior is a sign of conditioning. Typically conditioning means that more pyramid tips are emitting, some of the sharpest tips might be eroding, and generally the array emission is becoming more uniform. In the past this process has taken around 2 hours, but with this sample we only operated the cathode for about 1 hour.

Beam Divergence Measurements

Theory suggests the mesh contributes $\delta\theta \sim h/8R$ to the beam divergence, where h is the mesh aperture and R is cathode-anode spacing (see Fig. 3) [5]. For our mesh the wire diameter is about 20 μm and the 100 lines per inch corresponds to an aperture of about 230 μm. For our typical anode-cathode spacing of 4.5 mm, $\delta\theta$ is about 0.4 degrees. We observed emission from Mo-13 on the screen through the mesh at 5.8, 8.8 and 13.8 mm mesh-screen distances. The images of this emission are shown in Fig. 6. In general we expected to see the mesh image increase in size with increasing anode-screen spacing. We also expected to see the distribution of beamlet current (image brightness) change between the three images. This indicates that the cathode is not well conditioned. We did not expect that the images of the wires would appear brighter than the surrounding spaces, especially over the large range of anode-screen distances we tested. While obvious in hindsight, we did not initially

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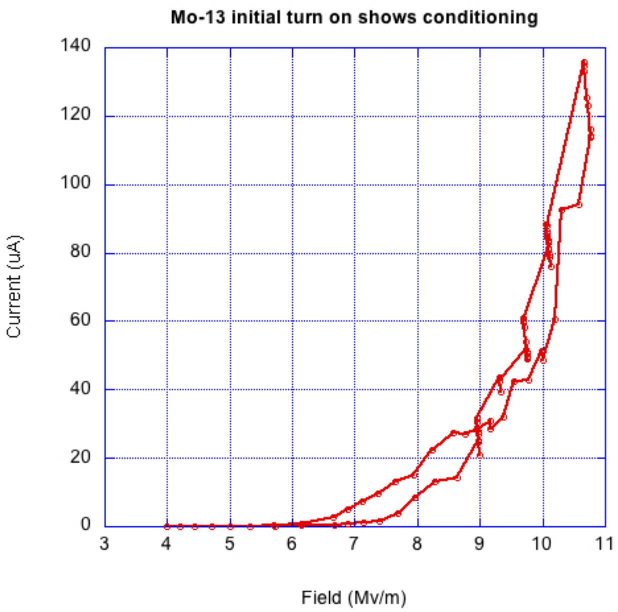

Figure 5: Emission current as a function of applied field for Mo-13 (set-up shown in Fig. 2). Starting at 9 MV/m the features where the current increases for constant field show that the cathode is conditioning.

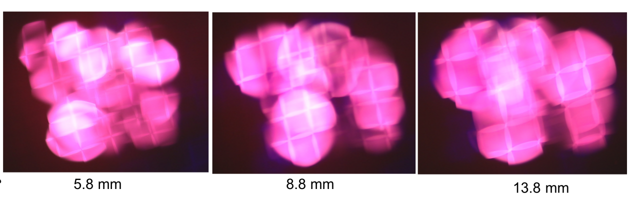

Figure 6: Images of the mesh anode at three anode-screen spacings shown. As expected we see a general magnification of the image with increasing distance.

expect that the small, localized mesh imperfections would yield such large differences in the projected image from one beamlet to another. Figure 7 shows the full angle beam divergence with the theoretical mesh contribution subtracted over a range of values of anode-screen spacing for two values of anode-cathode gap. These initial measurements show a full angle divergence of 1-2 degrees. Accounting for many sources of error, we estimate this value to be accurate within a factor of 2, putting an upper bound on divergence of about 4 degrees. The largest source of error in these measurements is the lack of mesh uniformity. Previous emittance measurements [6] have measured the emittance of an portion of an array, while we are instead trying to measure the inherent beam divergence of a single tip.

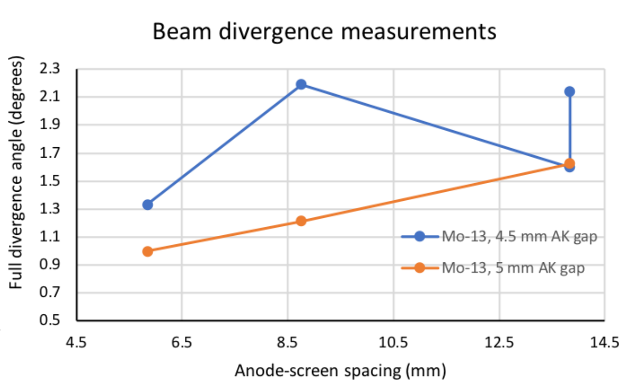

Figure 7: Beam divergence (full angle) with estimated mesh contribution subtracted.

FURTHER WORK

To confirm the beam divergence measurements presented here we would like to conduct more experiments with samples having either many fewer tips, or more broadly spaced tips. This work will also benefit from using a significantly more uniform mesh if one can be obtained. Finally, we plan to condition the sample before making divergence measurements in order to make the emitted current more stable.

ACKNOWLEDGMENT

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