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ANALYSIS OF ELECTRON BEAM DIVERGENCE IN DIAMOND FIELD EMITTER ARRAY CATHODES*

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Abstract

This paper describes the design and recent test results of electron beam divergence and focusing lens studies from a single diamond emitter. For the divergence measurements, we designed and assembled a test stand consisting of a sparse diamond cathode, a mesh anode, and an ZnO:Al_2O_3 (AZO) screen coated on a sapphire substrate. By assembling a focusing lens between the mesh and the screen, we focus our diverging beam to a micrometer-scale spot size. The measured experimental results of the beam divergences and focusing lens studies are compared to the beam dynamic simulations.

INTRODUCTION

At Los Alamos National Laboratory (LANL), we have recently established a capability to fabricate diamond array cathodes for electron beam sources [1, 2]. With nanometer size emitting areas (10-20 nm radius of tips) and high per-tip current (> 15 μA per-tip), diamond field emitter arrays (DFEAs) are promising cathodes for a dielectric laser accelerator (DLA). However, the large beam divergence may represent a challenge to match a dielectric accelerator microstructure [3]. Thus, the present study is conducted to determine the electron beam's divergence angle and demonstrate focusing to a small spot size using variable focusing lens in order to fit the beam into the DLA cavity structure [1].

BEAM DIVERGENCE MEASUREMENT

Experimental and Simulation Setup for Beam Divergence Studies

Figure 1 shows a schematic of the beam divergence study and real images for the needle cathode, the mesh anode, and the ZnO:Al_2O_3 (AZO) screen in the experiment. The fabricated diamond cathode has about 10 nm radius nanotips [Fig. 1(b)] on the top of the 20 μm base pyramids and is mounted on the cathode holder. A negative voltage of 40 kV is applied to the cathode. The mesh plate with an aperture diameter of 9.52 mm [Fig. 1(c)] and the conductive AZO screen [Fig. 1(d)] are mounted separately on movable stages. Both the mesh plate and the screen are connected to ground through 20 kΩ resistors. We measure the voltages across the resistors to calculate the total emission current. Initially, the mesh anode was 15 mm from the cathode and was slowly brought close to the cathode to induce the field emission. We changed the distance between the mesh anode and the screen, measured the size of the beam on the screen, and calculated divergence angle (α+δθ).

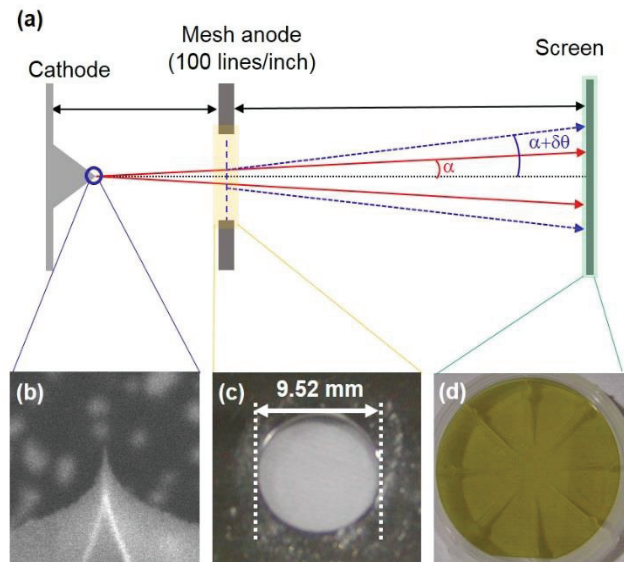

Figure 1: (a) A schematic of the experimental setup (b) The diamond nanotip, (c) the mesh anode, and (d) the AZO screen.

We also conducted beam dynamics simulations using Computer Simulation Technology [5] (CST) Studio and General Particle Tracer [6] (GPT) codes. Based on measured sizes of the fabricated pyramids, we simulated a 20 and 10 μm base single pyramid with a nanowire tip shape (250 nm height and 10 nm tip radius) and calculated electrostatic fields with CST studio. The electric field profiles from CST studio were imported to accelerate electrons in GPT. The electrons were initially uniformly distributed along the hemisphere shape of 10 nm radius.

Experimental Results and Comparison to the Simulation

As shown in Fig. 2(a), the measured divergence angles were dependent on both the anode-cathode (AK) gap, as well as the base size of the pyramids. The divergence angles did not show much dependence on the base size of the pyramids.

Figure 2(b) shows that the divergence angles remained the same with a constant AK gap when the applied voltage was changed. In the simulation, the voltage between the

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anode and the cathode was increased to 100 kV, but we observed almost the same divergence angles. This can be explained by the fact that the ratio of the transverse electric field to the longitudinal electric field does not change with voltage.

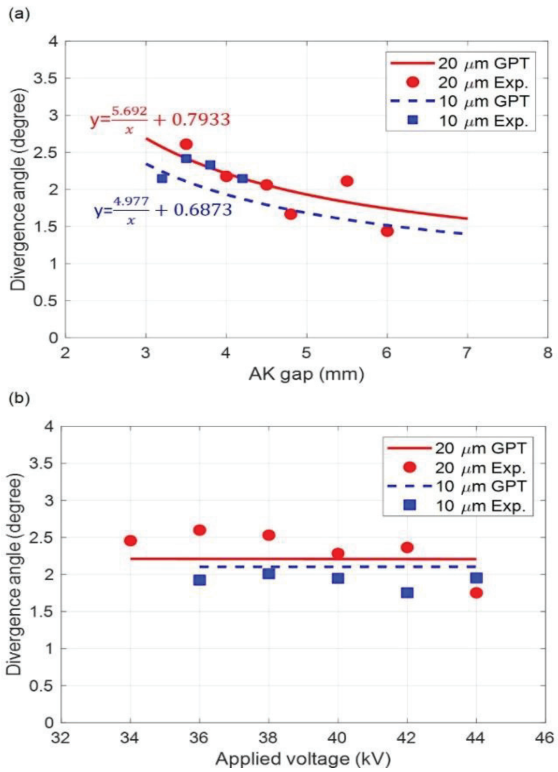

Figure 2: Measured and simulated divergence angles at different AK gaps and applied voltages. (a) The AK gap was varied from 3 to 6 mm, and the applied voltage was fixed at 40 kV. (b) For the 20 and 10 μm pyramids, the AK gap was fixed at 4 mm and 3.6 mm, respectively, while the applied voltage was varied.

FOCUSING STUDIES

Experimental and Simulation Setup for Focusing Studies

Once the beam divergence studies had been concluded, we then modified the experimental setup in order to allow us to develop a method of focusing the beam to a small spot size of only several μm. The schematic of the focusing experimental setup is shown in Fig 3(a), a photograph of the setup itself [Fig. 3(a)] and another photograph of wire holder [Fig. 3(b)]. The thin 80 μm wire can be seen in the aperture.

Similarly to the divergence studies the experiment consisted of applying a negative voltage of 40 kV to the cathode. In this case the mesh screen is mounted on a separate stage, the magnetic lens is mounted in a fixed position after the screen, and the copper wire and AZO screen are mounted on an additional stage. It is important to note that the AZO screen and the copper wire are electrically isolated from each other, which allows us to measure the current collected by the wire across a 20 kΩ resistor separately from the current deposited on the screen.

The reason for utilizing a wire scanning technique as opposed to measuring the spot size directly on the AZO screen is a matter of resolution. Previously we had been able to measure a spot size of approximately 10 μm [4] on the screen, but could not determine if the beam was any smaller than that due to the limited resolution of the camera.

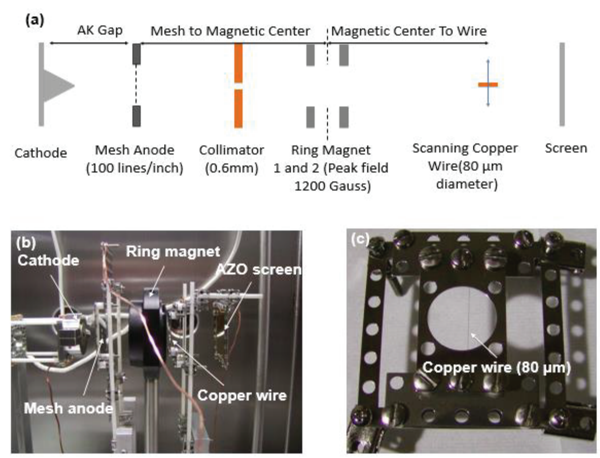

Figure 3: (a) Schematic of the focusing studies. (b) Photograph of the focusing study setup. (c) Photograph of the copper wire holder. The wire is 80 μm in diameter.

Instead, by measuring the voltage on the copper wire as we moved it across the beam horizontally, we are able to determine the size of the spot with much finer resolution that is instead limited by the resolution of the stage and not the resolution of the camera and AZO screen. The stage has a resolution of approximately 200 nm.

Figure 4 shows a picture of the beam on the AZO screen positioned at a distance of 16 mm from the magnetic center of the focusing lens. (We used this image to determine the location of interest for the wire scan to take place.) The two vertical white bars show the area that the wire scanned. We then scanned from left to right for a distance of 0.5 mm at an increment of 1 μm. We collected 10 data points at each location along this scan and averaged those 10 points together. This averaging was done in order to correct for the observed fluctuations in cathode current.

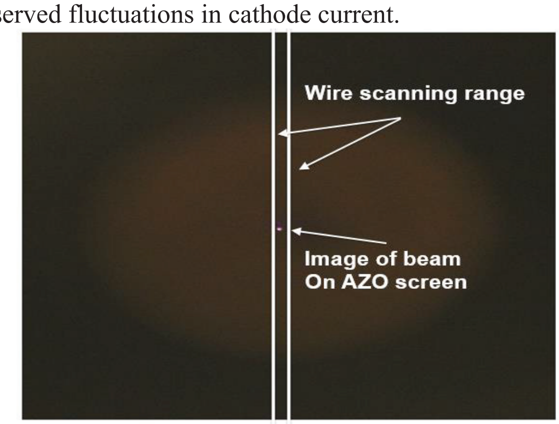

Figure 4: Snapshot of the beam at a distance of 16 mm from the magnetic center of the lens. The white bars indicate the wire scanning range.

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The experimental parameters for the focusing test are detailed in Table 1.

Table 1: Experimental Parameters

Experimental Parameter	Value
AK Gap	3.9 mm
AK Voltage	40 kV
Mesh to Wire Distance	67.19 mm
Magnet to Wire Distance	16 mm
Pyramid Base	8.3 µm
Pyramid Spacing	400 µm
Measured Spot Size	5.72 µm
Peak Magnetic Field	1200 Gauss
Measured Average Current	15.78 µA

We then conducted additional beam dynamics simulations using the same CST code electric field profiles, and importing them into GPT. We generated the magnetic field of the lens using POISSON [7] and imported that into GPT as well in order to simulate focusing and estimate the expected focal point, as well as the expected spot size of the beam.

Experimental Results and Comparison to Simulation

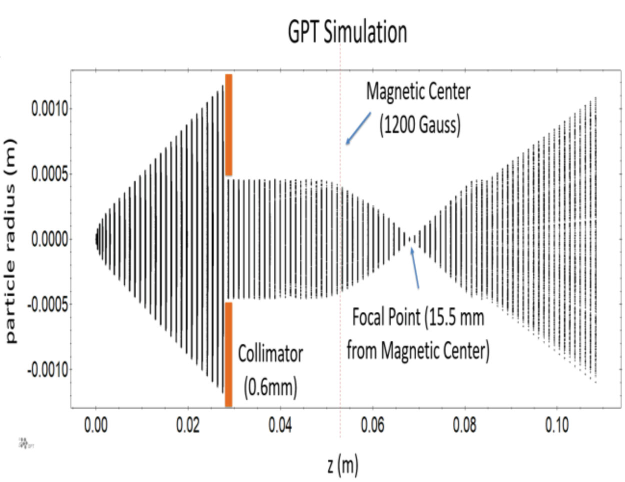

Figure 5: GPT simulation of the beam converging to a 3 µm spot size at a distance of 15.8 mm from the magnetic center.

The simulation results shown in Fig. 5 predicted that the beam will be focused at a distance of 15.8 mm from the magnetic center with a spot size of 3 µm. This is in good agreement with experimentally measured spot size in Fig. 6. Figure 6 shows the results of scanning the 80 µm wire across the beam. The voltage was measured on the wire when it overlapped with the beam, giving us a spot size of 5.72 µm. The difference between the simulation value and the measured value can most likely be attributed to small misalignments in the experiment as well as a lack of uniformity in the diameter of the copper wire. It is also possible that the wire is vibrating as the stage is moving, and could be distorting our results. It is worth noting the two 'peaks' that appear in Fig. 6 on either end of the measurement. These peaks require further study and analysis in order to determine if they are real, or only abnormalities generated by the measurement process.

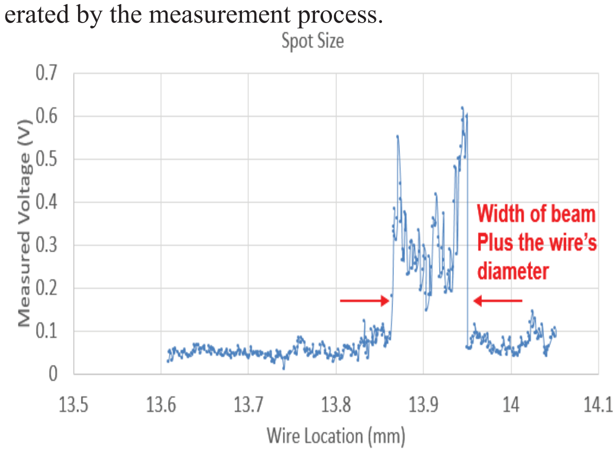

Figure 6: Graph of the measured voltage on the copper wire versus the location of the wire. Showing a spot size of 5.72 µm.

CONCLUSIONS AND FUTURE PLANS

We have fabricated and tested diamond field emitter array cathodes for divergence and focusing studies. First, we performed the electron beam's divergence studies using our two cathode samples. As the AK gap increased with fixed voltage, measured divergence angles decreased which was in good agreement with simulation. The divergence angles were constant even if the applied voltage was varied for the constant gap.

We then added a simple focusing lens [4] in order to measure and study the effects of focusing the diverging beam to a point small enough to enter a DLA [2]. In order to measure this effect we have upgraded from using a screen to utilizing a wire scanning technique. This technique has allowed us to measure a spot size of 5.72 µm. This result agrees with simulations from GPT but is not yet ideal. Additional measurements must be made, as well as adjustments to the experimental setup in order to further refine the resolution of our spot size measurement. This refinement will take place by further increasing the mechanical alignment of the experimental setup, as well as decreasing the diameter of the wire used to perform the test, and further characterizing any change in that wire's diameter and jitter.

ACKNOWLEDGEMENTS

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