FOCUSING STUDIES OF AN ELECTRON BEAM IN DIAMOND FIELD EMITTER ARRAY CATHODES*

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Abstract

We report the results of tests and simulations for focusing studies performed on diamond field emitter array cathodes. This experiment utilized a simple variable-focus solenoidal lens to focus the beam produced by a diamond field emitter array cathode. The spot size was measured by scanning a thin copper wire across the beam in 1 µm increments, with voltage being measured and averaged at each location in order to map the location and intensity of the beam. Scans were taken at different distances away from the magnetic center of the lens. However, there were some unforeseen challenges associated with measuring the exact spot size of the beam, and we will explain them here.

INTRODUCTION

At Los Alamos National Laboratory (LANL), we have the ability to fabricate diamond array cathodes for use as electron beam sources [1, 2]. These cathodes feature nanometer scale emitting areas (10-20 nm radius per tip) and high current per tip (up to 15 µA per-tip), diamond field emitter arrays (DFEAs) are promising candidates for use in a dielectric laser accelerator (DLA). However a DLA structure requires a very tightly focused beam (1 µm scale) [1, 3]. In order to achieve this requirement we have been conducting focusing studies on diamond pyramids to learn if we can sufficiently focus the beam.

FOCUSING STUDIES

Experimental Setup

Figure 1 (a) is a schematic of the experimental setup for our focusing studies. Figure 1 (b) is a photograph of the experimental setup, and another photograph Fig. 1 (c) shows the copper wire in place attached to the wire holder. Table 1 shows the setup parameters for the experiment.

The experimental setup included a cathode in a cathode holder, a mesh anode, a focusing lens with a collimator, a copper wire, and a conductive luminescent screen. The cathode being used was a 3 by 3 array of diamond pyramids, each with a 25 µm base and 1000 µm spacing. A 100 lines per inch, mesh anode was mounted on a single axis controllable stage in order to vary the intensity of the electric field from cathode to anode. The anode to cathode distance (AK gap) was set at 5.5 mm. The variable focus magnetic lens [4] was mounted in a fixed position, 48.1 mm behind the mesh anode, and had a peak magnetic field of 1200 Gauss. The copper wire, and $ZnO:Al_2O_3$ (AZO) screen are mounted on a two axis stage, grounded and are isolated from each other electrically in order to allow us to measure the current collected by the wire across a 20 kΩ resistor separately from the current that is deposited on the AZO screen. The wire is positioned between 13.5 mm and 16 mm from the magnetic center of the lens depending on where we wanted to measure the size of the beam. The screen was used to align the wire with the beam path, as well as to understand the beam's behavior and for troubleshooting purposes.

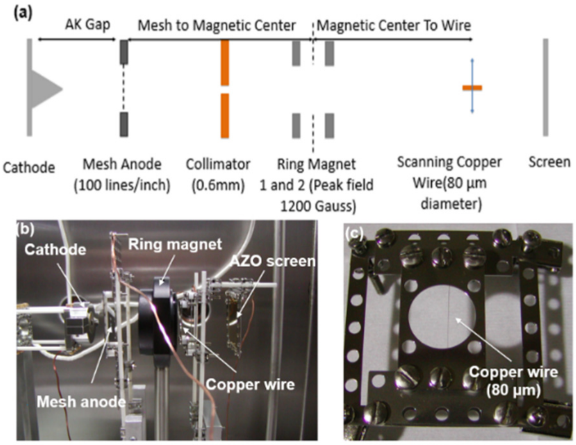

Figure 1: (a) Schematic of the scanning wire focusing studies. (b) Photograph of the focusing study setup. (c) Photograph of the wire holder. The wire in the photo is a copper wire, 80 µm in diameter. A 5 µm tungsten wire was also used in the experiment in place of the copper wire.

Table 1: Setup Parameters

Experimental Parameter	Value
AK Gap	5.5 mm
AK Voltage	-40 kV
Lens to Wire Distance	13.98 mm, 14.50 mm, 15.48 mm
Lens to Mesh Distance	48.1 mm
Pyramid Base	25 µm and 20 µm
Pyramid Spacing	1000 µm and 900 µm
Peak Magnetic Field	1200 Gauss
Wire Diameter	80 µm and 5 µm
Wire Material	Copper or Tungsten
Computed focal length	15.1 mm
Computed focal diameter	10 µm

Methodology and Initial Results

We performed beam spot size measurements utilizing a wire scan method. We began by moving the 80 µm copper wire in one direction in increments of 1 µm. We measured the current collected on the wire and observed the images on the screen. During the first scan the wire was located

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13.98 mm from the center of the lens. We observed the shadow of the wire on the AZO screen moving in the direction opposite of the wire Fig. 2 (a). Next, we moved the wire to 15.48 mm from the center of the lens, and observed the shadow of the wire on the AZO screen moving in the same direction as the wire Fig. 2 (c). Finally, we moved the wire to 14.50 mm from the center of the lens, and observed that the shadow of the wire on the AZO screen now moved in both directions at once, appearing to close in from both sides of the image Fig. 2 (b). Figure 3 illustrates the explanation of the observed shadow's behaviour in relation to the wire's location, and size.

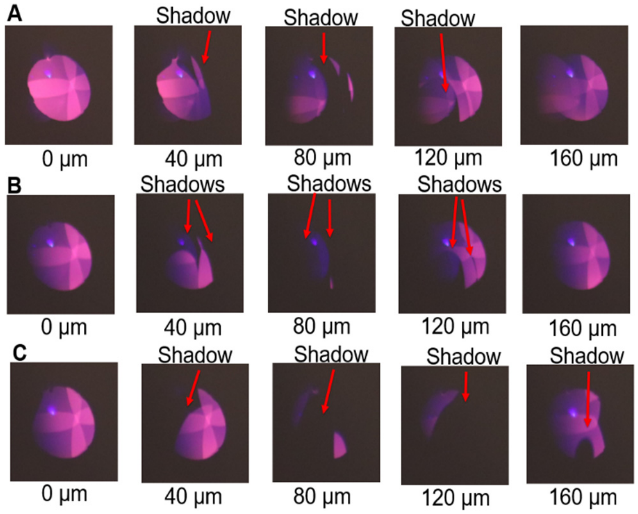

Figure 2: (a) Images of the beam taken at measurement plane A, 13.98 mm from the magnetic center. (b) Images of the beam taken at measurement plane B, 14.50 mm from the magnetic center. (c) Images of the beam taken at measurement plane C, 15.48 mm from the magnetic center. Images are taken after the wire has moved 40 µm in the same direction.

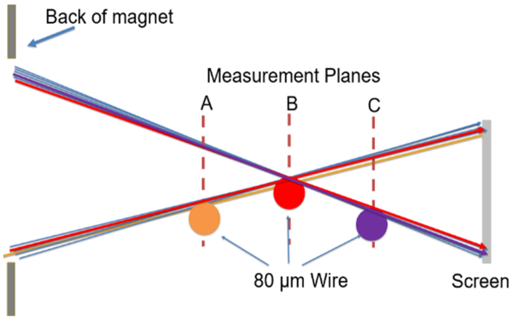

Figure 3: Schematic of electron trajectory, and wire scan location. The location of the wire determines what side of the screen the shadow will appear on. We tested this by measuring at planes A, B, and C. The color of the wire is matched with colors of the particle lines that it may impede when being inserted into the beamline.

As shown in Fig. 3, the placement of the wire is what causes the 'shadow' effect on the screen. When measuring before the focal point, at plane A, the electrons are blocked before they have crossed over the focal point, which causes the shadow to appear on the opposite side of the screen. This is shown in Fig. 2 (a). Figure 3, plane C shows that the electrons are blocked after they have passed the focal point, and thus we would expect the 'shadow' to move in the same direction as the wire. This is shown in Fig. 2 (c). These two points behave as you would expect when taking into account the electron trajectory, but an interesting interaction occurs when measurements are taken at plane B. Due to the large 80 µm diameter of the wire, as it approaches the beam near the focal point it will block electrons both before, and after the focal point. This results in a 'shadow' that appears to converge from both sides of the beam at once. This effect can be seen in Fig. 2 (b), and results in an additional limiting factor in measuring a minimum beam spot size. Simply put, the minimum spot size that we can measure with our setup will be limited by the diameter of the wire. The reason this interaction limits our minimum spot size is the wire now picks up current from particles that are both still converging on the focal point before reaching it, as well as particles that are diverging from the focal point after passing through it. When measuring the spot size, with this interaction in place, we are able to measure a diameter of 90 µm, but this number is rather large when compared with an expected diameter of 10 µm from GPT [5] simulations that are shown in Fig. 4.

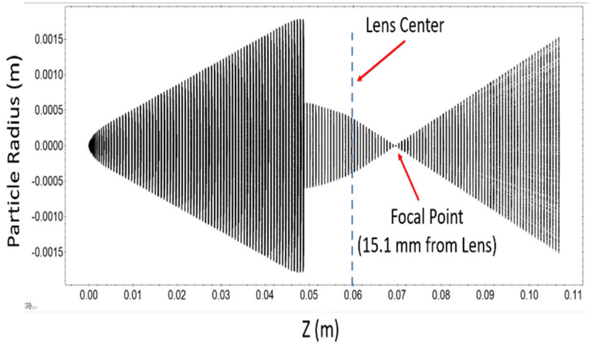

Figure 4: GPT simulation of the electron beam. The focal point is measured at 15.1 mm from the magnetic center, and has a spot size of 10 µm.

Figure 4 shows electron trajectories that result in an expected beam spot size of 10 µm, and a focal point that is 15.1 mm from the center of our lens.

In order to refine the resolution of our setup, we replaced the 80 µm copper wire with a 5 µm tungsten wire, and attempted to perform the same measurements. For this experiment, we also utilized a different cathode, due to the original cathode being damaged during experimentation. This new cathode consisted of a single row of 12 diamond pyramids, with a base size of 20 µm and a spacing of 900 µm. The images on the AZO screen for this experiment are shown in Fig. 5. We observed that the shadow on the screen did not behave in a way that we would have expected. The 'shadow' appeared to be rounded near the top, and didn't look straight, crossing through the entire beam.

In order to understand why the shadow had an unexpected shape we first analysed the magnetic field of our variable focusing lens [4]. As noted in [4], the lens itself has significant spherical aberration to it, and would result in a rotational force being applied to the electrons as they travelled along the beamline. This rotational force or mode would explain why the shadow appears to have a rounded top, but not why the shadow does not blocks a path across the entire beam diameter.

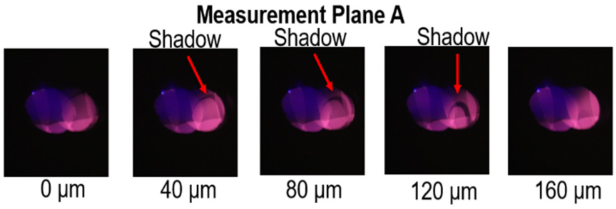

Figure 5: Images of the beam taken at measurement plane A, 13.98 mm from the magnetic center. This shows the beam intersected by the 5 µm tungsten wire.

The strange appearance of the shadows can be explained by the fact that 40 keV electrons could in fact partially penetrate through the 5 µm tungsten wire. Using GlobalSino [6] we calculated the approximate penetration depth that we could expect from our beam. Upon calculating an expected penetration of 2.71 µm in tungsten it became clear to us that the reason we see the abnormalities in the shadow on the screen, is that the electrons are able to penetrate through our wire in locations where it is not at least 2.71 µm thick. This penetration meant that using the available 5 µm wire was not going to be a viable solution to our resolution issue.

This realization, caused us to re-evaluate our methodology, and determine that we should pursue using a sharp knife edge in order to more accurately measure the beam's diameter. A sharp knife edge will allow us to avoid the rounded shape of the wire, and thus use a material that is of uniform thickness, to avoid locations in which electrons may penetrate the material.

CONCLUSION

We have reported the results of simulations and measurements of focusing studies performed on a 40 keV electron beam, which uses a DFEA cathode as a source. In order for DFEA cathodes to be a viable source for DLAs we must focus the beam down to a spot size of just one or two micron. We have designed a lens that should be able to focus the beam into a 10 µm diameter spot, with the ability to more tightly focus the beam by increasing the magnetic strength thanks to its variable design. We have conducted wire scanning measurements using an 80 µm diameter copper wire, and measured a beam size of approximately 90 µm. The reason for this discrepancy is discussed in this paper, and is attributed to the wire's diameter and curvature. We performed additional testing using a 5 µm diameter tungsten wire, but were unable to measure the beam's size due to the electrons penetrating through parts of the wire's material. Our next step moving forward is to conduct an improved version of this experiment, by utilizing a sharp knife edge which will allow us to control the thickness of the material uniformly, as well as eliminate the curvature that was present in the wires, in order to more accurately measure the beam at the focal point.

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[5] General Particle Tracer, `http://www.pulsar.nl`

[6] GlobalSino, `http://www.GlobalSino.com`