PULSED UNIFORMITY CONDITIONING AND EMITTANCE MEASUREMENTS OF DIAMOND FIELD-EMITTER ARRAYS

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Abstract

We present recent advances in the uniformity conditioning of diamond field-emitter arrays (DFEAs), and new results from emittance measurements of their emitted electron beams. DFEAs have shown considerable promise as potential cathodes for free-electron lasers. They have demonstrated their rugged nature by providing high per-tip currents, excellent temporal stability, and significant resistance to back-bombardment damage during poor vacuum, close-diode DC operation. Until now, the successful conditioning of high-density arrays has been precluded by thermal damage to the anode. We report successful uniformity conditioning of densely packed DFEAs using microsecond-pulsed high-current conditioning (HCC). A high degree of spatial uniformity was confirmed in low-current DC testing following these HCC procedures. The conditioned arrays will be used to refine previous measurements of the normalized transverse emittance of the emitted electron beams.

INTRODUCTION

The development of free-electron lasers of higher power, shorter wavelength and increasing utility depends on the development of electron-beam sources of higher brightness and better reliability and durability. Photocathodes are usually used for this purpose, but durable metal cathodes have quantum efficiency that is too low for high-power applications and semiconductor cathodes are too fragile for applications such as light sources that must operate reliably. In addition, photocathodes require advanced lasers to drive them. Field-emitter arrays promise to deliver beams of high brightness with reliability and durability, and they don't require a laser driver. However, they are at a relatively early stage of development.

Field-emission arrays can be operated either gated, to control their emission, or ungated. Additional electrodes can be incorporated to focus the beamlets from individual emitters. In the following, we discuss only ungated emitters. In the past, emitters have been formed from many materials, including Si and Mo. Diamond has the advantage that it is durable, having a strong covalent bond structure, and chemically inert, and we restrict our remarks to diamond field-emitter arrays. These are fabricated by microlithography, forming first an array of pyramidal depressions in a silicon substrate, oxidizing the surface of the mould to form a sharper tip, and then filling the mould with diamond [1,2]. After this, the diamond is brazed to a molybdenum substrate, and the Si mould is etched away to expose the tips. An example of an array formed this way is shown in Fig. 1.

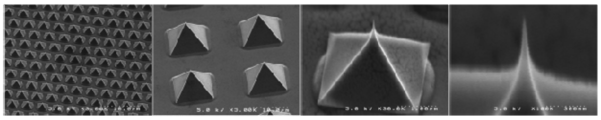

Figure 1: 4- and 20-µm pitch arrays (left) and detail of the emitter tips (right).

CONDITIONING

The DFEAs are conditioned in the apparatus shown schematically in Fig. 2. The phosphor or metal anode is spaced about 120-280 µm from the tips by means of quartz capillary spacers. For sparse arrays, for which the individual beamlets don't overlap, the arrays may be conditioned by sustained operation at high current. However, for dense arrays, for which the beamlets overlap, the intensity at the anode is sufficient to damage the anode, causing sputtering and back-bombardment of the cathode that destroys the emitters. To avoid this, we operate the conditioning apparatus in a pulse mode, using microsecond pulses repeated at tens of hertz repetition rate. An example of a high-current pulse from a 448x224, 20-µm pitch array is shown in Fig. 3. In pushing to higher total current density we have performed pulsed testing on a 20×250, 4- µm pitch array at a peak current of approximately 25 mA. This corresponds to a current density of about 30 A/cm^2. A current vs. time trace of one of these pulses is shown in Fig. 4. The large spike at the beginning of the pulse is the charging current for the anode cathode capacitance. We would note that this operation was limited by the voltage range of our pulser, and that per-tip currents three times greater have been observed in testing of other arrays. For this same level, the current density would approach 100 A/cm^2.

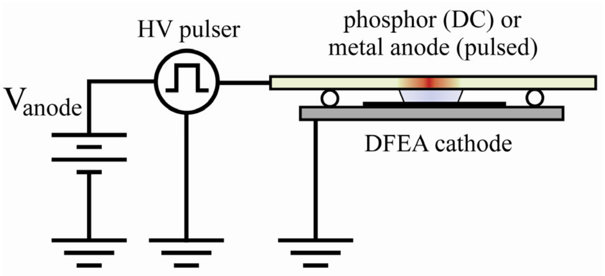

Figure 2: Schematic representation of the close diode testing arrangement for pulsed conditioning.

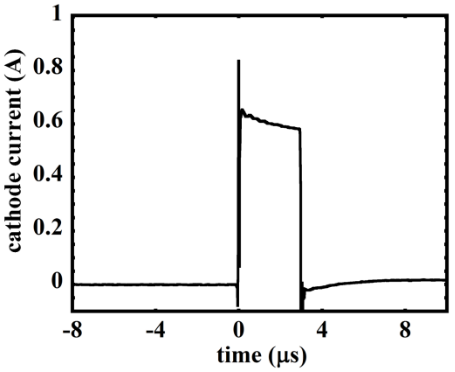

Figure 3: Current vs. time for a 224x448 array operating at a peak current of ~0.6 A.

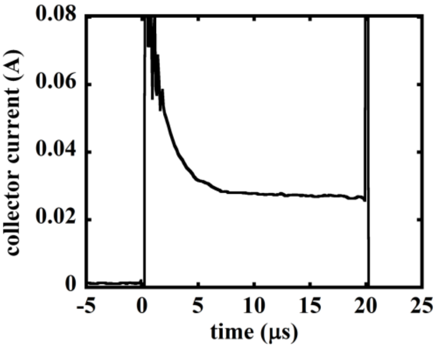

Figure 4: Current vs. Time for a 30 A/cm^2 pulse from a 20x250-tip array.

The improvement in emission uniformity achieved by pulsed high-current conditioning for a 224x224 array is shown in Fig. 5. The conditioning occurs by several mechanisms. Important among them are changes in the morphology of the tips; the strongest emitters become duller, which reduces their emission. This leads to modest increases in the voltage required to achieve the same current, as illustrated in Fig. 6. An IV curve of the peak current during the conditioning process is shown in Fig. 7.

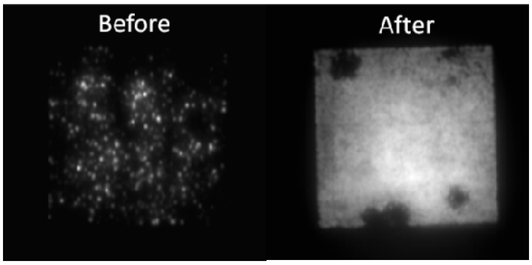

Figure 5: 224x224 array before and after pulsed conditioning.

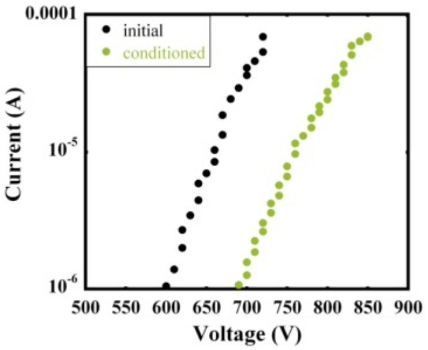

Figure 6: Current versus voltage for a 224x224-tip array with 14-µm pitch and a 170-µm anode-cathode spacing before (black) and after (green) conditioning.

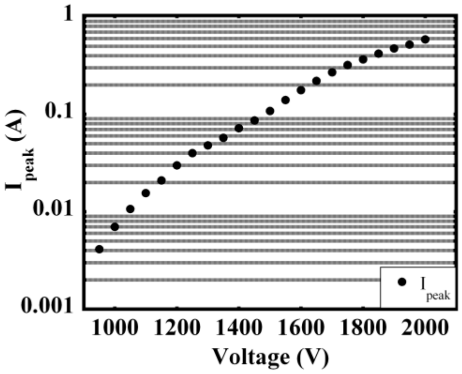

Figure 7: Peak total current achieved in the pulsed conditioning process for an array of ~50,000 tips.

EMITTANCE MEASUREMENTS

An important figure of merit for an electron beam is the normalized emittance, defined as

$$\varepsilon_x = \beta\gamma\Delta x\Delta\theta$$

where βc is the electron velocity, c the speed of light, γ the Lorentz factor, Δx the width, and $\Delta\theta$ the angular divergence of the electron beam. The emittance is useful for describing the focal properties of the electron beam. For a well-conditioned array, the emission is uniform over the cathode, so the rms width of the beam is $\Delta x = W / \sqrt{12}$, where W is the width of the array. To determine the emittance it is sufficient to measure the angular spread at one point in the array. This is done in the apparatus shown in Fig. 8, using the so-called "pepperpot" technique. The anode-cathode spacing was 230 µm, and the pepperpot-phosphor spacing was 3.55 mm. The apparatus had a base pressure of ~10^{-8} Torr, and was operated with an anode voltage of 1.3 kV.

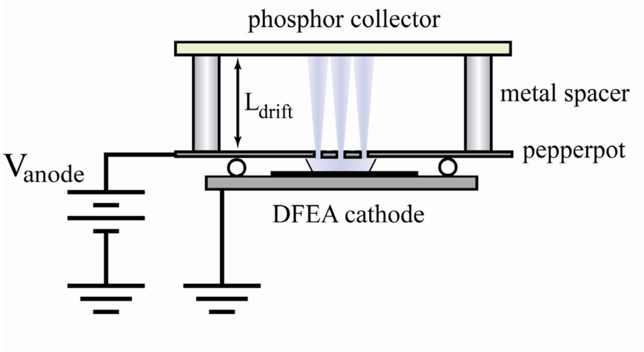

Figure 8: schematic of the experimental arrangment during pepperpot emittance measurements.

As shown in the figure, the electrons are accelerated to the anode, where they pass through small holes that form the pepperpot. After passing through a hole, the beam expands in the field-free region between the anode and the phosphor screen. Provided that the spot on the phosphor screen is large compared with the hole, the size and shape of the spot are independent of the size and shape of the hole, and the spot size is a measure of the beam divergence. The spacing between individual holes in the pepperpot must be large compared to the spot size of the individual beams emerging from the holes to prevent overlap of the spots. Since the electrons pass from the accelerating field into a field-free region, the beam divergence must be corrected for the defocusing effect of the hole. To provide a good measure of the average divergence of the beam from the cathode, the hole should be small compared to the anode-cathode separation, so that the hole doesn't disturb the field at the cathode, and the hole should sample several tips at varying distances from the axis of the hole. That is, the spots at the anode from the individual tips should be large compared to the spacing (pitch) between the tips.

The pepperpot was fabricated by femtosecond-laser machining from 50-µm thick steel shim stock. As shown in Fig. 9, the holes were about 50 µm across with a pitch of 1 mm. Figure 10 shows a phosphor image of a beamlet and a horizontal-line scan as well as one of the apertures for size comparison. A Gaussian fit of the beam profile gives an rms angular divergence of 67 mrad, and after correction for the defocusing of the aperture fields, 46 mrad. For a 1x1 mm uniform cathode, the normalized transverse rms emittance is then $\varepsilon_N \sim 0.94$ µm-rad.

Previous measurements using a sparse array show that for an individual tip the spot size at the anode is on the order of 80 µm. This is large compared to the pitch (20 µm) of the arrays used in these measurements.

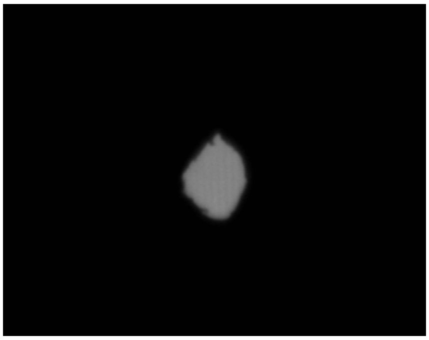

Figure 9: Laser-machined hole in the pepperpot of typical diameter of 50 µm.

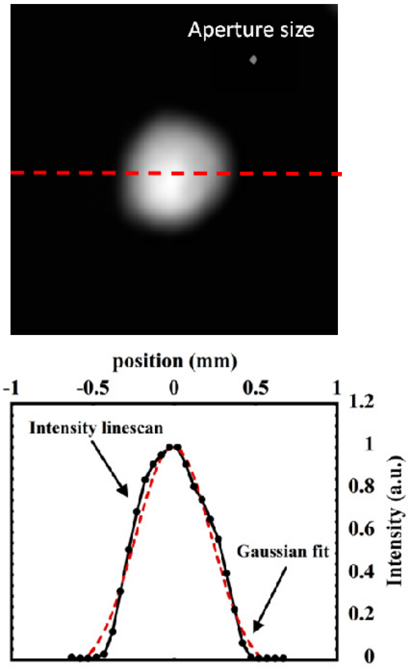

Figure 10: Line scan and gaussian fit of a beamlet from a pepperpot aperture

CONCLUSIONS

DFEAs continue to demonstrate promise as potential beam sources for free-electron lasers. They are rugged, chemically inert, and have a high thermal conductivity. We have successfully demonstrated pulsed uniformity conditioning at microsecond time scales and have achieved current densities of ~30 A/cm^2 for microsecond pulses. The normalized transverse rms emittance of dense arrays has been measured by a pepperpot technique and was found to be ~1 mm-mrad for a 1x1 mm uniform cathode. Future work will include high current density pulsed operation in UHV conditions, conditioning and emittance measurements of gated devices

REFERENCES

[1] J. D. Jarvis, H. L. Andrews, C. A. Brau, B. K. Choi, J. L. Davidson, W.-P. Kang, S. Raina and Y.-M. Wong, "Fabrication of diamond field-emitter-array cathodes for free-electron lasers," Proceedings of the 30th International Free-Electron Laser Conference, Gyeongju, Korea, August 2008.

[2] W. P. Kang, J. L. Davidson, M. Howell, B. Bhuva, D. L. Kinser, D. V. Kerns, Q. Li, J. F. Xu, J. Vac. Sci. Technol. B, 14, 2068 (1996).