

# TOWARD ENERGY-SPREAD MEASUREMENTS OF DIAMOND FIELD-EMITTER ARRAYS

Jonathan D. Jarvis, Heather L. Andrews, Charles A. Brau, Bo Kyoung Choi\*, Jimmy Davidson\*, Weng Kang\*, Supil Raina\*, Chris. L. Stewart, Yong Mui Wong\*

Department of Physics and Astronomy, Vanderbilt University, Nashville, TN 37235, U.S.A.,

\*Department of Electrical and Computer Engineering, Vanderbilt University, Nashville, TN 37235, U.S.A

## Abstract

A high-resolution retardation energy analyzer has been developed to examine the energy spread of electron beams from diamond field-emitter arrays. Analyzer design was guided by previous work at UMER [1], and simulations performed in SIMION. The analyzer incorporates a cylindrical focusing electrode which, when properly tuned, gives millivolt resolution for multi-kilovolt beams. The analyzer is integrated into a low-energy cathode test stand that allows arbitrary adjustment of the anode-cathode spacing and planarity during operation.

## INTRODUCTION

Recent experiments have demonstrated the potential of diamond field-emitter arrays as cathodes for free-electron lasers [2, 3]. As such, it is important to characterize the fundamental emission properties of these cathodes. These include per-tip-current limits, temporal emission stability, transverse emittance, and beam energy spread.

To measure the emitted energy spread we have developed a high-resolution retardation energy analyzer based on previous work at UMER [1]. The measured energy spread in a standard retardation analyzer is artificially high due to trajectories having nonzero transverse momentum. By including a cylindrical focusing electrode, the energy resolution can be improved by several orders of magnitude. A schematic of the analyzer accompanied by a cathode is shown in Figure 1.

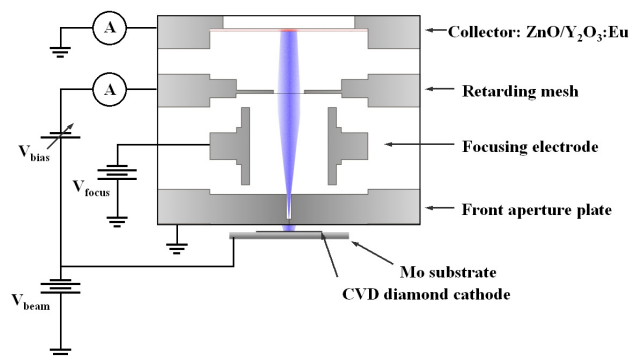


Figure 1: Energy analyzer schematic (with cathode).

## SIMULATION

In order to predict performance of the analyzer we have modeled the system in SIMION 7.0, an ion/electron optics workbench. An isometric-cutaway view of the analyzer is seen in Figure 2. To find the achievable energy resolution, we provide the analyzer with a monoenergetic

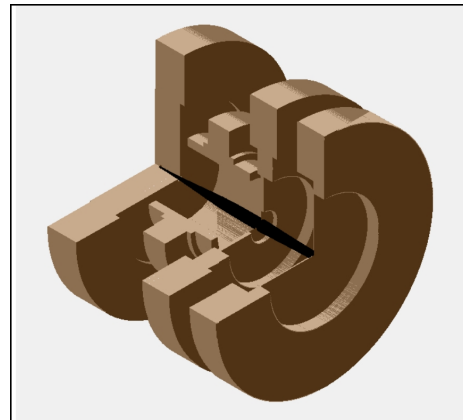


Figure 2: Isometric-cutaway view of analyzer in SIMION.

beam having a  $5^\circ$  correlated-full-angle spread. Prior to energy scans, the focusing electrode is adjusted until the electron trajectories are normal to the retarding mesh. Alternatively, the measured energy spread may be minimized as a function of focusing voltage as seen in Figure 3.

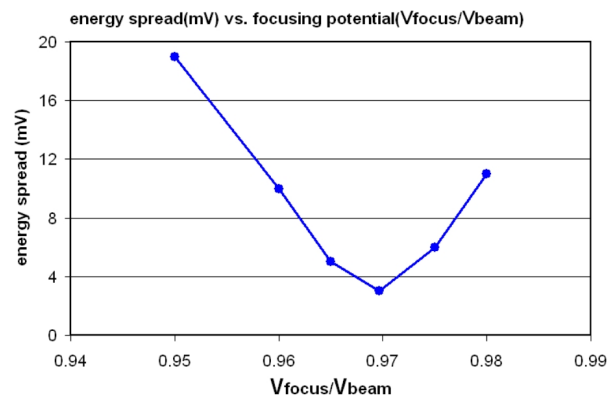


Figure 3: Measured energy spread (mV) vs. applied focusing bias as a fraction of total beam energy ( $V_{focus}/V_{beam}$ ).

Operating the analyzer at this minimum provides resolution that is smaller than the kinetic-energy error in the simulation. The optimum focusing voltage is found to be  $V_{focus} = 0.97V_{beam}$ . Figure 4 shows the integrated collector signal as a function of retardation voltage for beams of different energies. The error as a fraction of the total beam energy is 10 ppm, 10 mV for a 1 kV beam. Equipotentials and trajectories for an energy scan of a 1 kV beam with  $V_{focus} = 970V$  are presented in Figure 5.

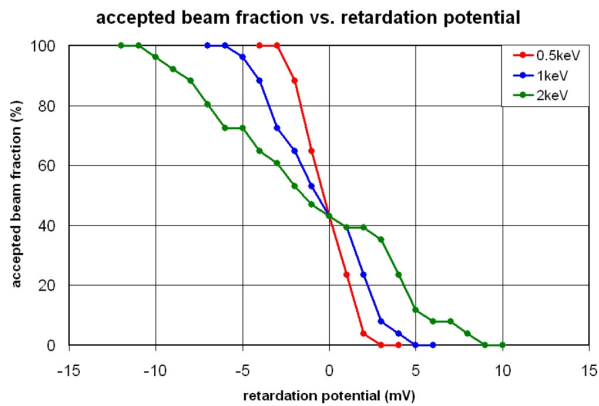


Figure 4: Collector signal vs retardation potential (relative to  $V_{beam}$ ) for different beam energies.

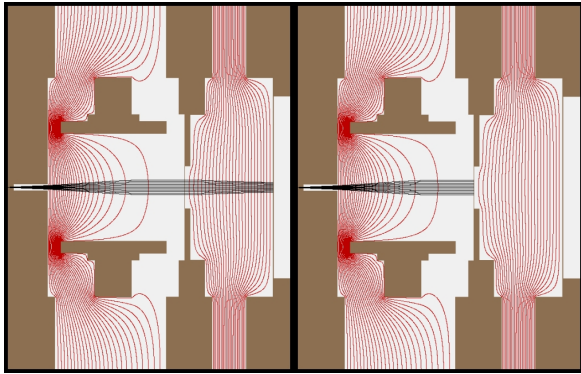


Figure 5: Equipotentials and trajectories with  $V_{beam}=1$  kV, and  $V_{focus}=970$  V, for  $V_r=-999.995$  V (left) and  $V_r=-1000.005$  V (right).

## EXPERIMENT

The analyzer is incorporated into a UHV-compatible DC test stand capable of providing fields up to  $\sim 50$  V/ $\mu\text{m}$ . The cathode holder is fixed to a kinematic-style mount that allows real-time adjustment of anode-cathode planarity and spacing during high-voltage operation. Connecting the retarding mesh and cathode to the same power supply allows the collection of energy spectra relative to the cathode's Fermi level. A fiberoptically-coupled bias supply with millivolt stability has been developed for controlling the energy scans programmatically. The data acquisition system is capable of energy scans lasting a fraction of a second, enabling the observation of energy spectra from transient surface adsorbates.

The analyzer has been successfully tested using a  $3\times 24$  diamond field-emitter array. The array was conditioned for uniform emission prior to testing. For initial alignment the retardation mesh and collector are grounded. The cathode tip-tilt is adjusted until sufficient current is detected at the collector/mesh. A hard shadow of the front aperture is observed, suggesting a well-correlated beam from a single emitter, while the simultaneous flickering of multiple adsorbates is present. After alignment, the collector and mesh are rewired for measurement of energy spectra. Due to contributions

FEL Technology

from multiple adsorbates, the signal can be noisy over time scales of  $\sim 1$ sec. These fluctuations can not be normalized out by measurement of the mesh current because adsorbates are known to change the emitted energy spectra of other field emitters, such as carbon nanotubes [4]. To mitigate the effect of these fluctuations the energy spectra are averaged over hundreds of scans.

Energy spectra were taken as a function of focusing voltage to find the optimum focusing voltage setting. The results in Figure 6 reproduce the value suggested by simulations,  $V_{focus} = 0.97V_{beam}$ .

Examining the high energy side of the sharpest spectra, we can see that the analyzer has a resolution of at least  $\sim 0.1$  eV. While the best resolution is likely much better

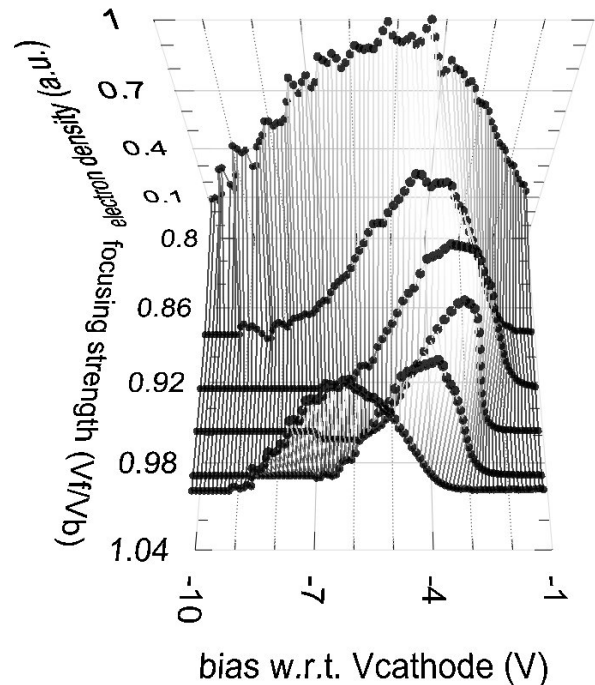


Figure 6: Electron energy spectra as a function of focusing voltage. Optimum focusing is found to be 97% of the cathode voltage.

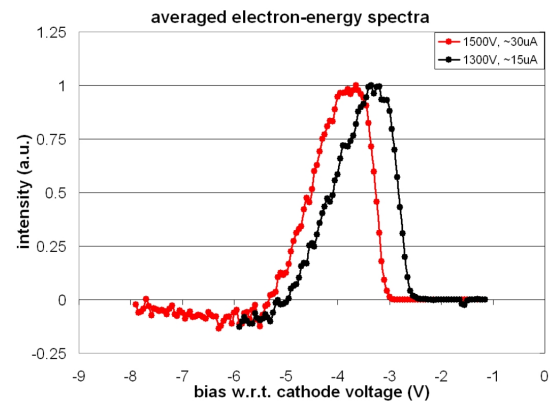


Figure 7: Averaged energy spectra taken for optimized focusing at two different (I, V) combinations, peak shift is likely due to resistive voltage drop.

than this, measuring that limit is not possible with the current electron source. Averaged spectra for optimized focusing at two different current levels are shown in Figure 7. The origin of the negative part of the spectra at low energy is presently not understood.

The minimum measured energy spread has a FWHM of  $\sim 1.3$  eV, which is large compared to that of metallic field emitters ( $\sim 0.3$  eV). This disparity may be due to adsorbate modification of the energy spectrum, or it may be a property of the diamond cathode. There may be no reason to expect that a complicated carbon structure with a mixture of  $sp^2$  and  $sp^3$  bonded carbon should behave as a metallic emitter in this respect.

In the next round of experiments spectra will be taken at UHV as opposed to the high pressure of the current experiments,  $\sim 10^{-7}$  Torr. Self Joule heating of the nanotips during high-current operation will remove surface adsorbates and enable measurement of energy spectra from clean diamond emitters.

### CONCLUSIONS

We have presented results in the simulation and testing of a high-resolution retardation energy analyzer. The high-resolution capability is provided by the analyzer's cylindrical focusing electrode, which removes spectrum broadening due to transverse momentum in the beam. We estimate an optimum resolution better than the kinetic-energy error of the simulation. The energy analyzer was

successfully commissioned using the electron beam from a diamond field-emitter array. Averaged spectra were taken to mitigate the effects of adsorbate fluctuations on the emitters. The width of these spectra is  $\sim 1.3$  eV, much larger than that of metallic field emitters. Future experiments with optimized cathode and improved vacuum conditions will measure, for the first time, spectra from clean diamond field emitters.

### ACKNOWLEDGEMENTS

The authors gratefully acknowledge Mic Howell for assistance with the diamond CVD systems, and Travis Wade for phosphor procurement. This work was supported by the Office of Naval Research under grants N000014-06-0572 and N000014-07-1-1037

### REFERENCES

- [1] Y. Cui, Y. Zou, A. Valfells, M. Reiser, M. Walter, I. Haber, R. A. Kishek, S. Bernal, and P. G. O'Shea, *Rev. Sci. Instrum.* **75**, 8 (2004)
- [2] J. D. Jarvis et al, *Uniformity Conditioning of Diamond Field-Emitter Arrays*, these proceedings
- [3] J. D. Jarvis et al, *Transverse Emittance of Diamond Field-Emitter Arrays*, these proceedings
- [4] S. T. Purcell, P. Vincent, M. Rodriguez, C. Journet, S. Vignoli, D. Guillot, and A. Ayari, *Chem. Vap. Deposition* 2006, **12**, 331-344.