# P1-5: Field Emission Electron Gun using a Reticulated Vitreous Carbon Cathode

***Brady C. Smith, Charles E. Hunt, Arthur C. Carpenter***
Department of Electrical and Computer Engineering
University of California, Davis
One Shields Ave., Davis, CA 95616
brcsmith@ucdavis.edu, hunt@ece.ucdavis.edu, accarpenter@ucdavis.edu

**Abstract:** *The advantages of argon-ion-irradiated reticulated vitreous carbon (RVC) as a cold-cathode electron source are investigated in the context of a high current density, medium energy, low energy spread, high brightness electron gun.*

**Keywords:** reticulated vitreous carbon; RVC; field emission cathode; electron gun; phase contrast imaging.

## Introduction

Field emission (FE) sources for electron guns can be preferable to thermionic emission sources because of higher current density, fast turn-on and turn-off times, potential lower energy spread, and other factors. As an FE cathode material, carbon nanostructures have received a great deal of attention in recent years, partially because of high mechanical strength and chemical stability, low-field emission, and generally good field emission properties. Additionally, the electrons emitted by carbon nanostructures are highly coherent and if the structures, such as nanotubes, are randomly oriented to start out with, they bend to become aligned with a high electric field.

## Driving Application

The target application of this work is an electrostatically focusing electron gun. This can be used specifically in an x-ray source for phase-contrast imaging for medical and other uses. Other applications of the field-emission cathode include other x-ray sources; microwave traveling-wave tube power amplifiers, klystrons, gyrotrons, and free electron lasers; triodes, pentodes, etc., generally; power line switches for a more quickly-switched power transmission line system; terahertz radiation emission sources, for use in airport security, for chemical analysis, and other uses; and even energy efficient lighting. Figure 1 shows proof of principle simulation results for the cylindrically-symmetric gun using the CST Particle Studio software [1]. The gun is described in [2]. Phase-contrast x-ray imaging makes use of the electron beam to excite a few lines of characteristic x-rays from a foil (which would replace "APERTURE" in Fig. 1). In the ultimate device, the electron beam would be deflected after the foil and collected off-axis, allowing the desired x-rays to exit through a window in the original direction of the beam, with the undesired Bremsstrahlung radiation emitting perpendicular to the beam, thus being reduced. The spherical and chromatic aberration coefficients (referred to the image) are estimated to be $C_{si}$ = 23.4" and $C_{ci}$ = 21", respectively.

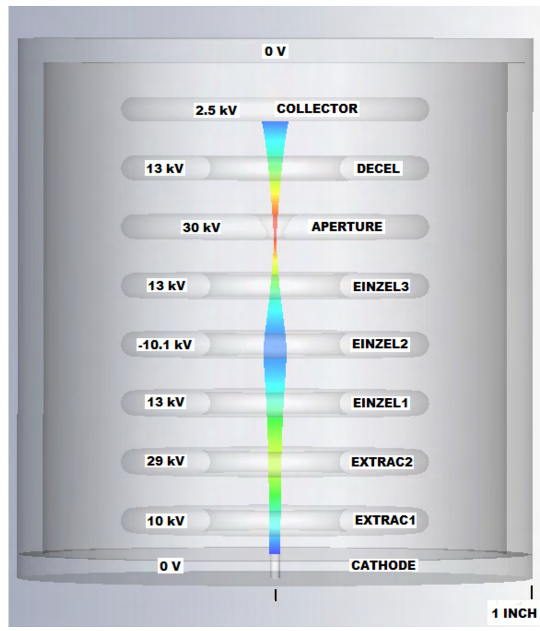


**Figure 1.** Simulation results of electrostatic focusing field-emission electron gun.

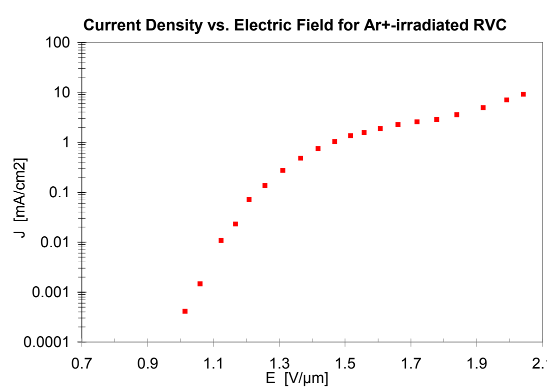


**Figure 2.** J (mA/cm2) vs. E (V/µm) for $Ar^+$-irradiated RVC [3].

## Cathode and Beam Characteristics

The cathode is made of $Ar^+$-irradiated RVC and exhibits a few advantages over typical carbon nanostructure devices. RVC is naturally a good field emitter, but ion irradiation grows a large number of various graphene-rich nanostructures including single- and multi-wall carbon nanotubes (CNTs) over the surface of the RVC enhancing its emissivity by a factor of 10. This cathode exhibits an order of magnitude higher current density than the best CNT field-emission cathodes found (Fig. 2 [3]).

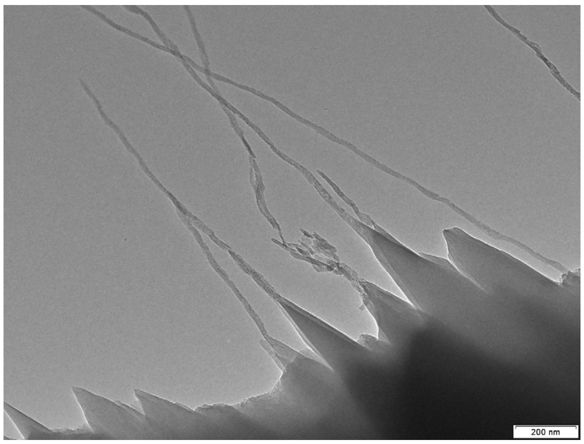


**Figure 3.** TEM image of $Ar^+$-irradiated RVC. "200 nm" in lower right [3].

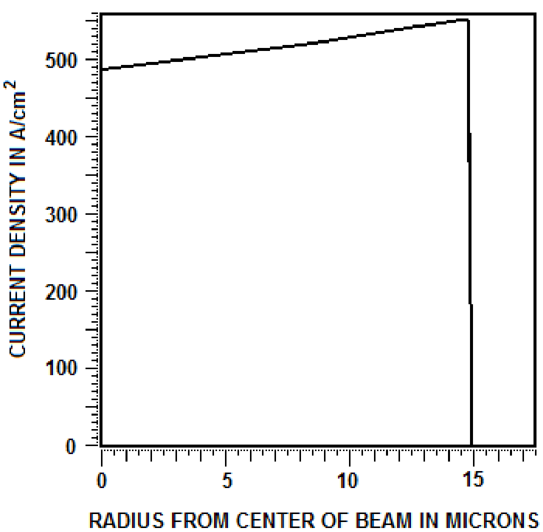


**Figure 4.** J (A/cm$^2$) vs. beam radius (μm) at focus as calculated from numerical data referenced above.

Since ion bombardment is responsible for the *self-assembly* of the graphene-rich carbon nanostructures, ion bombardment of the cathode during operation does not destroy the field-emission properties of the RVC, but, rather, *maintains* the excellent field emission properties of the cathode.

Another advantage of RVC is that the foam-like structure is resistively self-ballasting, mitigating bistable fluctuations in the field emission process, normalizing current and preventing damage.

Comparing J vs. E curves with [4], the individual carbon nanostructure currents are approximately $< 300$ μA in the proposed device. It is documented [5] that conventional thermally annealed CNTs fail at 100 μA, predominantly by uprooting of the tube, but this figure is based on devices where the CNT is attached to a different material, such as Ag. In our device, the carbon nanostructures are anchored, as can be seen in Figure 3[3], to more carbon through a cone of material, making use of the strong C-C bonds. Extrapolating from single nanotube data [6] the energy spread at 300 μA is $\leq 1$ eV. It is theorized that the shift in center peak energy in multi-tipped cathodes results in $\Delta E \approx 3$ eV [7]. For the purposes of the simulation in Figure 1, an energy spread of 4 eV was assumed, which broadened the beam almost negligibly for this electron gun. Calculated current density versus radius at the focus of the beam is given in Figure 4. The beam is cut off sharply because the piece of RVC is limited to a 1 mm diameter Current density rises toward the edge because a Wehnelt is not used and the electric field is stronger toward the outside of the RVC.

## References

1. CST Particle Studio, simulator produced by Computer Simulation Technology AG, Darmstadt, Germany.
2. B. C. Smith, C. E. Hunt, and I. Brodie, "Electrostatic Focusing of Electrons off a Large-Area Reticulated Vitreous Carbon (RVC) Field Emission Source," (accepted) *International Vacuum Electronics Conference,* 2010
3. A. C. Carpenter, "High Current Field Emission Electron Source using a Reticulated Vitreous Carbon (RVC) Cathode," Master's Thesis, Univ. of Ca., Davis, 2009.
4. W. Zhu, *Vacuum Microelectronics,* pp. 265-274, John Wiley & Sons, New York, 2001.
5. E. Minoux, O. Groening, K. Teo, et al., "Achieving high-current carbon nanotube emitters," *Nano Letters,* Vol. 5, no. 11, pp. 2135-2138, November 2005.
6. T. Fujieda, M. Okai, and H. Tokumoto, "Energy Spread of Field Emission Electrons from Single Pentagons in Individual Multi-Walled Carbon Nanotubes," *Japanese Journal of Applied Physics,* Vol. 47, no. 4, pp. 2021-2023, April 2008.
7. M. J. Fransen, T. L. van Rooy, and P. Kruit, "Field emission energy distributions from individual multiwalled carbon nanotubes," *Applied Surface Science,* Vol. 146, no. 1-4, pp. 312-327, 1999