Electrostatic Focusing of Electrons off a Large-Area Reticulated Vitreous Carbon (RVC) Field Emission Source

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Abstract: *An electrostatic- focused electron source with an Ar$^+$-ion irradiated reticulated vitreous carbon (RVC) field-emission cathode is designed and simulated. The electron beam from a 1 mm emissive surface is focused to a 30 µm diameter spot, retaining low energy spread and high brightness, yet high total current, for application to phase-contrast x-ray imaging.*

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

Introduction

Field emission electron guns offer advantages over thermionic emission guns, including elimination of the heat source, potential simple design, high reliability, and low energy spread, leading to better focusing. The possibility of minimizing energy spread by focusing the emission from a collection of field-emission tips, instead of a single tip, also exists. This can be understood by examining the energy spread of a field emission source (Figure 1 [1]) as a function of total current from the source. By focusing many low-current sources, rather than using a single emitter, the lower energy spread of those sources can be retained at a high total current.

In the work presented here, the electron source chosen is a reticulated vitreous carbon (RVC) cathode that has been irradiated by Ar$^+$ ions to grow a large number of grapheme-rich carbon nanostructures distributed randomly over the already irregular surface of the RVC [2]. Such a cathode has experimentally demonstrated high current at significantly-lower macroscopic electric fields [3] when compared with other carbon nanostructure field-emission electron sources; consequently, in this implementation, near the beam, electric fields above the breakdown field of vacuum in the electrostatic-focused electron gun are not required [1,4,5]. Figure 2 shows the pattern of emission (on a phosphor screen) of an irradiated RVC cathode with 100 pores per inch and 3 mm diameter. Even with the blooming on the phosphor screen, it is seen that emission comes from multiple sites over the emission surface, giving the above-mentioned lower energy spread for each source.

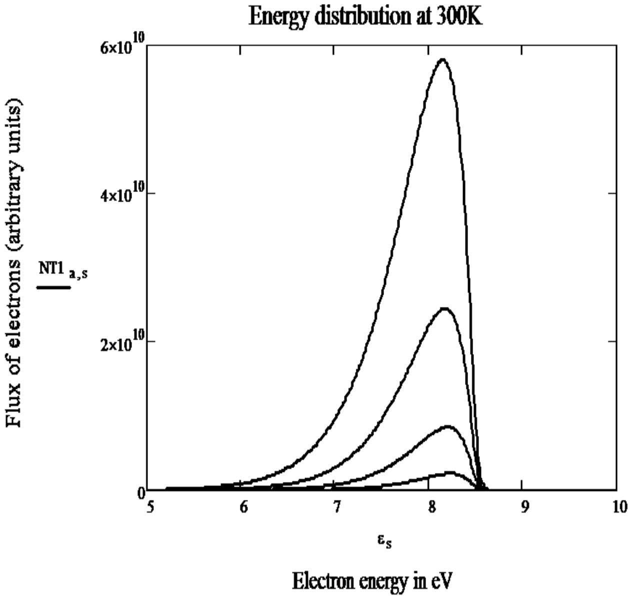

Figure 1. Energy distribution of emitted electrons from a field emission tip at different total currents illustrating differing energy spreads [1].

Simulation

Using the Ar$^+$-irradiated RVC source, an electrostatic electron gun has been designed for application in an x-ray source for phase-contrast imaging. The requirements are energy = 30 keV, I ≈ 5 mA, and spot diameter ≈ 20 µm at the target. A cylindrically-symmetric gun design is employed, with edge-rounded acceleration plates. Figure 3 shows proof of principle simulation results, using CST Particle Studio [6]. "APERTURE" represents the target foil. The electrons are emitted (bottom) from the RVC, approximately 1 mm in diameter. The electric field formed at the cathode is 2.795 V/µm. The Einzel lens has been designed with a very low center voltage to increase focusing power while reducing spherical aberration as much as possible [7].

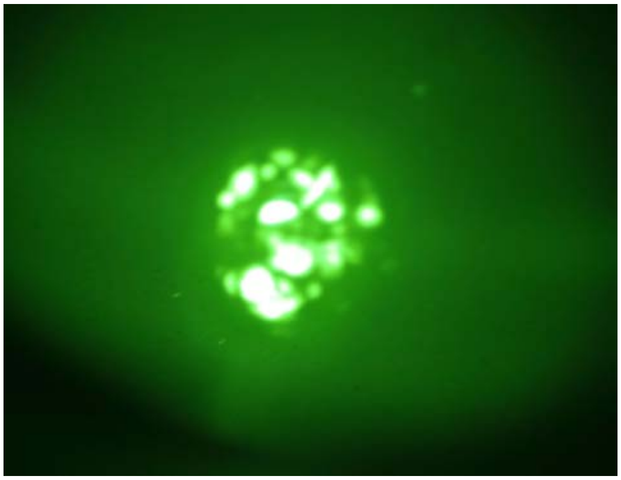

Figure 2. Emission pattern from a 3 mm diameter Ar^+-irradiated RVC cathode [1].

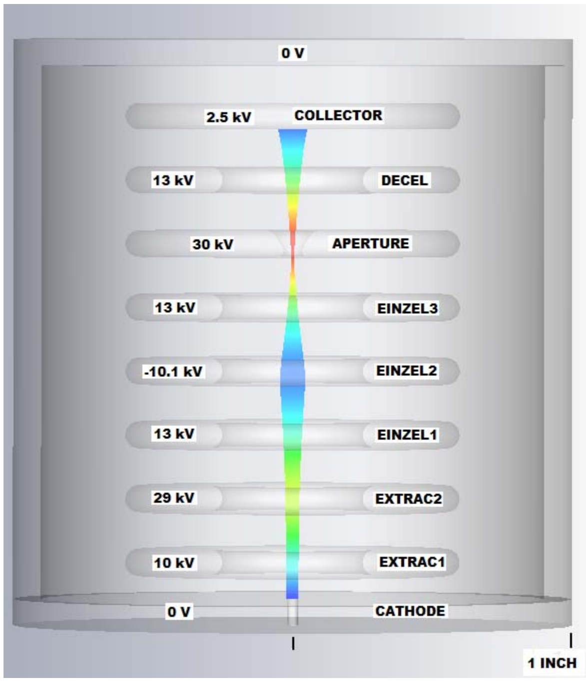

Figure 3. Simulation results of electrostatic focusing field-emission electron gun.

An energy spread of 4eV was used, given the high current from the individual carbon nanostructures. In the experimental implementation, the aperture is replaced by a contiguous high-Z foil and deceleration of the electrons is accomplished in three dimensions to divert the beam for collection off-axis, allowing the monochromatic x-rays to exit in the original direction of the beam.

Results

The simulation shows the specifications can be met, with 30 keV electron energy, 4 mA current, and 30 µm spot diameter. The spherical and chromatic aberration coefficients (referred to the image) were estimated to be C_{si} = 23.4” and C_{ci} = 21”, respectively. Normalized to the radius of the openings in most of the electrodes, the figures of merit are then $C_{si}/R = 93$ and $C_{ci}/R = 83$. The electric fields at the inner surfaces of all electrodes are a maximum of 10 V/µm, avoiding vacuum breakdown. At the outer rounded edges of EXTRAC2 and APERTURE, the electric field rises to 12.4 V/µm, but this can be dealt with by using insulating encapsulation.

Conclusion

A proof-of-principle field-emission electron gun for an x-ray source has been designed and simulated. Experimental verification is underway. A high total current, focusing to a spot of 30 µm diameter, can still retain the low energy spread of the cathode’s emission sites. The Ar^+-irradiated RVC cathode offers an improved field-emission source with application to x-ray sources, microwave amplifiers and other uses.

References

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