# Carbon nanotube cold cathodes for application in low current x-ray tubes*

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Low current x-ray tubes operating at 25–40 kV have been developed using monolithic carbon nanotube (CNT) cold cathodes as electron sources. The authors have tested CNT cathodes from various sources. They were systematically evaluated and conditioned in a vacuum chamber and then went through high temperature baking and high voltage processing of standard tube production processes. Acceptance criteria were developed for each step in order to ensure that the final tube will meet the performance requirement of a commercial product. The tubes were subsequently operated continuously for an extended amount of time for life and reliability measurements. It was found that it is possible to use individually selected and preconditioned CNT cathodes in a commercial x-ray tube product. However, to find wide application and, particularly, to compete with existing hot filament thermionic cathodes, CNT cathodes need dramatic improvement in reproducibility and robustness. In addition, an empirical mathematical model for monolithic CNT cathodes has been developed for simulating the electron optics required in x-ray tubes. The model led to a successful design of a magnetically focused x-ray tube with a spot size of about 80 $\mu$m. © *2008 American Vacuum Society.* [DOI: 10.1116/1.2802092]

## I. INTRODUCTION

Carbon nanotubes (CNTs) hold the promise of being ideal electron field emitters due to their high aspect ratio, superior electrical and thermal conductivity, and relatively high chemical and mechanical stability. CNT cold cathodes have been a subject of studies for over a decade and are relatively easy to make, either by chemical vapor deposition *in situ* growth or by postgrowth transfer onto a substrate.[1–3] Yet, there have not been many practical devices that employ a CNT cathode due to various issues that arise in all vacuum electron devices.

In this article, we will focus on the application of CNT cold cathodes in low current x-ray tubes operating at 25–40 kV. Detailed discussions will include cathode performance requirements from a commercial product point of view, the performance and status of current cathodes, factors that affect the tube production yield, and operating life and reliability. Measurement of electron beam distribution from CNT cathodes and its implication in designing focused tubes will also be discussed.

## II. CNT CATHODE PERFORMANCE AND REQUIREMENTS

The typical layout of a CNT field emission x-ray tube is shown in Fig. 1. It is composed of a high vacuum enclosure, often sealed, in which a cold electron gun, which consists of a CNT cathode and an extraction grid, and a metallic target facing each other. Electrons are emitted by the electron gun (cathode) and accelerated towards the target (anode) by a high voltage electric field (tens to hundreds of kilovolts depending on the application). X rays are produced by the collision of the high velocity electrons on the target. The extraction grid is held in close proximity to the CNT cathode. When it is biased positively relative to the cathode, the electrical field between the grid and the cathode extracts electrons from the cathode. A host of criteria need to be met in order for a CNT cathode to be qualified for commercial x-ray tube production. Having a low extraction field for electron emission and delivering enough current are only a small part of it, and had been the major concerns in CNT cathode development. However, emission stability over both long and short terms is critical. The short term emission stability has more often been neglected in CNT cathode development while, in practice, it is essential for an x-ray source in any instrument to be able to deliver a specified dose of x-ray over the data acquisition time period. In addition, if the electron beam is to be focused, the angle at which electrons launch from the cathode surface is important for the spot size of the

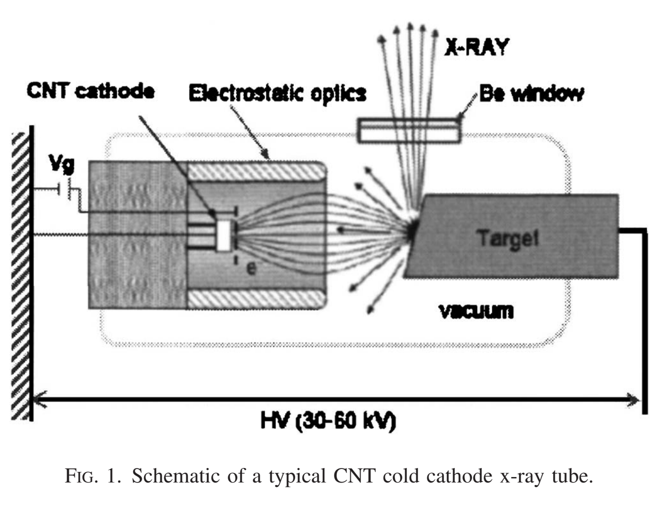


FIG. 1. Schematic of a typical CNT cold cathode x-ray tube.

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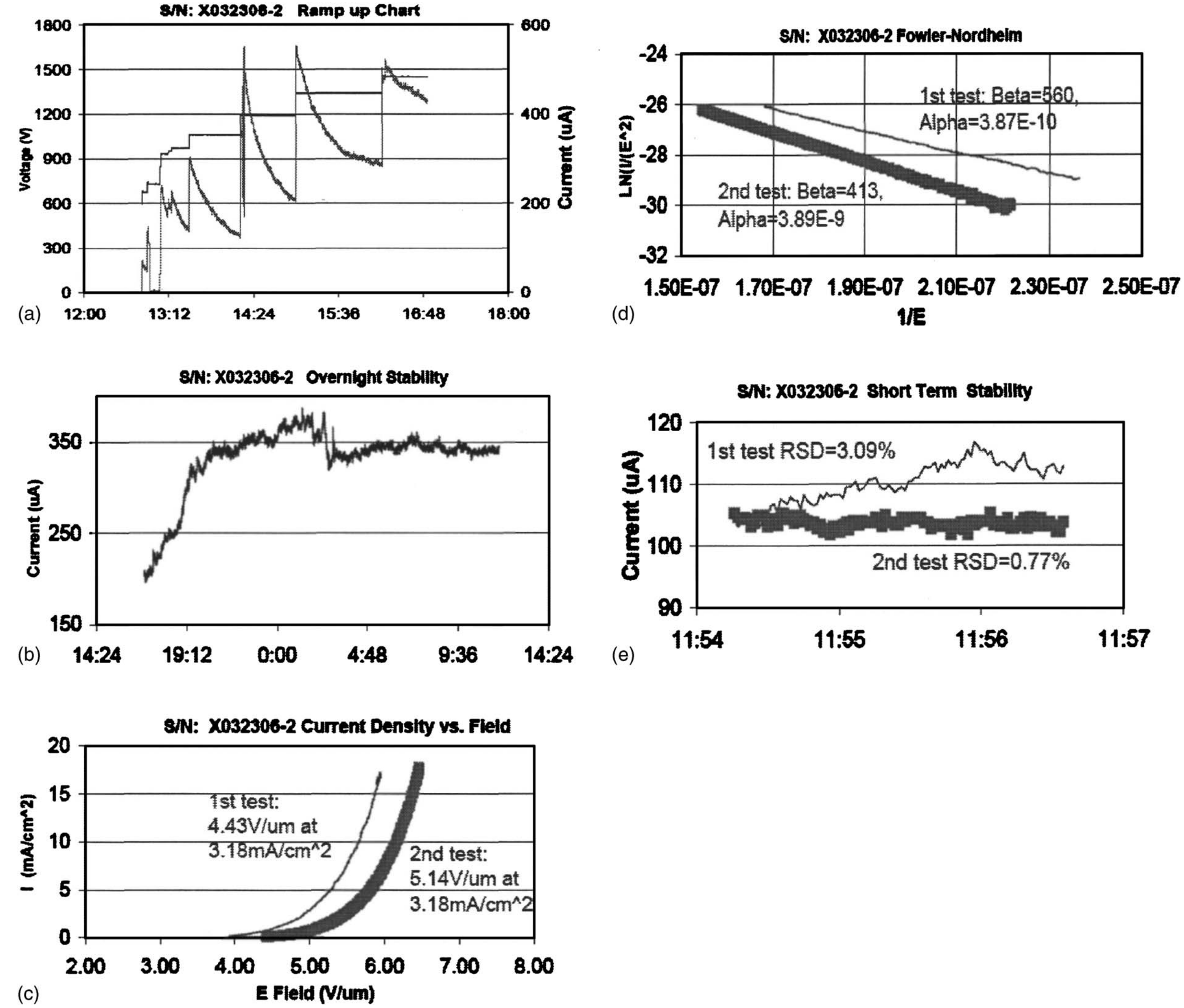


FIG. 2. Sample test of a CNT cathode.

beam. All those cathode emission characteristics are also somewhat affected by the cathode preconditioning.

Emission performance alone cannot qualify a cathode. It also has to be able to survive the standard vacuum tube production processes. A high temperature bake-out, at 450 °C, for instance, is carried out for an extended time to achieve a vacuum of $10^{-9}$ torr in the envelope. After baking out, high voltage burning (HV processing) follows, in which the cathode ages in a controlled manner up to one and a half times the tube operation voltage. Under such a high voltage, any loose material from the cathode, such as amorphous carbon or a weakly attached CNT, will be pulled out by the high electrical stress. As a result, the CNT cathode has to have a high thermal and mechanical stability. Any loose carbon or other particles induced from the cathode at the end of processing and during emission will cause arcing or current leakage, and therefore, a failed tube, even if it is the smallest amount of particles undetectable by any means.

We have developed cathode acceptance criteria for each of these processes. Figure 2 illustrates the tests we performed on one of the cathodes. The current was ramped up by steps to a level at least five times that of tube operation [Fig. 2(a)], and left to continuously operate at least 24 h at a current level of at least twice that of tube operation in order to age the cathode [Fig. 2(b)]. After aging, an *I*-*V* curve was taken [Fig. 2(c)] and FN plot made to extract $\alpha$ (the ratio of effective emission area to the cathode total area) and $\beta$ (field enhancement factor) values. The cathode was then further tested for short term stability [Fig. 2(d)]. Variation of emission current under constant field is recorded and calculated within 100 s. Only the ones that had a low emission threshold field, demonstrated good stability during overnight operation, and had a root square deviation RSD (percentage of standard deviation over the average) less than 1% during the 100 s test are accepted. In the same figure are also shown the results of a second test performed after the cathode was aged at a high current level for an extended time. Typically, cathode aging results in larger $\alpha$ and smaller $\beta$ and improves short term stability, as is shown in the figure. Cathode aging at a higher current in a vacuum test chamber also helps to reduce loose particles in the cathode.

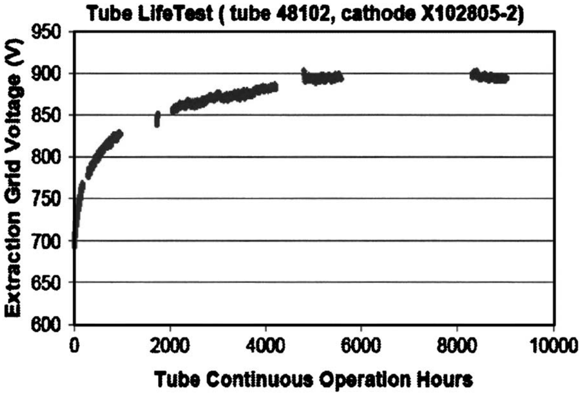


FIG. 3. Life test of an x-ray tube with a CNT cathode.

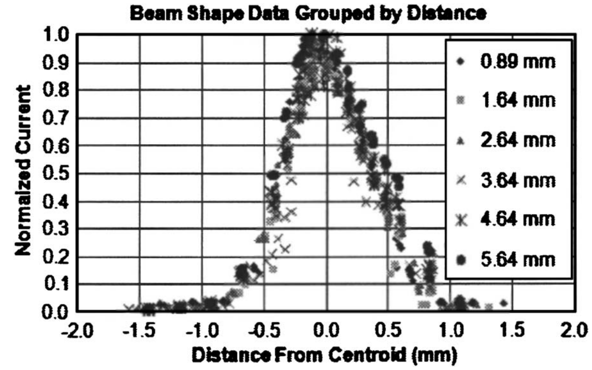


FIG. 5. Normalized current vs the distance from the cathode surface. The currents are normalized to the maximum for each cross beam scan.

Selected cathodes were built into x-ray tubes and tube life and reliability were further evaluated through continuous operation. Figure 3 shows lifetime test result of one of the tubes. The data record the voltage required from the extraction electrode in order to maintain a constant emission current (100 $\mu$A) from the CNT cathode. As the cathode ages, the voltage increases. When the maximum voltage of 1 kV of the grid power supply is reached, the tube life is considered ended. The gaps in the plot were due to data losses caused by power surges that erased data files before they were manually saved. As is shown in the figure, longer than 1 year of continuous operation time and more than 2 years of projected continuous life time, which is more than required to meet the life expectations of a commercial x-ray tube product, have been achieved. Therefore, the state of the art CNT cathode can be used to build commercial products. In fact, Oxford Instruments X-Ray Technology Group has made the tube we developed commercially available (Eclipse series), and made use of tube in its commercial handheld x-ray fluorescence (XRD) spectrometer (Horizon XRF spectrometer).

It should be noted, though, despite this success, CNT cathodes face severe challenges in commercialization due to its poor reproducibility from batch to batch and within a batch. Currently, a good cathode has to be meticulously selected by extensive evaluation and preconditioning individually.

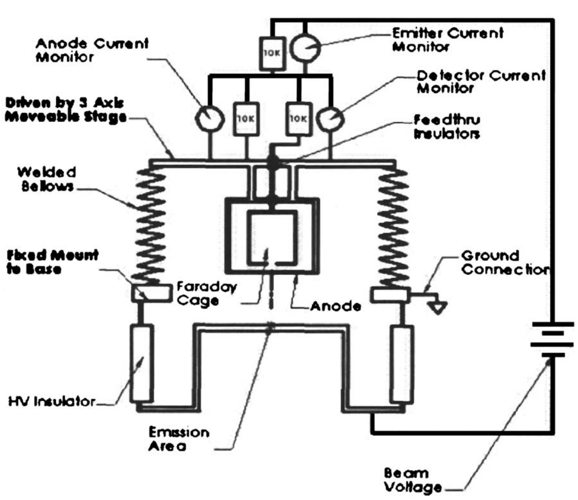


FIG. 4. Schematic of the electron beam analyzer.

## III. MEASUREMENT OF ELECTRON BEAM DISTRIBUTION FROM MONOLITHIC CNT CATHODE

A necessary step in x-ray tube design is electron optics modeling. The modeling of electron trajectories requires an understanding of the initial conditions at the surface of the emitting cathode. Models have existed for thermionic cathode emission but none for monolithic CNT cathode emission. To characterize monolithic CNT cathode emission, an electron beam analyzer was constructed to measure the electron beam distribution from a CNT cathode. Figure 4 shows a schematic of the analyzer. A narrow strip of CNT emitter is used as the electron source. The cathode and anode are parallel to each other and mounted such that the electric field is uniform over both surfaces and the space between them so that all the electrons emitted from the cathode experience the same electrostatic field. Electrons are collected by the anode except those that are incident on the slit in the center of anode plate. Electrons passing through the slit are collected in a Faraday cup that is isolated from the anode by a ceramic insulator. The distribution of the current across the beam is measured by scanning the narrow slit detector across the electron beam. With repeated scans, each being at larger spacing from the cathode, we can determine how the beam spreads in a uniform electric field. The cathode mount is isolated from the balance of the analyzer to allow acceleration voltages of up to 25 kV. As the spacing is increased, so is the voltage in order to keep the electric field and current constant for each series of scans. A typical set of scans will cover the distance from 50 to 6000 $\mu$m from the cathode surface. Likewise, for each axial position we can increase voltage, and thereby the emitted current. Thus, we obtain the behavior of the beam over a wide range of current and current density.

Figure 5 shows the raw data collected from the beam analyzer, plotted as the normalized current versus the distance from the centerline of the cathode for various distances

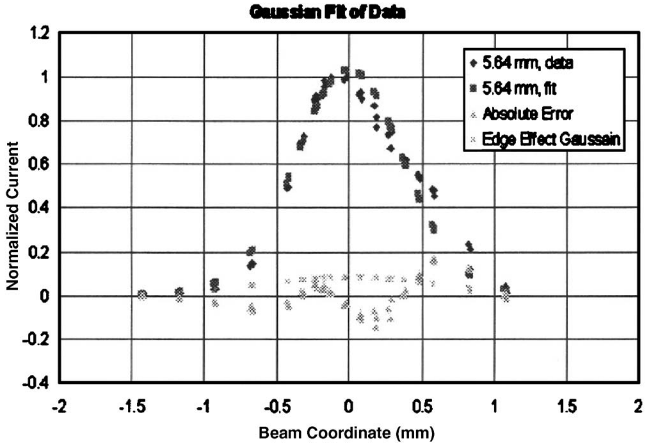


FIG. 6. Sample Gaussian fit of the beam data at 5.64 mm from the cathode after removing asymmetry and edge effect.

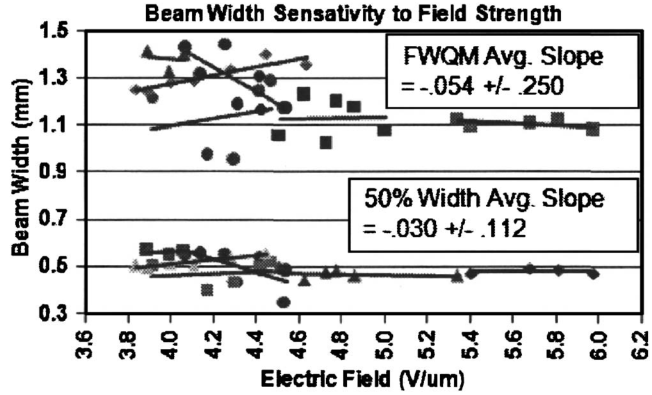


FIG. 8. Beam width sensitivity to the electrical field strength.

from the cathode surface ranging from 0.64 to 6.64 mm. The current is normalized to the maximum for each cross beam scan. The indications are that the electron beam diverges but it diverges slowly. The divergence is to the first order independent of the macroscopic electric field strength. Small random and systematic errors in the data make it possible to extract only general characteristics from the beam profile such as centroids and moments of the beam. From this information it is possible to create multiple beam width definitions, such as full width at half maximum (FWHM) and quarter maximum (FWQM). Also, beam width defined as 50% of the enclosed current was defined and examined (50% width). The beam data were further fit to Gaussian profiles (Fig. 6) in an attempt to reduce scatter in the data by removing asymmetries and edge effects by combining the data sets. Asymmetries and edge effects likely result from systematic errors in the experimental setup, as there is no other physical explanation.

In the absence of edge effects and asymmetries, the FWQM beam full angle divergence was determined to be 3.0°, while that of FWHM was 0.88°, as is shown in Fig. 7. The fact that the FWQM beam spreads faster than the FWHM beam indicates that most of the beam spread comes from the lower density beam fringes containing smaller portion of the beam current. The FWHM or FWQM of the electrical beams are also plotted as a function of electrical field at various distances from the cathode (see Fig. 8). At a fixed distance from the cathode, the emission current increases as the electric field increases. The beam width appears to be independent of electric field to the resolution of the data. Because of this independence, the transverse velocity of the electrons at the emission site was determined to be proportional to $|E|^{1/2}$. This modification to the electron emission model was incorporated into the software for the electron optics design and simulations. Figure 9 show a magnetically focused x-ray tube designed using this model. A 80 $\mu$m x-ray focal spot was achieved. Fair to good agreement was found between the model and the actual device performance.

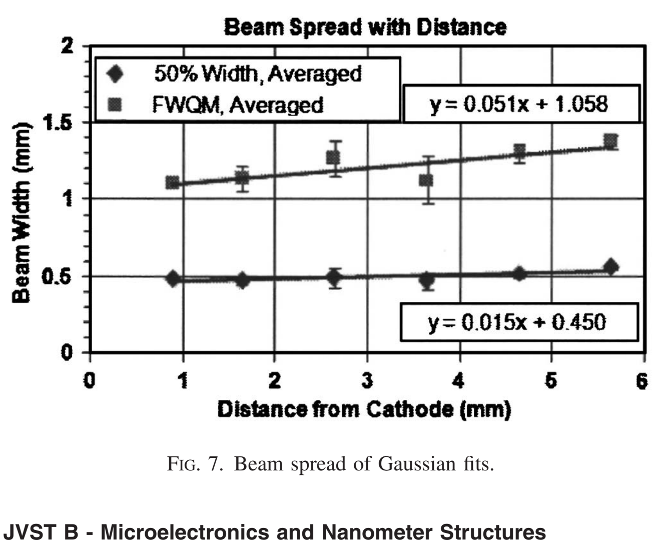


FIG. 7. Beam spread of Gaussian fits.

## IV. CONCLUSION

We have tested CNT cathodes from various sources for the application of low current 25–40 kV range x-ray tubes in a commercial production setting. Cathodes were systematically evaluated and conditioned in vacuum chamber and then went through high temperature baking and HV processing of standard tube production processes. Acceptance criteria were developed for each step in order to ensure that the final tube would meet the performance requirement of a commercial product. The tubes were subsequently operated continuously for an extended time for life and reliability measurements. It is found that it is possible to use individually selected and preconditioned CNT cathodes in a commercial x-ray tube

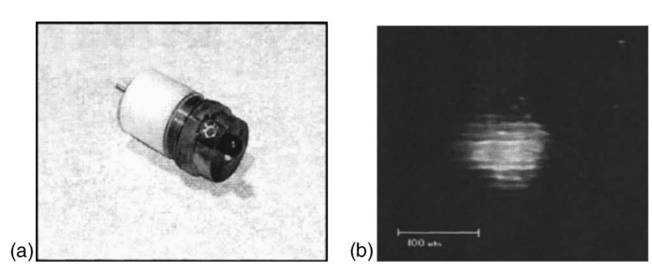


FIG. 9. (a) Magnetically focused x-ray tube and (b) x-ray spot size measurement of the tube.

product. However, to find wide application and, particularly, to compete with existing hot filament thermionic cathodes, CNT cathodes need dramatic improvements in both reproducibility and robustness.

An empirical mathematical model for monolithic CNT cathode has been developed for simulation of electron optics required in an x-ray tube. The model led to a successful design of a magnetically focused x-ray tube with a spot size of about 80 $\mu$m.

## ACKNOWLEDGMENTS

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