

# EXPERIMENTAL RESULTS OF CARBON NANOTUBE CATHODES INSIDE RF ENVIRONMENT

L. Faillace<sup>#</sup>, S.M. Boucher, J. Hartzell, A. Murokh, RadiaBeam Technologies,  
Santa Monica, CA 90404, USA

J.C.T. Thangaraj, FermiLab, Batavia, IL 60510, USA

D. Mihalcea, H. Panuganti, Northern Illinois University, DeKalb, IL 60115, USA

P. Piot, FermiLab, Batavia, IL 60510 and Northern Illinois University, DeKalb, IL 60115, USA

## Abstract

Carbon Nano Tubes (CNT's) as field-emitters have been investigated for more than two decades and can produce relatively low emittance electron beams for a given cathode size. Unlike thermionic cathodes, CNT cathodes are able to produce electrons at room temperature and relatively low electric field (a few MV/m). In collaboration with FermiLab, we have recently tested CNT cathodes both with DC and RF fields. We observed a beam current close to 1A with a  $\sim 1\text{cm}^2$  CNT cathode inside an L-band RF gun. Steady operation was obtained up to 650 mA and the measured current vs. surface field plot showed perfect agreement with the Fowler-Nordheim distribution.

## INTRODUCTION

High-brightness electron beams are required for a number of applications, from advanced accelerators to 4<sup>th</sup> generation light sources. However, the current technology for producing such beams requires an expensive, complicated laser system to drive a photocathode in an RF gun. Furthermore, this technology is difficult to extend to very high duty cycles, as is necessary for superconducting accelerators.

Carbon nanotubes (CNTs) have been investigated [1] for more than two decades as field-emitters and can produce relatively low emittance electron beams [2] for a given cathode size, without a need of the laser. Unlike thermionic cathodes, CNT cathodes are able to produce electrons at room temperature and relatively low applied electric fields (a few MV/m). Nevertheless, they have historically either produced low currents and are prone to damage. Moreover, they are difficult to gate with conventional techniques and therefore are unable to produce short pulses.

RadiaBeam has recently tested CNT cathodes both with DC and RF fields. We have observed beam currents up to about 1A (averaged over macropulse) with a CNT cathode inside an S-band RF gun. Steady operation was observed up to 650 mA and the measured current versus surface field plot showed good agreement with the Fowler-Nordheim distribution [3, 4] (see Figure 1).

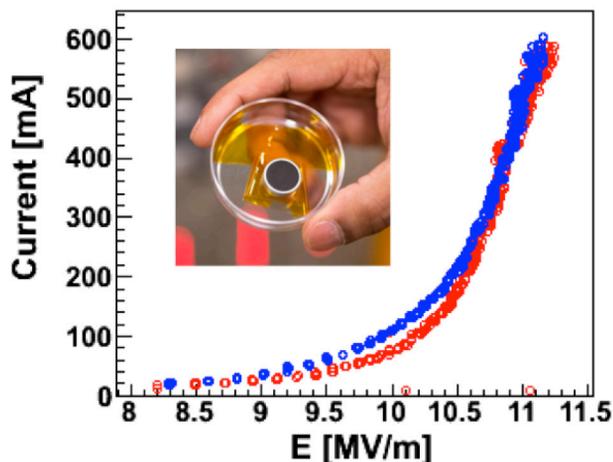


Figure 1: I-E curves. The measurements were performed with solenoids off (red) and solenoids on (blue).

## DC TESTS AT RADIABEAM

Various CNT cathode samples were optimized and characterized at RadiaBeam. The cathode design as well as the whole high-voltage (HV) pulsed DC test setup were carried out according to the load-lock system for cathode insertion inside the 1.3 GHz RF gun already functioning at the HBESL facility. Eventually, two cathodes, a smaller and a bigger sample, were tested inside RF environment at Fermilab showing promising results for future applications.

### Workflow

The workflow diagram that was followed for all operations is shown in Figure 2. The fabrication and cleaning of the cathode substrates were performed in-house. The CNT deposition processes, electrophoretic deposition (EPD) and chemical vapor deposition (CVD), were carried out at the California Nano-Systems Institute CNSI (UCLA) by our collaborators as well as Xintek (for the two samples used in FermiLab experiment). We then performed HV pulsed DC tests at RadiaBeam. The final RF testing took place at HBESL-FermiLab.

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#faillace@radiabeam.com

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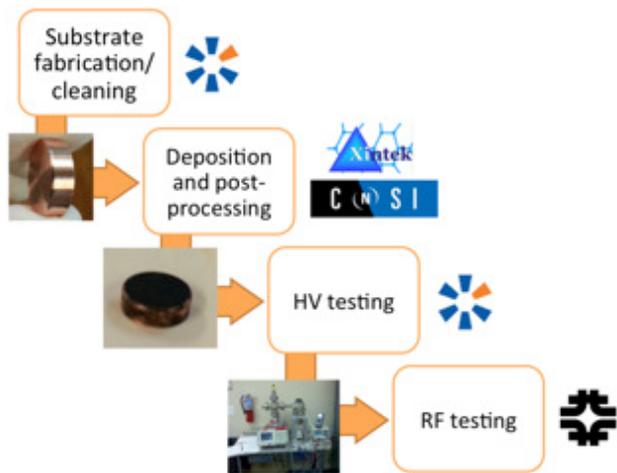


Figure 2: Workflow chart for the production, deposition and tests of CNT cathode samples.

In order to be able to reuse a single vacuum chamber for all the HV-DC tests on various cathode substrates, we designed a cathode mount (as shown in Figure 3) and a cathode holder to which different cathode substrates in the shape of thin discs, 1/2 cm height, can be attached and exchanged simply by means of a screw. The geometry of the cathode holder was dictated by the load-lock system attached to the RF gun at FermiLab that we used for the RF tests.

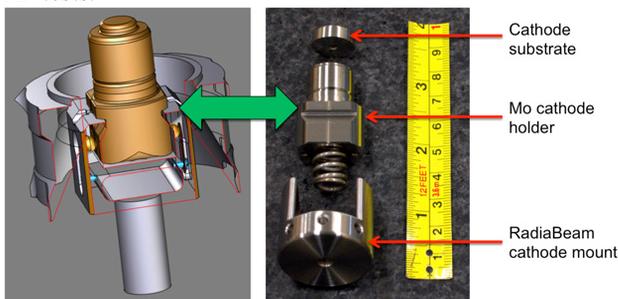


Figure 3: Fermilab's load-lock holder on the LEFT, from their HBESL RF gun and RadiaBeam's quick-change modification and adapter on the RIGHT.

The materials that were used for the cathode substrates were copper, 316 stainless steel (SS) and molybdenum. Copper is easier to machine while SS samples are more robust for the insertion in a load-lock system and molybdenum is preferred for its better response to CNT deposition processes. Two types of geometries were machined: "large" cathodes with ~1cm diameter circular cross section and "small" cathodes of 2 mm diameter section (nipple) as in Figure 4.



Figure 4: left, two "large" cathode samples; right, "small" cathode sample.

### EPD and CVD: Cathodes Preparation

A picture of a molybdenum sample after EPD deposition is shown in Figure 5 (left). High density CNTs are deposited as shown with an SEM photograph in the same figure (right). The CVD growth setup consists of a quartz tube, which contains a laminar flow of gasses, placed inside a table-top tube oven.

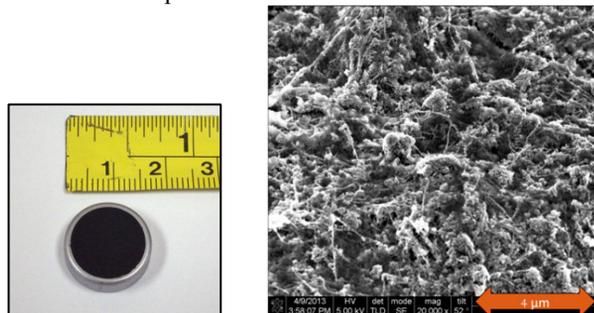


Figure 5: left, molybdenum cathode substrate after EPD deposition; right, SEM picture showing density of nanotubes and other carbon allotropes.

In order to be used in a gun (both DC and RF) for injection into an accelerator, the cathodes must have a sufficient current being emitted at reasonable electric fields. Our initial goal was to make cathodes that are stable at ~20MV/m. We employed a pulsed mode test station for initial characterization. The test station that we built at RadiaBeam is shown in Figure 6 as well as a close up drawing of the inside of the vacuum chamber. It has a variable gap of  $0-25 \pm 0.02$  mm, can apply 0-2.5 kV, and a minimum macro-pulse length of 5  $\mu$ s. For each cathode we study, we perform a series of individual runs, each at the same fixed electrode spacing. Each run consists of measuring the current while incrementally increase the voltage from 0 V until the cathode arcs. We then turn off the power supply to allow the system to stabilize and then repeat. Doing this allows us to progressively increase the maximum electric field the electrodes will support until we reach a stable operating point.

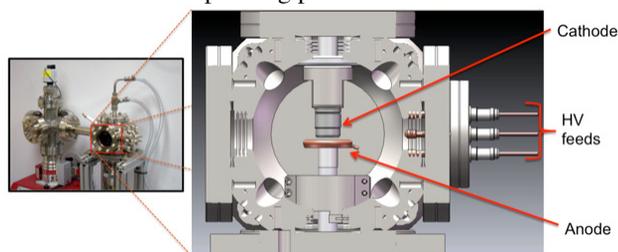


Figure 6: Picture of the HV pulsed DC test station at RadiaBeam. A close up drawing of the inside of the vacuum chamber is also shown.

By measuring the emitted current across the voltage range after each arc, we can clearly see that the emitted current is reduced as each arc damages a portion of the CNTs (see Figure 7). Once we reach a certain electric field, any loosely attached pieces of carbon are pulled off or a particularly long CNT is burnt off the cathode, initiating an arc. After the breakdown, the cathode can support a

stronger field, albeit at a lower current, until the next breakdown. To confirm this idea, we used adhesive tape to mechanically remove all but the most strongly attached CNTs from the cathode and repeated the test. This substantially increased the voltage handling at the expense of reducing the emitted current.

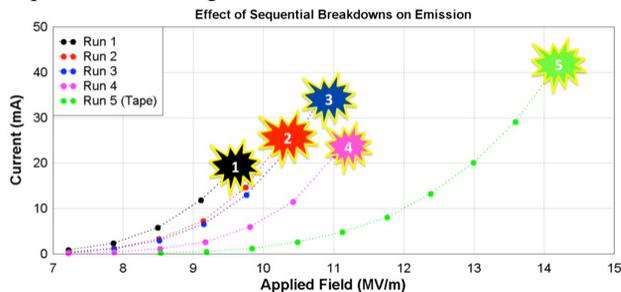


Figure 7: A series of runs on the same cathode, each ending in a breakdown. A final run after using tape to clean the cathode improves the voltage handling (green).

After using pulsed mode testing to evaluate a large number of cathodes, we select the best candidates and begin lifetime studies in a CW mode test station. This test station also has a variable gap of 0-25 mm, but the voltage range is extended up to 20 kV and continuous average current of 110 mA. A custom fabricated water cooled anode can dissipate the full energy the power supply can deliver. Preliminary results show that after an initial burn-in period of approximately 4 hours, the cathode emission stabilizes at about 70% of the initial current. Some degradation of emission is expected as the longest CNTs erode until all of the CNTs are approximately the same length and emitting the same average current.

### RF TESTS AT FERMILAB

A diagram of the experimental setup for the RF tests of the CNT cathodes at FermiLab is given in Figure 8. A “large cathode” (~15mm diameter) and a “small” one (~2mm diameter) were tested. The emitted current profile from the large sample is plotted in Figure 1, showing perfect agreement with Fowler-Nordheim distribution

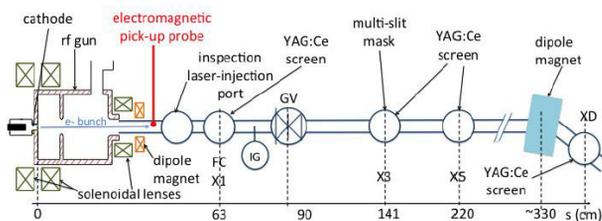


Figure 8: Experimental setup schematics at HBESL-FermiLab.

The samples are inserted inside the 1.3 GHz RF gun, usually used as a photoinjector driven by a powerful and expensive laser. The RF power is provided by a 2 MW klystron. The macropulse duration is adjustable and it was set at 40  $\mu$ s and 0.5 Hz repetition rate. The measurements

indicate a transverse horizontal emittance of  $\epsilon_{n,x} = 2.64 \pm 0.8 \mu$ m for the small cathode (see details in Figure 9). Measurements for the large cathode were compromised by the large energy spread.

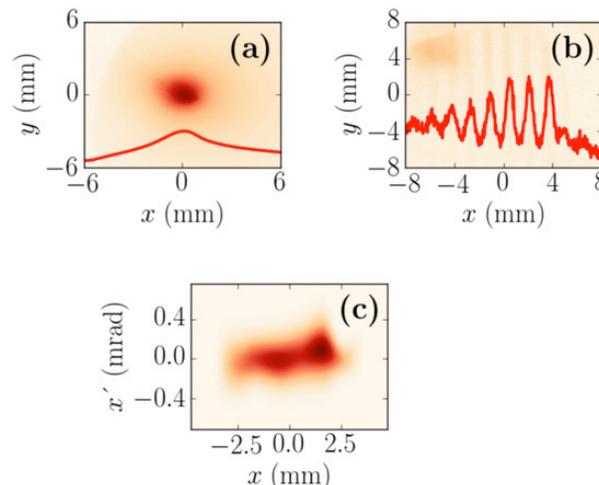


Figure 9: Emittance measurement snapshots showing the beam’s transverse distribution at X3 (a), the transverse distribution of the beamlets transmitted through the multi-slit mask observed at X5 (b) with associated horizontal projections (red traces). Image (c) shows the reconstructed horizontal trace space at the location of X3 from processing of images (a) and (b). These measurements were performed for the small cathode.

A lifetime study shows stable emission up to 650 mA from the large cathode (see Figure 10).

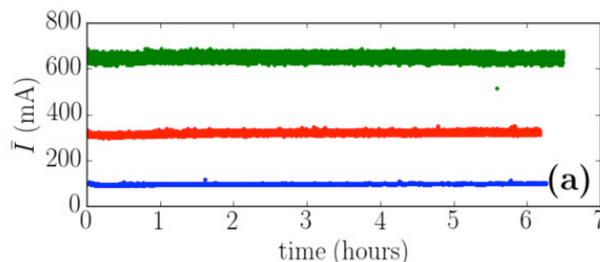


Figure 10: Current evolution over a >6-hour period (a) for 100 (blue), 300 (red), and 650 mA (green) from the large cathode.

### CONCLUSION

CNT cathodes were successfully tested inside RF environment in collaboration with FermiLab. A “large” sample with a circular cross-section with diameter of 1.5cm showed an emitted current close to  $\bar{I} \approx 1$ A (current averaged over the macropulse), charge per bunch  $Q \approx \bar{I}/f_0 = 0.5$ nC and length  $\sigma_t \approx 70$ ps when exposed to RF fields with relatively low peak field (~12 MV/m). The main operability features of such cathodes are possibility to emit at room temperature, highly beneficial in superconducting accelerator, as well as the compactness of the electron source that can avoid the use of a powerful and expensive laser.

## REFERENCES

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