DEVELOPMENT OF CARBON NANOTUBE (CNT) CATHODES AT RADIABEAM

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Abstract

RadiaBeam is developing Carbon Nanotube (CNT) cathodes for DC-pulsed and radio frequency (RF) driven electron sources. CNT cathodes, if realized, are capable of producing high current density with low thermal emittance, due to ambient operating temperature. The initial experimental results of CNT cathodes are presented, including the high-voltage tests, and life time studies. The potential applications of CNT cathodes in accelerator science and the microwave industry are discussed, and near term plans to test the CNT cathodes in an RF environment are presented.

INTRODUCTION

Carbon nanotubes are allotropes of carbon with a cylindrical nanostructure and exceptional electrical and mechanical properties [1]. They are typically fibers with a diameter of 1 to 50 nm, coming in either single-wall or multi-wall strands and an aspect ratio of up to 1000. Due to this very high aspect ratio, they have extremely large field enhancement factors, allowing efficient emission of electrons [2] at fields of only a few MV/m. Stable currents of more than 1μA have been measured from a single CNT fiber [3]. CNTs can also be fabricated in large, dense arrays, making them ideal as a cathode material. Peak current densities as high as 50 A/cm^2 have been reported from a macroscopic cathode operating in a pulsed mode [4].

The use of a cathode fabricated with CNT technology has a high potential to replace thermionic cathodes in vacuum electronic devices, such as TWTs. Due to their high field enhancement factor, it is possible to operate in a "cold" field emission regime with relatively high current densities and affordable voltages in a much wider temperature range, including at room temperature [5]. Moreover, CNT cathodes are able to provide high current beams from a very small total gun size.

CNT DEPOSITION AND HIGH-VOLTAGE TESTS

The CNT deposition process of the first sample (see Figure 1) was performed by the UCLA California NanoSystems Institute (CNSI). The process that was used is known as ElectroPhoretic Deposition (EPD, [6]). Currently, they are also starting to use a different technique, Chemical Vapor Deposition (CVD, [7]).

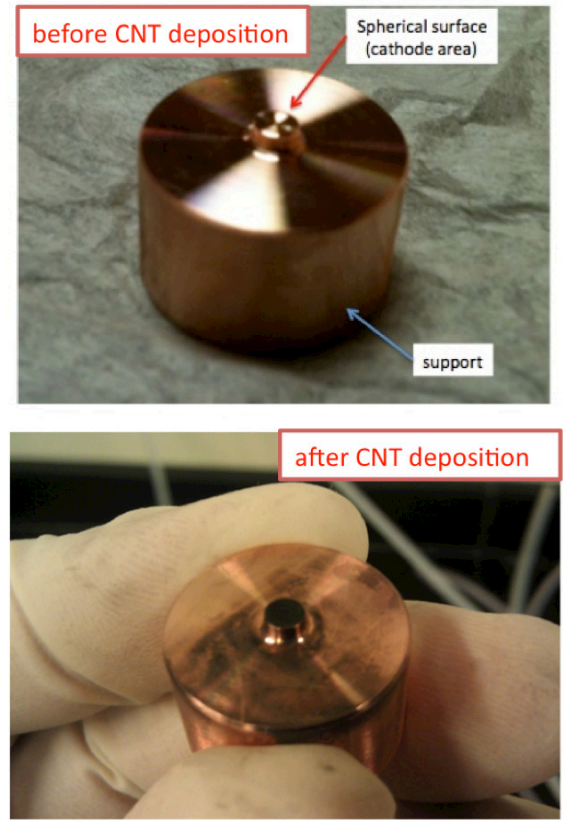

Figure 1: Above, Copper cathode substrate sample machined at RadiaBeam; Below, CNTs have been deposited on the spherical surface that represents the emission area.

The test box used for the high-voltage measurements has been assembled at RadiaBeam. A picture of the cathode assembly is given in Figure 2. On the left-hand side, the cathode is being inserted inside the vacuum chamber. The copper sample is connected to the inner conductor of a vacuum feed-through. On the right-hand side of the same picture, one can see how the assembly is placed inside the vacuum chamber: an aluminum sheet, beer-cap shaped, is wrapped around it and holds the box in the center of the pipe. At the same time, electrical and thermal conduct between the chamber the metallic box is obtained. Cathode part and the anode (box, cross and pipe) are isolated from each other by the quartz window.

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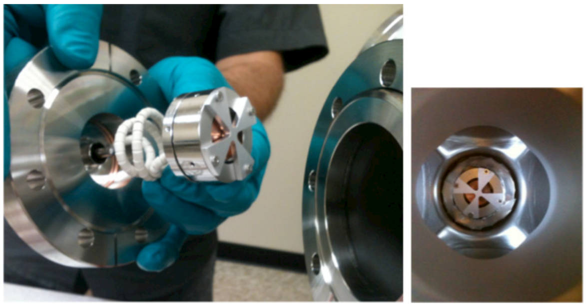

Figure 2: left, cathode assembly being inserted inside the vacuum chamber; right, cathode assembly inside the vacuum chamber.

The current density-electric field characteristic of the CNT diode configuration, plotted after the first experimental results, is shown in Figure 3. The applied voltage is varied between 1.2 kV to 6 kV over a 0.96 mm gap. One can see that the target current, about 103 mA, is achieved at ~6.4 MV/m electric field (6 kV voltage) averaged on the cathode. Thus, the current density obtained, for the given emission area (2.2 mm in dia.), is about 2.7 A/cm^2.

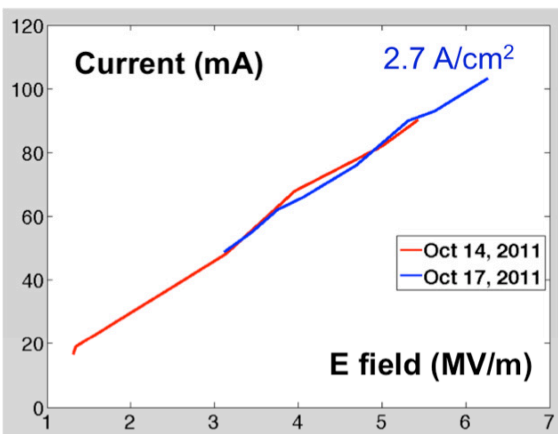

Figure 3: Current density vs. electric field from the high-voltage tests.

Before and after the high-voltage tests, we took pictures of the emission area with a Scanning Electron Microscope (SEM). Some very interesting features appeared: it seems that applying an intense electric field, causing heating the sample itself, gets rid of much of the adsorbants, smoothing out the surface, as shown in Figure 4. In particular, it has to be noted how the electric field lines tend to orient the tubes, greatly improving the tube spacing and height uniformity.

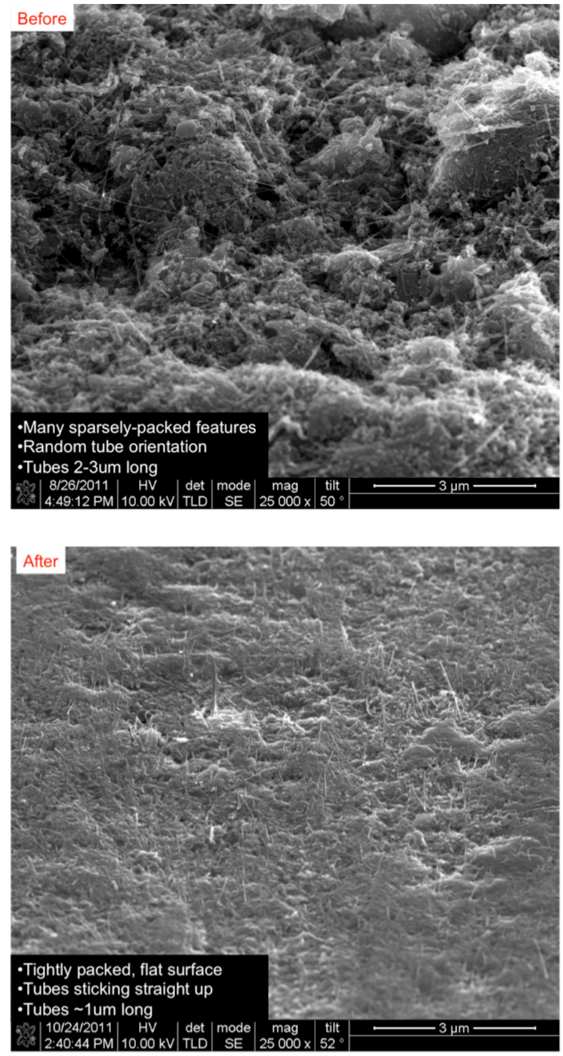

Figure 4: SEM pictures of the CNT deposition on the copper sample, before (above) and after (below) high-voltage tests.

PLAN FOR TESTS IN RF ENVIRONMENT

The first RF power tests inside an RF gun will be performed at the Fermilab A0 facility. In order to accommodate their insertion geometry, we have machined an identical cathode sample, made out of Moly, following their mechanical drawings. Nevertheless, before proceeding to the RF tests, we will first apply high-voltage, up to 5kV, in a DC and pulsed mode, using a simple cathode-anode test setup as shown in Figure 5. Both anode plate (copper) and cathode slug are electrically isolated from ground (inside the vacuum cube), possible by using a multi-pin high-voltage vacuum feed-through. A glass window is used to watch during operation and the anode can be aligned by means of an actuator type stage. The high-voltage power supply will be used in DC mode and also pulsed by using an external circuit. The current measurement will be obtained through a resistor located close to ground to pick up the current at a reasonably low voltage level.

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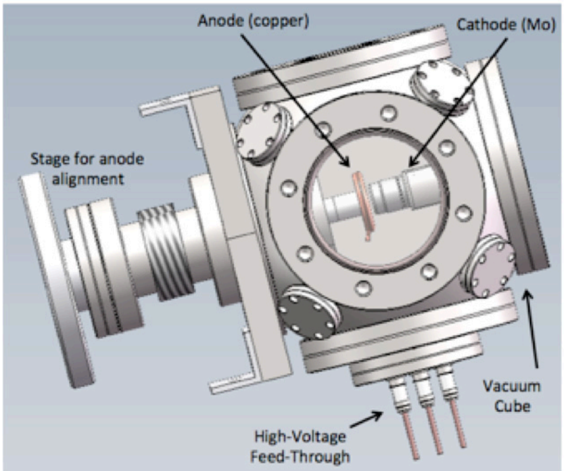

Figure 5: cathode-anode test setup inside a vacuum cube for DC/pulsed high-voltage tests.

A picture of the Moly cathode sample (CNTs are deposited over the flat head of 1cm in dia.) that will be used for RF tests inside the A-0 Gun at FermiLab is shown in Figure 6.

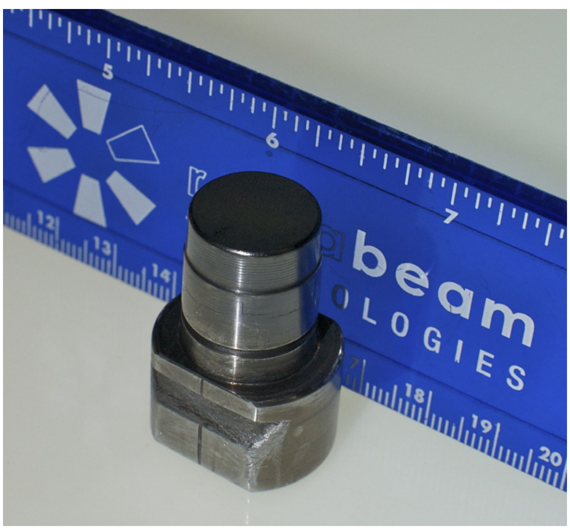

Figure 6: Moly cathode sample (after CNT deposition) for insertion inside the A-0 RF Gun.

Furthermore, we have started the RF design and engineering of a DESY PITZ-like High-fidelity Gun. The RF power test of this type gun will be performed at FermiLab, with the CNT cathode. The preliminary 3D model is shown in Figure 7. The RF power is fed from the beam output pipe by means of a rectangular-coaxial transition. This will allow to keep perfect field symmetry inside the Gun cells, eliminating any higher order mode field components that can deteriorate the beam quality. The cooling system, also shown in the picture, permits very high repetition rate operation.

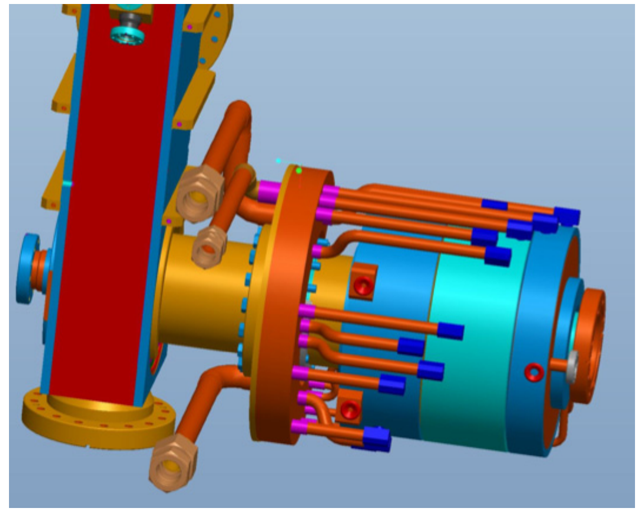

Figure 7: 3D CAD model of the high-fidelity RF Gun (Pitz-like).

CONCLUSIONS

In summary, the first cathode fabricated at RadiaBeam has already demonstrated a current density up to 2.7A/cm^2. Further testing must be done to fully characterize the emission and the lifetime. We will improve the high voltage (HV) test setup by developing a complete testing system for CNT cathodes. Several HV power supplies, vacuum pumps, and other components will be purchased to allow simultaneous testing of several cathodes at the same time. This will allow short term, rapid testing of several cathodes, while longer-term lifetime testing is ongoing in the background.

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