CONTINUED DEVELOPMENT AND TESTING OF CARBON NANOTUBE CATHODES AT RADIABEAM*

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Abstract

RadiaBeam is continuing to develop carbon nanotube (CNT) cathodes for DC-pulsed and radio frequency (RF) driven electron sources. CNT cathodes, if fully realized, are capable of producing very high current density with low thermal emittance, due to ambient operating temperature. Experimental results of CNT cathodes are presented, including the high-voltage tests, and life time studies. CNT cathodes potential applications in accelerator science and microwave industry are discussed, and near term plans to test the CNT cathodes in the 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 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 CATHODE PRODUCTION

After early initial testing, we have focused on producing CNT cathodes via electrophoretic deposition (EPD) (see Figure 1). This method has proven to be rapid and economical. We are able to produce and characterize approximately one cathode per week. This allows us to produce a large number of samples with varying properties (deposition density, annealing temperatures, etc) to find the best combination of performance and durability.

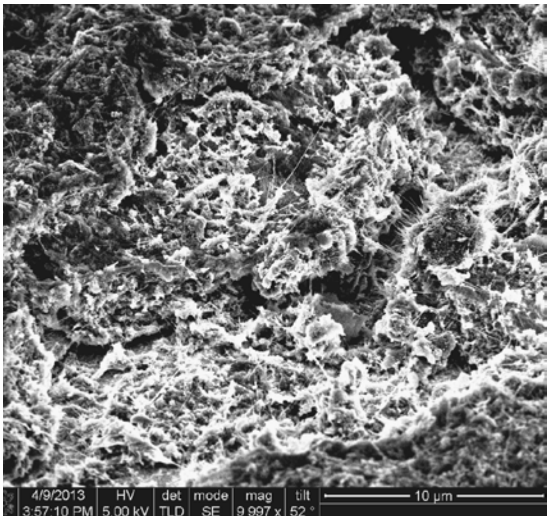

Figure 1: EPD deposition showing a very high density of CNTs.

As compared to earlier efforts, we have modified the substrate design to reduce the time required for machining and to accommodate the compact chemical vapor deposition (CVD) furnace that we helped our collaborators build. Our plan to eventually test the CNT cathodes inside the RF Gun at A0 (Fermilab) led to a design that has a reusable holder and removable cathode substrates. Figure 2 shows the new reusable holder with a variety of substrates ready for deposition.

Figure 2: Reusable cathode holder with molybdenum cathode substrate on the LEFT, based on Fermilab's A0 gun. Two undeposited cathodes (stainless steel and copper) on the RIGHT.

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As we are near the point of having optimized our EPD process, we are beginning early production tests of the CVD process. A computer controlled quartz tube furnace and digital mass flow controllers comprise the basic CVD production system. Unlike EPD, CVD allows us to grow CNTs directly on the substrate, offering more control of the microscopic properties of the deposition. We begin with elemental nickel nanoparticles (20 nm diameter, MKnano), which we suspend in isopropanol and then spin-coat onto the desired substrate. Since single nanotubes tend to grow from each nanoparticle and tube diameter is proportional to catalyst size [6] we check nanoparticle density via SEM to ensure they are sufficiently dispersed. For initial CVD process optimization we used silicon wafers as growth substrates, exploring the gas flow and temperature parameter space and characterizing samples in a SEM to develop a suitable growth recipe. We then adapted this recipe for growth of CNT on Ni nanoparticles dispersed onto Cu substrates, as we eventually wish to grow nanotubes directly onto copper cathodes. After a few trial growths, adjusting to reduce the significant amount of carbon which deposits onto the copper as graphene, we were able to successfully grow carbon nanotubes directly onto copper surfaces (See Figure 3).

Figure 3: CNTs deposited onto a copper substrate via CVD. The red arrow points to a blurred CNT, indicating that it was only attached at one end, and was free to vibrate in the SEM.

CNT CATHODE TESTING

In order to be used in the gun (both DC and RF) for injection into an accelerator, the cathodes must have a sufficient current emitted at reasonable electric fields. Our initial goal is to make cathodes that are stable at ~20MV/m. We employ a pulsed mode test station for initial characterization. The test station has a variable gap of 0-25 ± 0.02 mm, can apply 0-2.5 kV, and a minimum pulse length of 5 µs.

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. From 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 4). 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 the repeated the test. This substantially increased the voltage handling at the expense of reducing the emitted current.

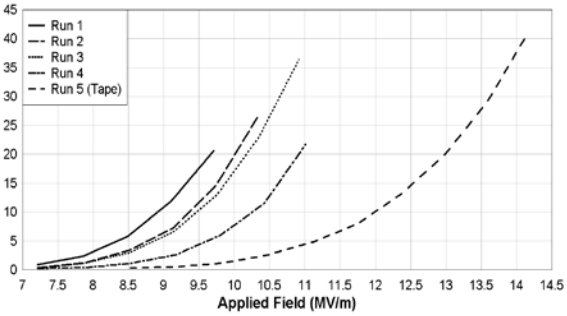

Figure 4: A series of runs on the same cathode, each ending in a breakdown. A final run after using tape to clean the cathode improves the voltage handling.

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 (see Figure 5). 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.

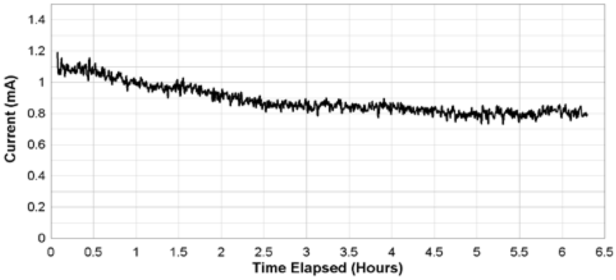

Figure 5: Lifetime study of small CNT cathode showing initial decay of current, stabilizing after approximately 4 hours.

PLAN FOR TESTS IN RF ENVIRONMENT

The initial high power tests inside an RF gun will be performed at the FNAL-A0 beamline at Fermilab. As discussed, our cathode design is compatible with their interchangeable cathode system. After verification in an RF environment, we will test our cathodes in a dual-frequency gun Radiabeam has designed and will fabricate (which will be given to Fermilab for general use after the experiments). The dual frequency gun uses the interference of a harmonic frequency with a primary accelerating frequency to effectively gate the emission of the CNT cathode to the proper phase of the acceleration RF. Since the CNT cathodes have a distinct threshold voltage, unlike thermionic cathodes, the bunch length can be made much shorter, eliminating the need for a bunching structure before injection into the accelerator.

We have started the RF design and engineering of a DESY/PITZ-like High-fidelity Gun. The preliminary 3D model is shown in Figure 6. The RF power is fed from the beam output pipe by means of a rectangular-coaxial transition. This will allow us 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.

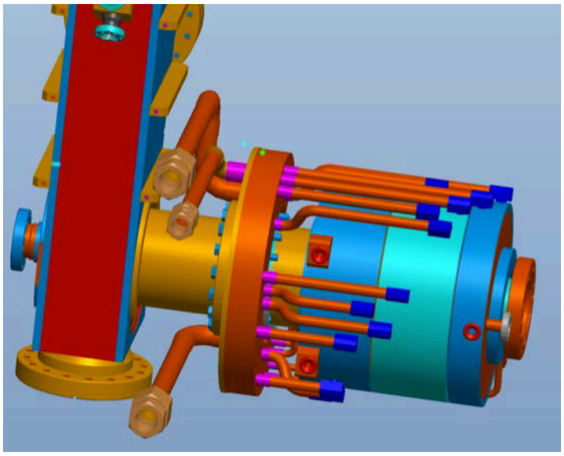

Figure 6: 3D CAD model of the high-fidelity RF Gun (Pitz-like).

This gun design will be adapted to use two frequencies (1.3 and 3.9 GHz) over the next several months. Fabrication is scheduled to begin in early 2014. The RF power test of the high-fidelity gun will be performed at Fermilab, with the CNT cathode, by the end of August 2014.

CONCLUSIONS

In summary, Radiabeam has made significant progress in bringing CNT cathodes to the point of experimental evaluation. Further testing must be done to fully characterize the emission and the lifetime, particularly for cathodes produced via CVD. The upgrades to the pulsed mode test system have greatly increased our throughput of samples, speeding up the optimization of our deposition processes. The CW mode test station was built and is evaluating samples under 100% duty cycle conditions to ascertain the effective lifetime of CNT cathodes.

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