STABILITY AND LIFETIME STUDIES OF CARBON NANOTUBES FOR ELECTRON COOLING IN ELENA

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Abstract

Electron cooling guarantees beam quality in low energy antimatter facilities. In the Extra Low ENergy Antiproton ring (ELENA), the electron cooler reduces the emittance blow-up of the antiproton beam so that a focused and bright beam can be delivered to the experiments at the unprecedentedly low energy of 100 keV. To achieve a cold beam at such low energy, the electron gun must emit a mono-energetic and relatively intense electron beam. An optimization of the electron gun involving a cold cathode is studied to investigate the feasibility of using carbon nanotubes (CNTs) as cold electron field emitters. CNTs are considered among the most promising field emitting materials. However, stability data for emission over hundreds of hours, as well as lifetime and conditioning process studies to ensure optimal performance, are still incomplete or missing. This contribution reports experiments aimed at characterizing these properties and assessing whether CNTs are suitable to be used as cold electron field emitters for many hundreds of hours.

INTRODUCTION

In ELENA the antiprotons coming from the Antiproton Decelerator (AD) with a kinetic energy of 5.3 MeV are decelerated to 100 keV [1]. Due to the deceleration process, intra-beam scattering and scattering with residual gas, the beam emittance, or transverse energy, rapidly increases leading to losses and a poor-quality beam. The electron cooling process takes place twice during the beam cycle and permits to reduce the antiproton beam emittance. During the two cooling plateaus the electron beam energy and current are $E = 355$ eV, $I = 5$ mA (first plateau), and $E = 55$ eV, $I = 1$ mA (second plateau) [2]. The thermionic gun currently used in operation limits the cooling performance due to the relatively high transverse energy of the emitted beam (> 100 meV). This is motivated by the required appliance of a high temperature enable the electron emission. The use of a cold cathode could bring several benefits regarding both the electron beam energy and the gun layout simplicity. Field emitting carbon nanotubes (CNTs) can be a promising option for fulfilling this task. CNTs are considered as the most promising field emitting materials as they can emit relatively high currents while being mechanically stable and chemically inert [3, 4]. Among all possible CNT arrangements, after several studies and tests we have chosen to focus our investigation on an honeycomb-like array, as shown in Fig. 1 [5, 6]. The CNT samples were then characterised with tests of stability, lifetime and performance during current switching in order to assess the feasibility of using such a cathode in the electron gun of ELENA's electron cooler.

EXPERIMENTS

To characterise CNT samples an apposite test bench was designed and developed, the cold cathode test bench (CCTB). The CCTB consists of a vacuum system where an experimental setup in diode configuration has been designed for each flange. The diode configuration is composed of a CNT sample, the cathode, and a Molybdenum plate, an anode. The two are 800 μm far and separated by a mica insulating spacer/mask with a center hole for allowing passage of the electron beam and delimiting the emission surface. The electrical connections are realised by means of Kapton/Copper wires and SHV feedthroughs for in-air connections. The cathode is then connected to a HV power supply and the anode to a digital multimeter for current measurements. In such a way it was possible to make DC measurements in order to test stability and lifetime of our samples [5, 6]. Furthermore, we developed a hardware current switching system for testing the current emission in pulsed mode. In ELENA, in fact, the electron beam must be turned on and off depending on the beam cycle of the antiproton beam. The current switching system was based on a Behlke push-pull [7], and the voltage on the cathode was switched between HV and ground. In this case the anode was connected to a shunt resistor and ultimately an oscilloscope was used to measure the current output as a voltage drop on the shunt resistor via the classic Ohm's law.

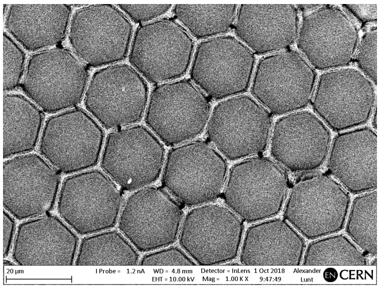

Figure 1: SEM image of a CNT honeycomb-like array.

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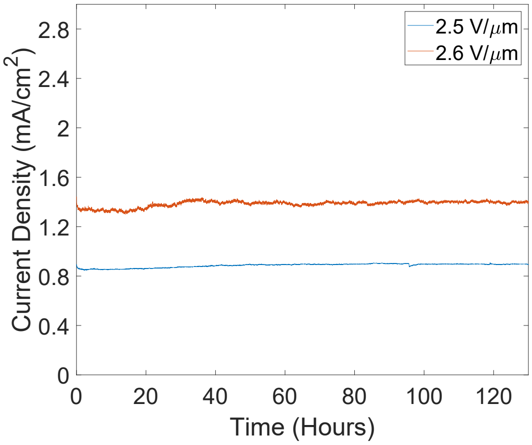

Figure 2: Current density as a function of time for a sample of CNT honeycomb-like array.

RESULTS AND DISCUSSION

Lifetime and Stability Measurements

Several tests have been performed on the CNT samples, which have proved that the emitting performance are greatly affected by the emission environment and by a prior conditioning process. A high pressure in the vacuum chamber can lead to phenomena such as ion bombardment and ionization processes, which can severely affect the emission properties and/or damage the cathode when the conditions are excessively extreme, e.g. high pressure and presence of adsorbates on the CNT tips [8, 9]. A suitable conditioning process is greatly beneficial in order to ensure reliable and repeatable results and performance. We have found that if the emission conditions are well controlled so to have a base pressure below 1×10^{-8}, a bake-out process is performed to clean the cathode's surface and emission region, and a slow conditioning process with voltage ramps is performed, the CNT cathode can stably emit for many hundreds of hours without showing any sign of deterioration [5, 6]. An example of such performance is reported in Fig. 2. In general, we proved a lifetime over 1500 hours for honeycomb-like arrays [5, 6].

In order to test the stability of the current emission, further measurements were performed for a total of about 100 hours of emission. Figure 3 shows an example of current density stability for 20 hours. For each step, the coefficient of variation (or relative standard deviation) was computed:

$$c_V[\%] = \frac{\sigma}{\langle J \rangle} \times 100\,. \tag{1}$$

where σ is the standard deviation of the current density and $\langle J \rangle$ the averaged current density.

The results concerning the standard deviation and the coefficient of variation in Fig. 4 show that the CNT cathode can stably emit even when increasing the applied electric field, and therefore the emitted current. Whilst the overall standard deviation is slightly increasing reaching 0.01 mA/cm^2 for a current density of 1.4 mA/cm^2, the coefficient of variation is instead stably decreasing and remaining below 1% for every step except the first. This indicates an optimal stability of the current emitted from carbon nanotubes. [5, 6]

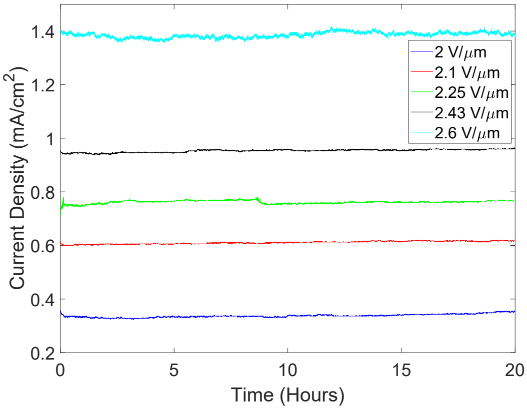

Figure 3: Current density as a function of time (hours) and electric field (V/μm). Five different measurements of 20 hours each at five different applied electric fields [5, 6].

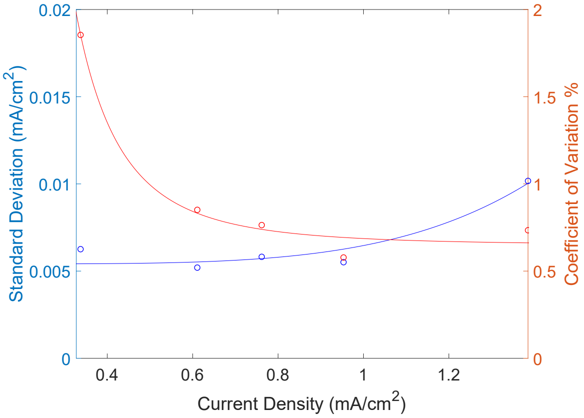

Figure 4: Standard deviation and coefficient of variation as a function of the current density for a sample of CNT honeycomb-like array at five different emitted current densities (five different applied electric fields).

Current Switching Measurements

The tests on the current switching mode have allowed calculation of the rise time and shutdown time of the emitted current from CNTs and at the same time provided proof of the cathode's unmodified emission stability when used in current switching mode.

The test was performed using a push-pull switch in combination with an appositely devised circuit and activated by a signal generator. With the signal generator we produced a square wave with amplitude of 5 V, as required for activating the push-pull switch. The results relative to the rise and shutdown times are reported in Figs. 5 and 6, respectively.

The main challenge encountered in these measurements was due to a capacitance effect. This translated in a voltage

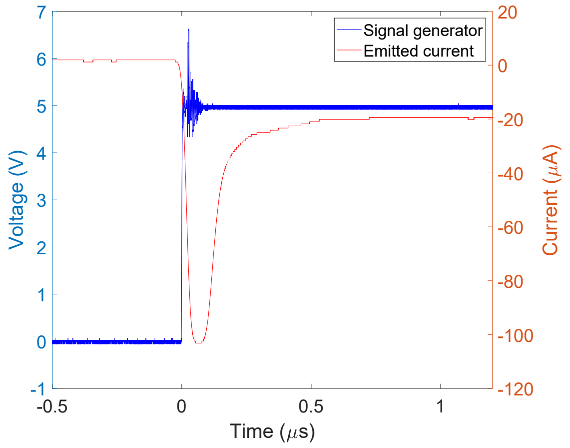

Figure 5: Emitted current rise at an applied voltage of about 900 V.

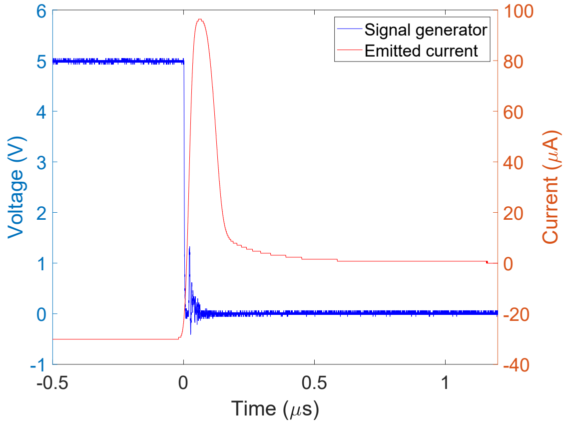

Figure 6: Emitted current shutdown at an applied voltage of about 900 V.

rise when any voltage was applied within the switching system. The effect takes place symmetrically on both sides of the square wave with inversed polarity. The decay time of the voltage drop is of about 500 – 600 ns. An increase of the voltage doesn't provoke an increase of the decay time, whilst inducing a higher voltage drop. This effect mainly caused two issues: (i) reaching the oscilloscope limitations at high voltages, (ii) and masking the first 500 – 600 ns of measurement. Nevertheless, these effects are taking place in under 1 μs and do not represent a serious problem considering our requirements. Currently, the ELENA electron gun switch has rise and fall times in the order of 1 ms. Therefore, rise and fall times in the order of 1 μs are already an improvement of about three orders of magnitude.

The rise and fall times are of approximately 600 ns, as it is possible to infer from Figs. 5 and 6. This time is practically due to the capacitance effect. Eventually, this study proves that the emission from the CNT cathode can be switched on and off in a time that is no longer than 600 ns.

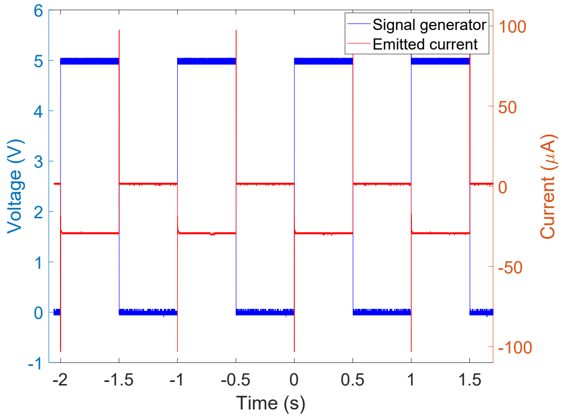

Figure 7: Current switching test at 1 Hz.

Finally we present a sample result of a 1 Hz fast switching of the emitted current from a CNT cathode, Fig. 7. We can notice how the emission is unvaried at each switching iteration. The peaks visible at every rise and fall are relative to the aforementioned capacitance effect.

CONCLUSIONS

CNT honeycomb-like arrays have shown very promising experimental results as cold electron field emitters. A lifetime over 1500 hours and an emission stability better than 1% have been proved. These results show that a CNT cathode can be a suitable candidate to be used in operation in the ELENA's electron cooler as field emitting cathode [5, 6].

Further tests performed in current switching mode show that a CNT cathode and a current switching system based on a push-pull switch can easily outperform the currently used switching system reaching rise and fall times below 1 μs, three order of magnitude below the performance of the currently used system in ELENA, where the rise and fall times are above 1 ms.

Finally, while testing the emitted current in switching mode, no sign of current deterioration were noticed and the stability of the current output was unvaried, effectively showing that a CNT cathode can perform successfully in current switching mode without any damaging incurring during operation.

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