ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB152

CARBON NANOTUBES AS COLD ELECTRON FIELD EMITTERS FOR ELECTRON COOLING IN THE CERN EXTRA LOW ENERGY ANTIPROTON (ELENA) RING

B. Galante[1,2,*], G. A. Tranquille, CERN SY-BI-XEI, Geneva, Switzerland
C. P. Welsch[2], O. Apsimon[2], The University of Liverpool, Liverpool, United Kingdom
J. R. Lopez, ICMUV-Institute of Materials Science, University of Valencia, Spain
[1]also at The University of Liverpool, Liverpool, United Kingdom
[2]also at The Cockroft Institute, Sci-Tech Daresbury, Warrington, United Kingdom

Abstract

Electron cooling is a fundamental process to guarantee beam quality in low energy antimatter facilities. In ELENA the electron cooler allows to reduce the emittance blow-up of the antiproton beam and thus deliver a focused and bright beam to the experiments at the unprecedented low energy of 100 keV. In order to achieve a "cold" beam at this low energy, the electron gun of the cooler must emit a mono-energetic and relatively intense electron beam. An optimization of the ELENA electron cooler gun involving a cold cathode is currently being studied.

INTRODUCTION

ELENA is the newest and smallest decelerator at CERN. Its goal is to decelerate antiprotons coming from the Antiproton Decelerator (AD) at 5.3 MeV down to 100 keV [1]. During the deceleration process the beam emittance, or transverse energy, increases due to adiabatic blow-up, intra-beam scattering and elastic scattering with residual gas, leading to losses and a poor-quality beam. Therefore, electron cooling (e-cooling) is applied to reduce the longitudinal and transverse energy spreads of the antiproton beam. The cooling process takes place twice during the beam cycle. E-beam energies and currents are respectively: 355 eV, 5 mA, and E = 55 eV, I = 1 mA [2]. A thermionic gun is currently used in operation, although its performance is limited due to the relatively high transverse energy of the emitted beam (> 10 meV). Thus, we are investigating the feasibility to use carbon nanotubes (CNTs) as electron field emitters, leading to a cold cathode e-gun. Field emission (FE) has recently become a very active research field because of the emergence of 2D nano-structures, which can greatly enhance the FE properties, allowing to extract high currents at low applied electric fields. For our study, CNTs have been chosen due to their remarkable properties. They are currently considered as the most promising FE material, allowing to reach high current densities whilst having good chemical and emission stability. Several groups have reported promising results using arrays of vertically aligned CNTs. This arrangement minimizes screening effects which can adversely affect the FE performance [3, 4].

* bruno.galante@cern.ch

EXPERIMENTS

Two types of array were characterized in this study: a honeycomb-like array (CNT1) and a squared-islands array (CNT2) (Fig. 1). To characterize their properties several experimental tests were completed, and further tests are scheduled for the near future focusing on the emitted current as a function of the applied electric field, emission stability, lifetime, switching and measurements of beam energy. As for now, the main experimental setup is in diode configuration. It consists of a CNT array, which is the cathode, and the e-beam is collected and measured at the anode, a Molybdenum plate. The setup can host up to 9 samples, each independent of each another and with sizes up to 45 mm of diameter. Several experimental techniques have been used so far to characterize the samples such as SEM (Scanning Electron Microscopy) for imaging of the CNT arrays, SEY (Secondary Electron Emission Yield Measurement), UPS (UV Photoelectron Spectroscopy) for evaluation of the work function (W), and RGA (Residual Gas Analyzer) for study of contaminants in the vacuum chamber.

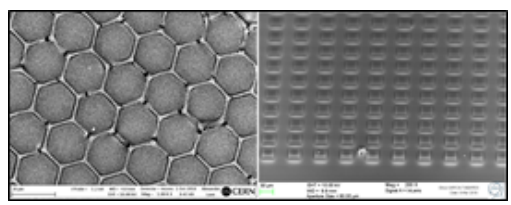


Figure 1: SEM images of the honeycomb-like array CNT1 (left) and squared-islands array CNT2 (right).

RESULTS AND DISCUSSION

Lifetime and Stability Measurements

The characterization of several CNT1s and CNT2s was made with a conditioning and stability test at a fixed field, followed by a slow ramping up of the voltage. This, together with a vacuum monitoring, has shown that the emitted current is strongly dependent on the vacuum level (Fig. 2). This can be partly explained by the shortening of CNTs during the current peaks and outgassing of CNTs. Other important factors are ion bombardment and residual gas ionization, effects that can become dominant if the pressure is not low enough. These last two effects surely play a major role in

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB152

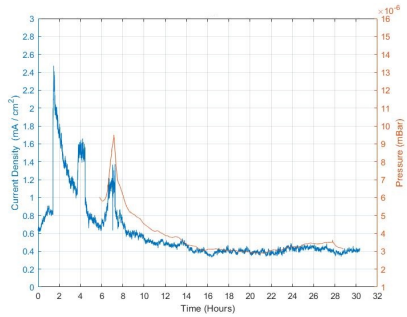


Figure 2: Conditioning test. Time vs Current Density and Pressure. $E = 1.94\,\mathrm{V/\mu m}$.

affecting emission stability and lifetime. Hence, a good vacuum and a slow conditioning process are essential to provide stable and reliable emission. Emission properties as a function of the applied electric field were also studied. The threshold field, defined here as the electric field needed to reach a current density of 1 mA/cm^2, is for two cases studied $E_{tr} = 1.67\,\mathrm{V/\mu m}$ (Fig. 3). However, the behaviors of the two curves, both fitted with the classic Fowler-Nordheim (FN) equation for simplicity, show a slight shift when the electric field increases, indicating that the conditioning process has indeed changed the emission properties (Fig. 3).

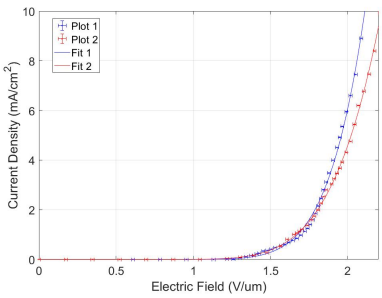
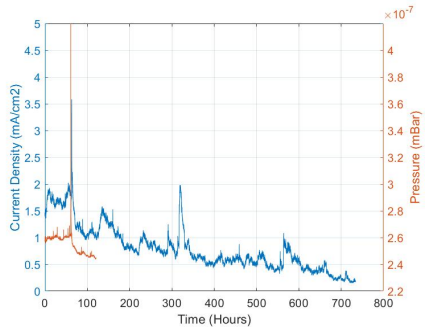
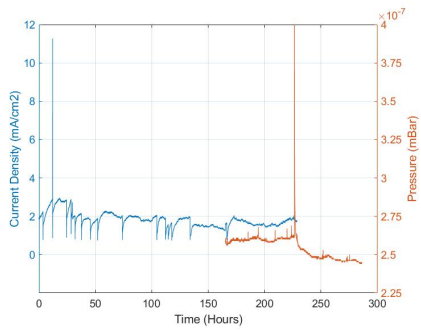


Figure 3: Current Density vs Electric Field at t_1=380 h and t_2=t_1+300 h.

Further tests have shown that these samples are able to emit for hundreds of hours without showing signs of burnout. CNT2 arrays have also been tested, but most chips did not show great performances. This array showed higher threshold field, $E_{tr} = 2.71\,\mathrm{V/\mu m}$ and although it showed an initial good stability, its lifetime was much lower than CNT1s, as shown in Fig. 4. The best among the CNT2 samples reached total burnout after approximately 500 hours, a value much smaller than for the previous array, for which an operational time of more than 1500 hours has been obtained without clear signs of burnout. As for now, none of the CNT1s have reached burnout after hundreds of hours of use. CNT2s have therefore been discarded. A further proof of how the environment severely affects the emission is shown in Fig. 4. At the time of CNT2 burnout a large vacuum spike can be seen (in red in Fig. 4b). This is the same vacuum peak shown in the lifetime measurement of CNT1 (Fig. 4a). In fact, the two chips were being tested simultaneously and after the vacuum peak the emitted current for the first array undergoes a steep peak and then drops significantly.



(a)



(b)

Figure 4: Lifetime test. CNT1 (a) and CNT2 (b).

Further studies at different vacuum levels on other samples showed how the difference in emission stability can be striking. For optimal performance, a pressure in the order of 10^{-8} mBar or lower is necessary to avoid significant contributions from ionization processes. Further proof of this behavior is given by the increased performance of CNT1s when the pressure was decreased below 1×10^{-8} mBar. It is indeed possible to infer from Figs. 5 and 6 how the emission stability has improved without clear signs of deterioration. However, a bake-out process has also been added to clean the vacuum chamber and the emission region. In Fig. 5 the stability test is conducted on the same CNT1 sample as in Fig. 4. In this case, the test was performed in switching mode in order to observe the feasibility of current switching as required for ELENA. It is possible to see how the switching does not cause significant variations despite the presence of local low peaks. In Fig. 6 the performance of another CNT1 sample is presented. The emission is remarkably stable for more than 250 hours at two different applied electric fields, particularly at the lower field. In this case there was an optimal pressure of less than 1×10^{-9} mBar and a bake-out process at 220 °C was performed before sample operation.

Work Function Measurements

As further characterization, we have performed measurements of the work function (W) of the samples during ther-

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB152

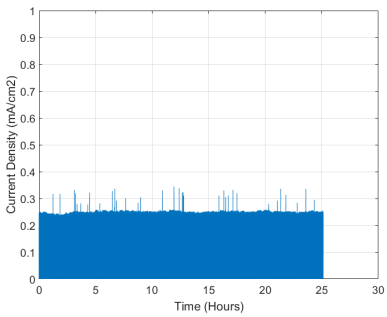


Figure 5: Stability and pulse mode for CNT1 array.

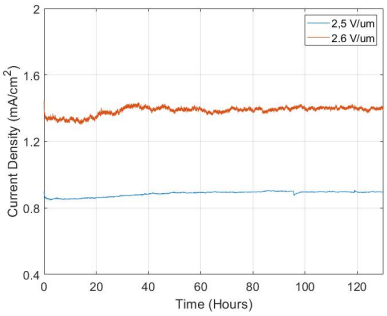


Figure 6: Stability of CNT1 for 2 applied electric fields.

mal annealing to investigate whether the air exposure affects the W value. From Fig. 7, sample 4, it can be seen that variations stay within the uncertainty of the measurement, 0.1 eV. The tests were conducted with two main techniques: SEY and UPS, on four different samples. FE strongly depends on W. Therefore, it is important to determine its correct value. In all cases we found $W = 4.4 \pm 0.1$ eV. The annealing was conducted in 4 steps: 180 °C for 30 mins, 180 °C for 120 mins, 250 °C for 240 mins, 300 °C for 180 mins. This is also supported by RGA measurements during the heating steps which showed how the presence of desorbed contaminants decreases significantly after annealing (Fig. 8). It is worth mentioning that the W measurements were made on an area of about 5 mm × 5 mm. Meaning that local contamination may still lead to altered W in localized areas. This could also play a role in the stability variations during the first stages of emission.

CONCLUSIONS

The samples tested so far have demonstrated promising results if operated in optimal conditions: $P \leq 1 \times 10^{-8}$ mBar and bake-out $T \geq 200\,°C$. Additionally, a conditioning process with voltage ramps is advised. UHV and bake-out perfectly match the requirements of ELENA, where nominal pressure is of about 10^{-11} mBar and bake-out is part of the start-up procedure. One of the biggest concerns about CNTs relies on their lifetime and stability. The tests performed so far indicate a good stability and the lifetime is promising for CNT1 arrays. For what concerns the maximum reachable current, all samples show that they can theoretically reach

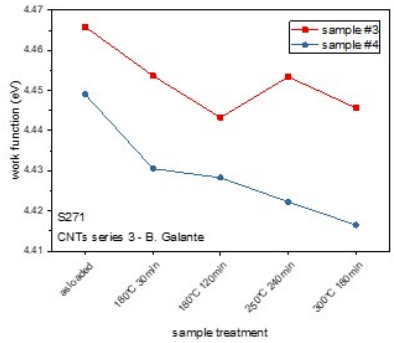


Figure 7: W measurements for 2 different CNT samples.

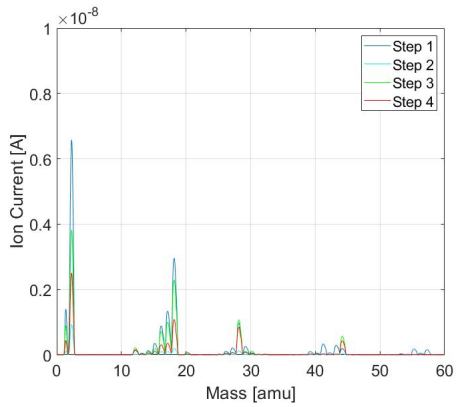


Figure 8: RGA during outgassing peaks at heating steps.

the maximum required value of 5 mA. We have successfully reached value as high as 2 mA/cm^2 with practically all samples. However, it has been noticed that stability and lifetime are improved at low emitted current as shown in Fig. 6. This behavior suggests that the use of a large area cathode would most likely be beneficial for optimizing the performance for operational use.

ACKNOWLEDGEMENTS

Mechanical parts and electronics realized with the participation of Jean Cenede, Alexandre Frassier and Wilfried Devauchelle. SY-BI-XEI, CERN. SEM analysis performed with A. T. Perez Fontenla, A. Lunt and E. Garcia-Tabares Valdivieso. EN-MME-MM, CERN. SEY, XPS, UPS and RGA analysis performed with M. Himmerlich. TE-VSC-SCC, CERN. Javier Resta acknowledges support by the Generalitat Valencia under grant agreement CIDEGENT/2019/058.

"AVA has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 721559."

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB152

REFERENCES

[1] S. Maury *et al.*, "Elena: The extra low energy anti-proton facility at cern", *Hyperfine Interact.*, vol. 229, pp. 105–115, 2014. doi:10.1007/s10751-014-1067-y

[2] G. Tranquille, A. Frassier, and L. Joergensen, "The elena electron cooler: Parameter choice and expected performance", CERN, Geneva, Switzerland, Rep. CERN-BE-2013-004, 2013.

[3] Y. Saito, *Carbon Nanotube and related field emitters: Fundamentals and applications*. Hoboken, New Jersey, USA: Wiley-VCH, 2010.

[4] C. Li *et al.*, "High emission current density, vertically aligned carbon nanotube mesh, field emitter array", *Appl. Phys. Lett.*, vol. 97, p. 113107, 2010. doi:10.1063/1.3490651