ISBN: 978-3-95450-243-1 ISSN: 2226-0374 doi:10.18429/JACoW-COOL2021-P1010

OPTIMIZATION OF THE ELECTRON EMISSION FROM CARBON NANOTUBES FOR ELECTRON COOLING IN ELENA

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Abstract

Electron cooling guarantees beam quality in low energy antimatter facilities. The ELENA e-cooler permits to reduce the emittance blow-up of the $\bar{p}$ beam, thus delivering highly focused and bright beams at the unprecedented low energy of 100 keV to the experiments. To have a “cold” beam at such low energy, the electron gun must emit a mono-energetic and relatively intense electron beam. Efficient cooling can be achieved with a 5 mA electron beam having transverse energy spread < 100 meV and longitudinal energy spread ~ 1 meV. The thermionic gun used in operation limits the cooling performances due to a relatively high transverse energy of the emitted beam (>> 100 meV). An optimization of the e-gun is being studied, aiming to develop a cold cathode gun based on carbon nanotubes (CNTs). The use of CNTs implies the need of an extracting grid to allow for a stable and uniform emission, although the grid’s features are critical to control the electron beam properties.

INTRODUCTION

In field emission the electron extraction is achieved applying a strong electric field between a cathode and an anode. The high intensity of the electric field necessary to enable significant emission has always hindered the use of field emitting cathodes. The arise of tip-like nano-structures has paved the way to field enhancement, so that it is now possible to extract large currents, in the order of many mA, with an electric field in the order of a few V/μm. CNTs are considered among the best field emitters because of their chemical stability, the possibility of mass production with scalable techniques and the large currents that they can emit and withstand [1, 2]. The major issues that have limited their use in operation are related to emission stability and lifetime. In ELENA, CNTs would be required to stably emit for hundreds or even thousands of hours without significant signs of degradation. In our previous work we investigated the best conditioning process necessary to ensure optimal emission stability and a lifetime that is compatible with operational use. If CNTs are operated in optimal conditions and trained appropriately, they can emit for hundreds of hours without significant degradation while emitting current densities of about 2 mA/cm^2; a value that would suffice for the requirements of ELENA’s e-gun, e.g. 5 mA [3, 4]. An emission for more than 1500 hours has been proved for a CNT array, testing it in both DC and switching mode [5, 6]. In order to extract electrons from a large area cathode while obtaining an homogeneous emission an extracting grid becomes necessary. For this reason, a thorough study of the grid effect is essential for tuning the electron beam features according to the requirements. Although in this work we are aiming at using CNTs, this study still holds in the case of any field emitting cathode and in general to any case where an extracting grid is deemed necessary.

EXPERIMENTS

Several grid parameters can affect the beam properties. The grid distance from the cathode defines the voltage to be applied on the grid in order to get the desired electric field. The hole size severely affects the beam properties because of the distortion of the field lines within the hole. The relation between hole size and the pitch determines the transmittance of the grid. Additionally, the hole shape and holes arrangement must be devised cleverly in order to maximize the grid’s transmittance. Finally, the feasibility of physically manufacture the desired grid according to the current technology must be taken into account. We have started analysing six different grid types: Grid 250 – 50. Hole size: 250 μm, Pitch size: 50 μm. Grid 200 – 40. hole size: 200 μm, pitch size: 40 μm. Grid 150 – 30: hole size: 150 μm, pitch size: 30 μm. Grid 100 – 20: hole size: 100 μm, pitch size: 20 μm. Grid 50 – 10: hole size: 50 μm, pitch size: 10 μm. Grid 25 – 5: hole size: 25 μm, pitch size: 5μm. The latter represents what is most likely the smallest grid which is possible to realise at the time of writing. All grids are devised to have squared holes in order to maximize the holes packing and consequently the transmittance. The pitch is hereby defined as the solid spacing between each hole.

All simulations are conducted with the software CST Studio and the simulation design allows for straight field lines in the whole emission region. The only source of field lines distortion is represent by the grid. The main simulation types are two and both have the layout illustrated in Fig. 1.

Simulation 1. Parametric simulation of the electron beam varying the grid distance from 0.4 to 5 mm with a step width of 0.2 mm. The electric field is kept constant. The initial beam energy is set to 0.1 eV in order to run a critical test for all grids. We were then able to derive the maximum deviation % of the voltage along the grid and the beam offset, "r" (calculated via the CST built-in "Envelope" option), which represents the difference between the radii of the emitted

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beam and the beam hitting the anode.

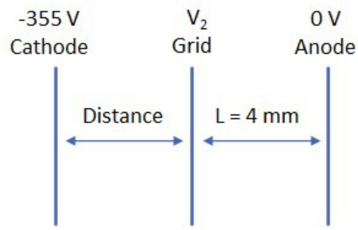

Figure 1: Simulation layout. Triode configuration: cathode, grid, anode. Cathode voltage: −355 V (the electron beam energy for the higher plateau in ELENA's e-cooler); anode voltage: 0 V. The grid voltage varies according to the distance and in order to keep a constant electric field of 2 V/μm. The emission is "Field Induced" with the parameters "a" and "b" of the Fowler-Nordheim equation derived from experimental results [6].

Simulation 2. Double parametric simulation varying the grid distance from 0.6 mm to 2 mm with 0.2 mm step width and the initial beam energy from 0 eV to 0.1 eV with 0.025 eV step width. Data analysed: beam offset.

In both cases we calculated the maximum transverse energy of the beam with the following formula:

$$E_{tr} = \frac{V_2^2 r^2}{2L^2\left(\sqrt{2(V+355)} - 26.646\right)^2} \quad (1)$$

RESULTS AND DISCUSSION

From "Simulation 1" we were able to extract several data. We can notice from Fig. 2a and 2b how the beam offset and the voltage deviation % both greatly decrease with the distance and for smaller hole grids. It is also clear from Fig. 2c how the beam offset is dependent on the voltage deviation %. The reason for the increase of the beam offset when the deviation increases is connected to the higher voltage fluctuations in the grid holes, which translates in curvatures of the field lines that consequently provoke the arise of transverse components in the beam trajectory. This trend is reversed increasing the distance, since higher distance translates in smaller voltage fluctuations along the grid. We were also able to quantify the transverse energy increase due to the passage of the beam through the grid using Eq. 1 in order to study its variation for each grid depending on the distance. The results are shown in Fig. 3 This calculation served us to understand whether the use of any of the investigated grids can fulfill our purpose considering our required beam transverse energy spread. From the inset in Fig. 3 we can assess that the only feasible grids are 50 − 10 and 25 − 5 at distances greater than 1 mm. All other grids add a transverse kick that is too high at every feasible inter-electrode distance. For this reason we focused the remaining simulations on the grid 50 − 10. In "Simulation 2" we studied how the beam offset and the beam transverse energy due to the grid change if the initial beam energy varies. The simulation is ran on the grid 50 − 10. The results are shown in Fig. 4. From Fig.

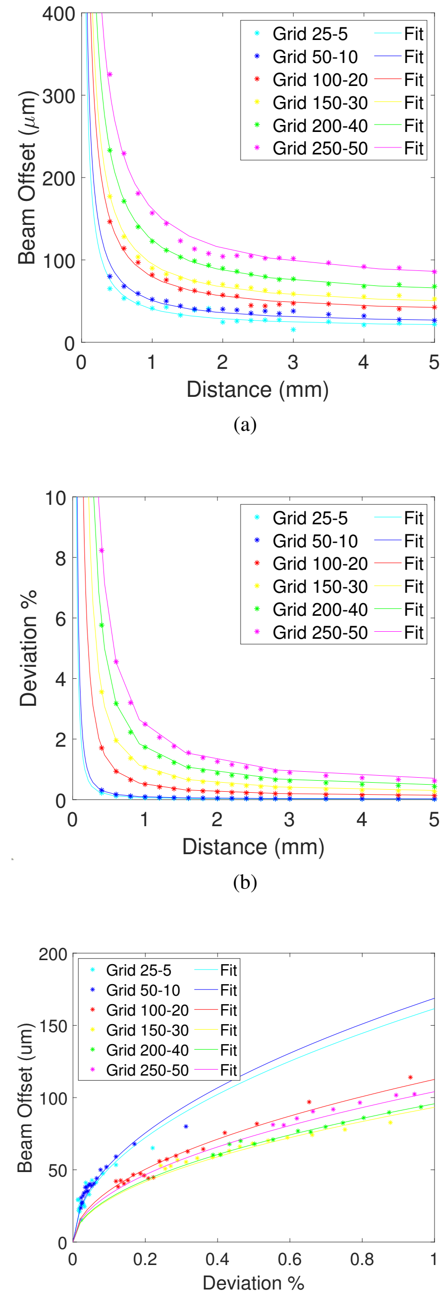

Figure 2: (a) Grid distance vs Beam Offset. (b) Grid distance vs Maximum voltage deviation %. (c) Maximum voltage deviation % vs Beam offset. All fits are done with a power equation of the type: $y = ax^b + c$.

4a we can notice that the beam offset decreases with the distance for every possible initial beam energy. The beam offset greatly increases when the initial beam energy increases, independently from the grid distance. From calculations of the transverse energy, Fig. 5, we can further notice that for smaller initial beam energy the additional beam transverse energy due to the grid is less significant. As expected, the transverse energy due to the grid and the total transverse energy both decrease when the grid distance increases.

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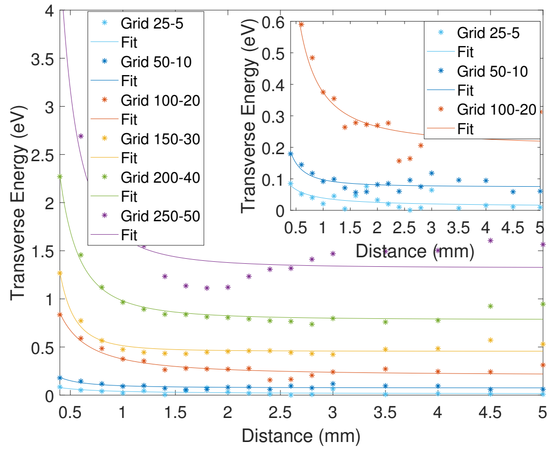
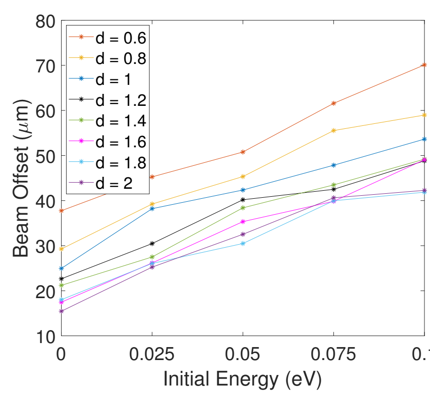
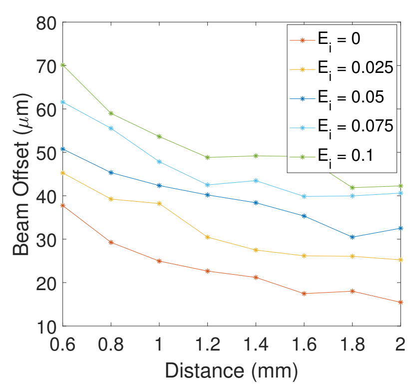


Figure 3: Grid distance vs Transverse energy due to the grid. Inset: magnification for better visualizing the behaviour of the grids 100 – 20, 50 – 10, 25 – 5. All fits are done with a power equation of the type: $y = ax^b + c$.



(a)

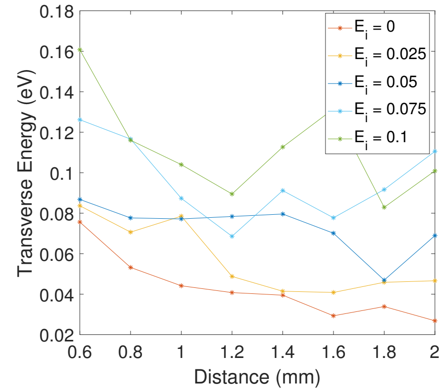


(b)

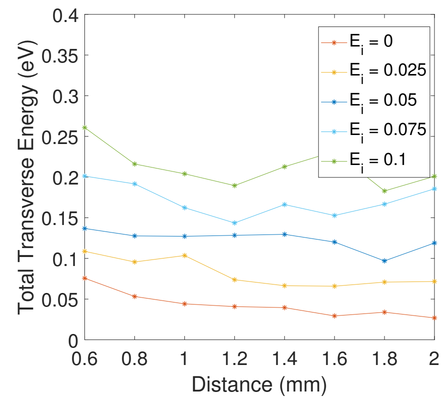
Figure 4: (a) Initial beam energy vs Beam offset, for different grid distances. (b) Grid distance vs Beam offset, for different initial beam energies.

CONCLUSIONS

The grid severely affects the beam properties and must be chosen carefully. The results achieved show how a grid 50 – 10 can provide a beam with transverse energy of less than 0.1 eV if the grid distance is > 1 mm and if the initial



(a)



(b)

Figure 5: (a) Grid distance vs Transverse energy due to the grid, for different initial beam energies. (b) Grid distance vs Total transverse energy after passing the grid, for different initial beam energies.

beam energy is ≤ 0.025 eV. These represent very strict requirements, but prove that the use of a grid is feasible. The grid 25 – 5 would provide for significantly improved beam properties since the impact of such grid on the transverse energy seems to be of less than half compared to the 50 – 10 grid, as suggested by the study in Fig. 3. Further tests are required to finalize the gun layout and a measurement of the CNT electron beam energy is necessary. This grid study gives important results for designing any gun or device involving an extracting grid and served us to determine the conditions for which a CNT-based gun is feasible for the ELENA e-cooler considering the actual state of technology.

ACKNOWLEDGEMENTS

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

Javier Resta acknowledges support by the Generalitat Valencia under grant agreement CIDEGENT/2019/058.

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