DEVELOPMENT OF A FIELD EMISSION ELECTRON GUN FOR LOW ENERGY ELECTRON COOLING

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Abstract

The use of carbon nanotubes (CNT) as a cold electron source for a low energy electron cooler has been studied in detail. To fully characterise different CNT arrays (conditioning process, emitted current, lifetime) and to investigate the optimum electrical configuration of the source to be used in an electron gun, a cold cathode test bench (CCTB) has been set up. From the measurements performed on the CCTB, an electron gun has been designed, constructed and is being tested to measure the properties of an electron gun using a larger (4 cm diameter) CNT array as the source. The CCTB has been modified to incorporate a beam transport system as well as the relevant diagnostics needed to perform the experiments. The results will be compared to the CST Particle Studio simulations and will be used to optimise the design for use in the ELENA low energy electron cooler.

INTRODUCTION

In ELENA (Extra Low Energy Antiproton Ring), electron cooling is fundamental to reduce the emittance blow-up of the antiproton beam so that a focused and bright beam can be delivered to the experiments [1]. Presently, the electron gun relies on thermionic emission, where a tungsten-doped barium oxide (BaO) source is heated to 1200 °C. However, this imposes several limitations on the transverse beam energy and the required magnet system. A cold emission-based electron gun might overcome these constraints, as field emission relies solely on high electric fields to both generate and control the electron beam.

Carbon Nanotubes (CNTs) are considered among the most promising materials for this purpose, and their feasibility as field emitters has been studied. Previous research [2] established CNT cathodes as viable candidates for the use in the electron cooler of ELENA. Still, there remains a crucial research gap in determining their optimal characteristics (maximal current density, lifetime, etc.). Bridging this gap is fundamental for advancing the development of a more efficient electron gun system in ELENA, especially in light of the requirements of future particle accelerators.

EXPERIMENTAL SET-UP

The gun assembly was installed in a vacuum tank to enable an Ultra-High Vacuum (UHV) environment and mounted on a specifically constructed Cold-Cathode-Test-Bench 2 (CCBT2).

Gun Description

The CNT-based gun prototype (see Fig. 1) is comprised of a sample holder with a 4 cm x 4 cm hollow well to place the CNT-Sample. Vertically aligned Carbon Nanotube (VCNT) arrays have been shown to have the most optimal emission properties for our purposes [2]. The VCNTs were grown on silicon plates by using chemical vapor deposition. The gun also features two finely conductive grids, made out of a highly n-doped silicon wafer with a mesh pattern (15 µm square holes with 3 µm walls). The first grid acts as a extracting anode by developing a local electric field, while the second grid is used to decelerate the beam. For insulation between the elements and to limit the beam size, two MACOR® rings are employed. The final component is an aluminium ring with a triangular-shaped cross-section, essential for maintaining straight field lines and keeping the transverse energy of the emitted beam low.

Einzel-Lenses

Given the considerable drift distance between sample and detector, an Einzel-Lens system (comprised of three cylindrical and symmetric electrodes) is used to transport and focus the beam onto an imaging screen. The configuration of voltages determines the fringe fields and thus how the particles will be deflected and focused - without significantly changing their kinetic energy. Typically, the outer electrodes share a common electrical potential, while the central electrode is held at a different potential. It was decided to use the lenses in the acceleration-deceleration mode, as this mode is preferable for longer focal lengths due to the minimized spherical and chromatic image aberration [3].

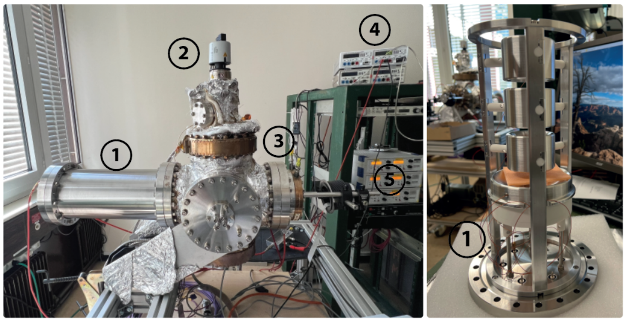

Figure 1: Left: Cold-Cathode-Test-Bench 2: ① Vacuum tank with gun assembly ② Pfeiffer Vacuum Dual Gauge ③PHOTONICS Ion Beam Profiler HM6012 Multimeter ⑤ ISEG HV Power Supply, Right: CNT-based gun assembly.

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Test-Bench Set Up CCBT2

The Cold-Cathode-Test-Bench 2 (see Fig. 1) encompasses the gun assembly installed in a vacuum tank, mounted on a 6-way cross, where three flanges are dedicated for the Edwards Vacuum Pump, a Pfeiffer TPG 362 Dual Gauge and a PHOTONIS Ion Beam Profiler (IBP). The Test-Bench can be used in two different configurations: by replacing the first grid with a copper plate serving as a Faraday Cup, the samples current can be read out by a HAMEG HM8012 Multimeter. Secondly, electron beam profile measurements can be made with the modified IBP, mounted 33 cm downstream of the gun assembly. It utilizes a Microchannel Plate (MCP) coupled to a phosphor screen, and a high resolution camera, to amplify and capture even very dim ion beam events.

In the CCTB2, the electron beam is transported from the main electron source to the IBP. Three potentials are responsible for this transport: the sample holder (fixed at −355 V), the first grid (variable - depending on distance and desired electric field), and the center Einzel-Lens (also variable). All other conducting components are grounded. These gradients result in a beam that allows the energy required for ELENA operation (355 eV).

SIMULATION SET-UP

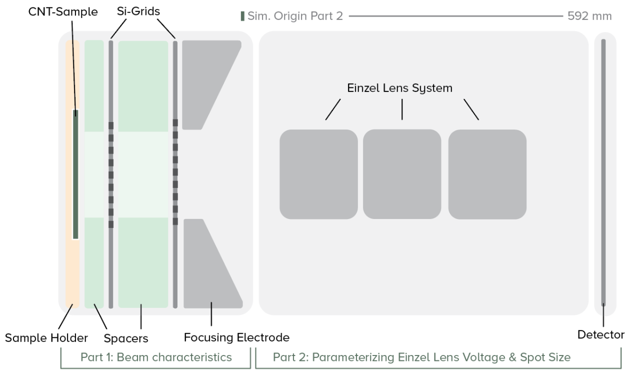

Figure 2: Schematic model for CST simulation with simplified gun components.

Due to the rectangular grids, cylindrical symmetry is disrupted, and therefore 3-dimensional simulations are imperative. All simulations were performed in CST Studio Suite ®(CST) (see Fig. 2) [4].

Firstly, a simplified model of the gun was constructed directly in CST, and therefore retaining parametric control for possible subsequent optimization. The grid consist of $\sim 4.9 \times 10^6$ holes and introduced several constrictions into the simulations. For example, CST is unable import the CAD-model of the grid, as it couldn't recognize it as a solid, preventing the simulation of a full-sized gun.

Furthermore, to maintain accuracy, each 3 µm thick wall necessitates a minimum of 2 mesh cells to ensure precise particle tracking. However, the number of mesh cells is correlated to the simulation time and is inherently constrained by the available computing power.

In considerations of these limitations, the electron gun was simulated at 1%, 2%, and 3% of its actual size. Each simulation was again divided in two parts to further reduce the number of mesh cells. The first part covers the electron source. The resulting beam was exported and reimported into the second part, which encompassed the beam transport through the three Einzel-Lenses. This approach allows to preserve simulation precision. In all simulations, beam position monitors are set perpendicular to the beam, enabling the tracking of beam parameters, such as beam divergence Θ, emittance ϵ, beam radius r and mean beam energy $\overline{E}$.

Beam Characterization

In the first simulation section, the beam starting from the CNT-Sample Holder until the end of the Grounded Electrode was simulated. A field-induced emission model was used and the following parameters were set based on previous studies [2]: the initial kinetic energy $E = 0.1$ eV, two Fowler-Nordheim equation related material specific constants $a = 3.1537 \times 10^{-11}$ and $b = 7.5793 \times 10^6$, and the angle spread $\alpha = 89°$. The potentials were set according to the requirements: the sample holder is fixed to −355 V while second grid is at ground potential. The extracting grid voltage was scaled with the same factor as the gun size (100%: 1 kV → 1%: 10 V, 2%: 20 V, 3%: 30 V) in order have comparable electric fields. Both the grid thickness and the CNT sample thickness retained their real sizes.

Local mesh properties, including a step width in x, y, and z of 1.2 µm at and near the grid, were carefully selected to maintain the previously mentioned precision without excessively extending the simulation time. It's worth noting that the 3% gun simulation had already reached 417×10^6 mesh cells.

Beam Transport and Spot Size

The objective of the second set of simulations was to investigate the beam dynamics of the Einzel-Lenses and their focusing properties. In almost all cases, the focal length of Einzel-Lens systems cannot be solved numerically and only computed analytically, thus making a simulation approach necessary. The three cylindrical lenses were modelled with their original size, and the corresponding beam interfaces obtained for each size were imported. This step serves as a representation of how a scaled CNT sample would behave in the actual test bench setup and was essential to allow comparison of the focusing behaviour.

Beam Transport Firstly, the voltage applied to the to the center lens (V_{center}) was varied, to observe changes in the electron trajectories. Negative values were dismissed, as they would lead to recoil. A range of nine values for parameterization was chosen between 0 V and 3000 V. To archive precision, a finer mesh was employed near the lenses (step size of 0.4 mm) .

Spot Size Based on these results, the next objective was to optimize the spot size at the approximate detector distance, which is located ~ 592 mm downstream after the Grounded Electrode. The maximum beam radius is limited to approximately 22 mm due to the size of the IBP phosphor screen. CSTs internal optimization tool allowed to fine tune V_{center}. A single goal was defined: to minimize the result of the post-processing template "x at 2nd y-Minimum of the Envelope" to a value of 592 mm. Specifically, the algorithm "Trust Region Framework" was employed, suitable for refining solutions in the vicinity of an initial guess within a defined region. The lower and upper bounds were set to 80% and 120% of the initial guess.

In addition, we sought to generally validate the simulation results to ensure that our simulation setup accurately represents the physical system.

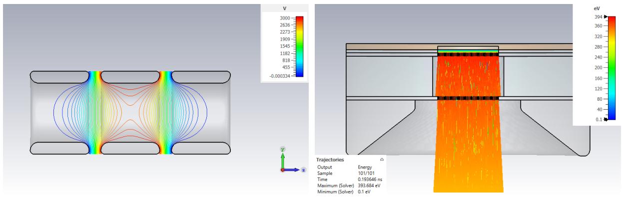

Figure 3: Left: Equipotential lines of fringe fields in lens system. Right: Electron trajectories near the CNT-Sample.

RESULTS AND DISCUSSION

Beam Characteristics

Table 1 summarizes the obtained beam parameters directly after the Grounded Electrode. The trajectories of the beam passing the two grids in the first simulation part can be seen in Fig. 3 (right). We observed that the beam energy is simulation-size-independent, while the beam radius increased with the size, as expected. The emittance is directly proportional to the size as well. Controversially, the beam divergence for the 1 % simulation is significantly larger than anticipated. This could be due to CSTs internal calculation of the beam properties and requires further investigation into the software specific formulas.

Table 1: Beam Parameters After Grounded Electrode

Simulation Scale	**1%**	**2%**	**3%**
Θ [mrad]	0.4414	0.2696	0.2095
ϵ_x [mm · rad]	0.0031	0.0039	0.0043
r [mm]	0.2095	0.3653	0.5394
$\overline{E}$ [eV]	339.050	338.036	338.913

Beam Transport and Spot Size

The simulations revealed that the mean electron beam energy remains consistent both before and after its passage through the lens system, aligning with theoretical expectations. This is true for all three simulation sizes.

In Fig. 4 (Bottom), the correlation of the focusing length and the applied voltage is clearly visible. We observed that below a voltage of 1 kV, there was no significant focusing effect, primarily due to the insufficient electric field strength. However, beyond this threshold, increasing voltage results in a reduced focal length and a higher lens refraction power, as expected. The steep angles after the focus point are caused by the high initial beam divergence and result in spot sizes significantly larger then expected.

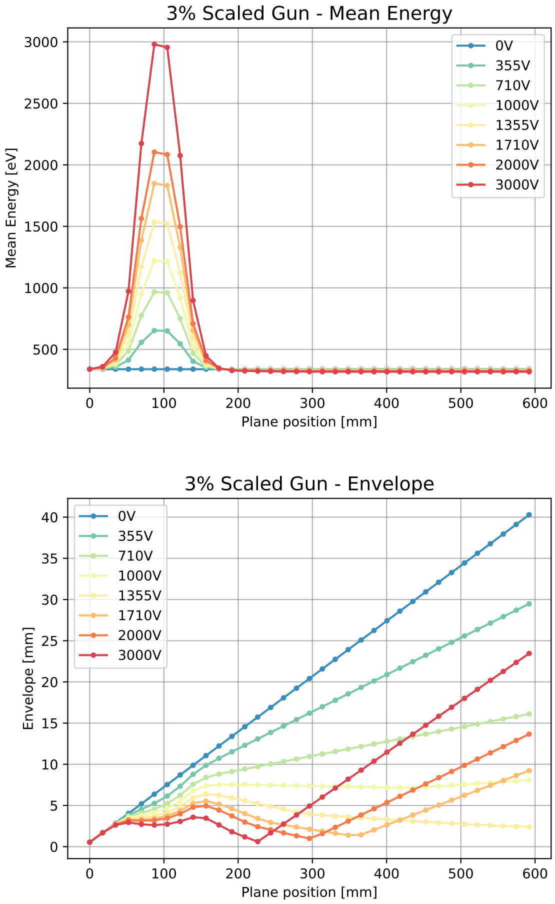

Figure 4: Selected simulation results for the beam passing the Einzel-Lenses for different center lens voltages V_{center}. Top: Mean Energy; Bottom: Envelope.

It was established that the optimal voltage setting for minimizing the beam radius at the detector distance is ~ 1355 V, for all three simulations.

CONCLUSION

The electron beam was modelled based on a field emission model and the focusing properties of a system of Einzel-Lenses were shown. The comparatively high beam divergence after passing the two grids warrants further investigation into the simulation approach. Our future research will focus on refining our simulation modelling techniques and eventually validate the data with experimental results of the CCBT2. We intent to manufacture new CNT-Samples in different sizes and measure the beam characteristics to improve the gun prototype and identify any potential challenges.

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