[1] CERN, Geneva, Switzerland
[2] Paul-Scherrer-Institut, Zürich, Switzerland

Development of a Field Emission Electron Gun for Low Energy Electron Cooling

E.-S. Welker[1], J. Cenede[1], B. Galante[2], G.A. Tranquille[1]

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. Presently, the **electron gun relies on thermionic emission**, where a tungsten-doped barium oxide 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**.

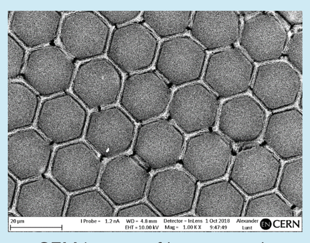
Field Emission (FE) relies solely on high electric fields to both generate and control the electron beam. **Carbon Nanotubes (CNTs)** are considered among the most promising materials for this purpose, and their feasibility as field emitters has been studied. Still, there remains a crucial **research gap in determining their optimal characteristics** (maximal current density, lifetime, etc.) as part of an electron gun.

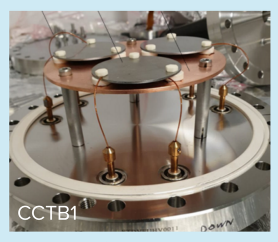
Bridging this gap is fundamental for **advancing the development of a more efficient electron gun system in ELENA**, especially in light of the requirements of future particle accelerators.

Previous findings

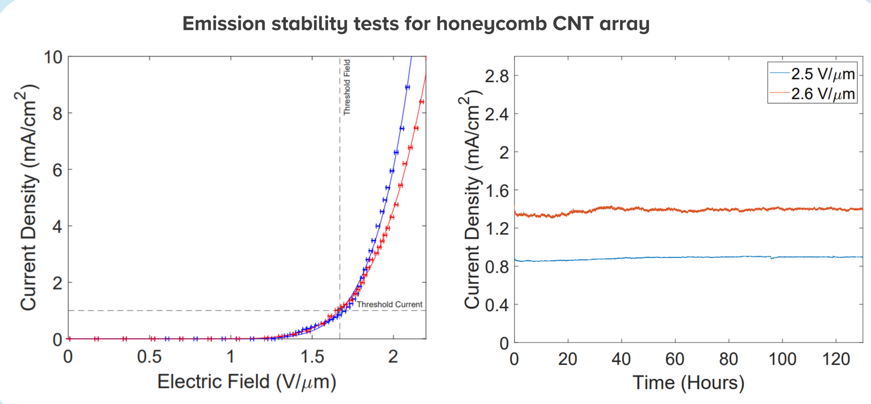
- The basic test set-up includes the sample, that is placed on the cathode, encapsulated in vacuum. An electric field is applied on the anode and the current and voltage are measured indirectly.
- **Lifetime and Stability studies** showed remarkable lifetime exceeding 1500 hours.
- Measurements of several sample types found that a **honeycomb-like CNT array** is the most optimal.
- Proposed a **CNT-based-Gun prototype.**

→ *Results establish CNT cathodes as viable candidates for use in the electron cooler of ELENA*

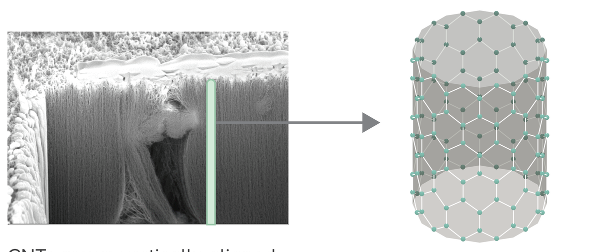

SEM image of honeycomb CNT array



Diode configuration: cathode (CNT sample), spacer & anode (Molybdenum plate)



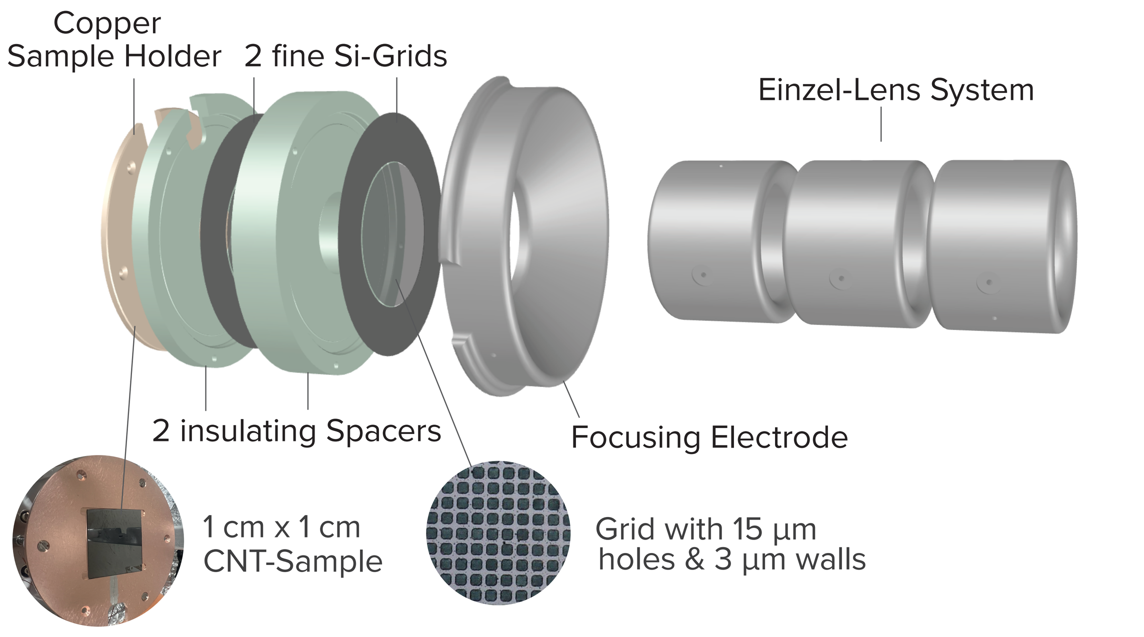
Carbon Nanotubes as Field Emitter


CNTs grown vertically aligned in predefined places on a patterned substrate
Single CNT ≈ "rolled-up Graphene Sheet" d ≈ 5-15nm, h ≈ 20-50μm

- Field Emission: Applying a high electric field to a metal, allowing electrons to tunnel through and escape from the material.
- Exceptionally low turn-on fields, high coherent energy spectra and high currents

Electron Gun Assembly

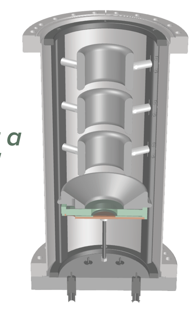
The prototype features two highly conductive grids, the first functioning as an extracting anode, the second for decelerating the beam. Given the considerable drift distance, an **Einzel-Lens System** (comprised of three cylindrical, symmetric electrodes) is used to transport and focus the beam without changing the beam kinetic energy. Typically, the outer electrodes are grounded, while adjusting the center lens voltage allows for changes in focusing.



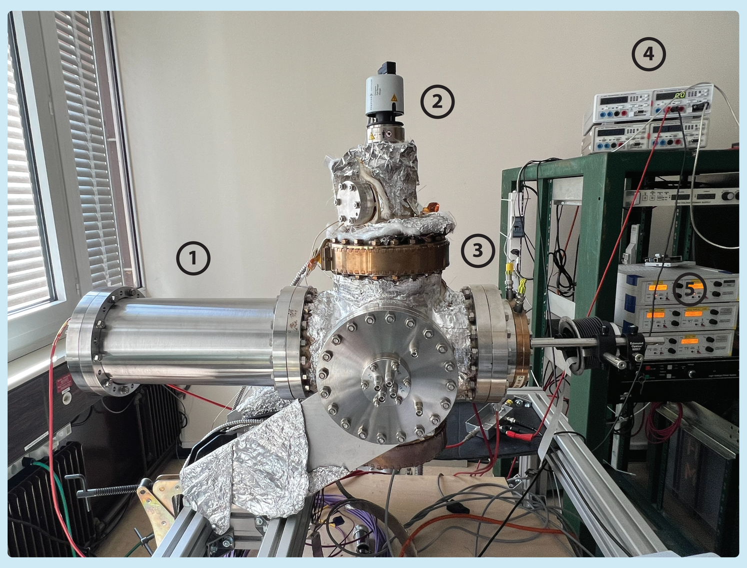
Three potentials are responsible for generating the gradients to achieve the energy required for ELENA operation (355 eV):

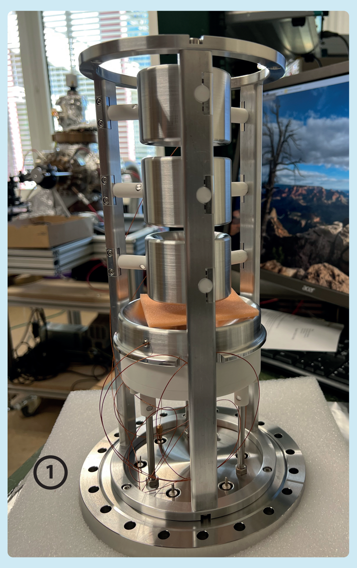
1. Sample Holder: -355 V
2. First Grid: 1-6 kV
3. Center Lens: variable

Scan me for a 3D Model!



Test Bench Set-Up CCBT2

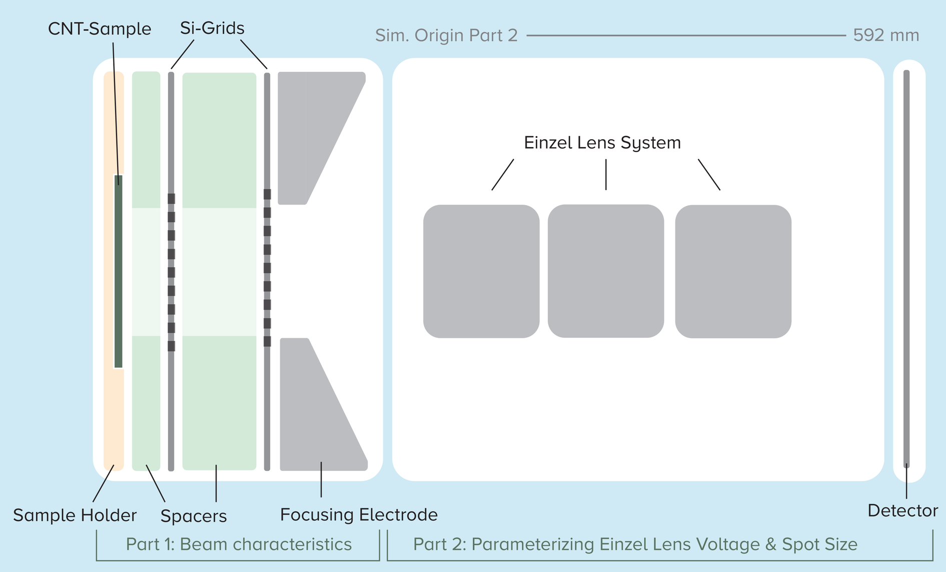




1. Vacuum tank with CNT-Gun Assembly and Einzel-Lenses
2. Vacuum Dual Gauge
3. PHOTONICS Ion Beam Profiler for Imaging
4. Multimeter to read current of samples
5. Power Supply to generate E-Fields

Simulation Set-Up

Simplified 3D-model simulated in **CST Studio Suite:**



Rectangular grid with 4.9 10^6 holes introduces **limitations,** as a **very high number of mesh cells** is needed to maintain correct trajectories.

Simulation **is split into two parts** and **scaled to 1%, 2%, and 3%** of actual size to manage computational complexity.

Part 1: Beam Characteristics until exit of Focusing Electrode

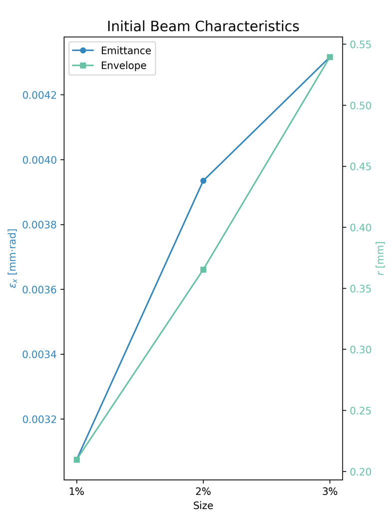
Part 2: Beam Transport, parametric sweep of Center Lens Voltage + optimizing Spot Size at detector distance

Key parameters (beam divergence, mean energy etc.) are **monitored and analyzed** for each simulation.

- **Predict beam at full-scale operation** and generally ensure internal consistency of simulations.
- Adapt CCBT2 arrangement, if necessary for optimal capture of beam.

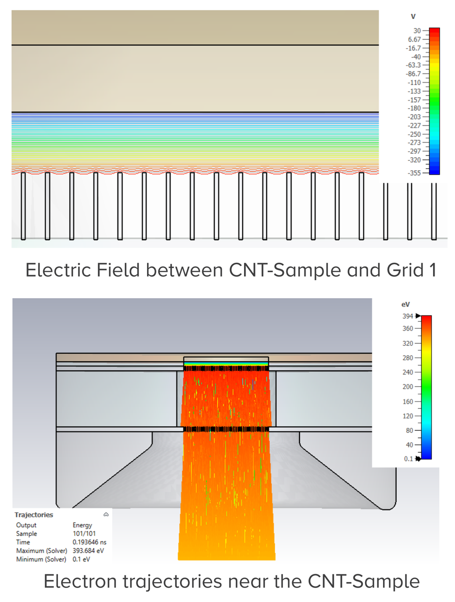
Simulation Results

Beam Charateristics



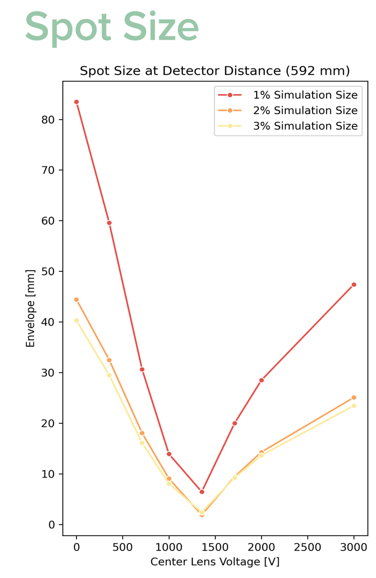
Main observations:

1. Beam energy remains simulation-size independent.
2. Beam radius increases linearly with size, as expected.
3. Emittance also increases with size.

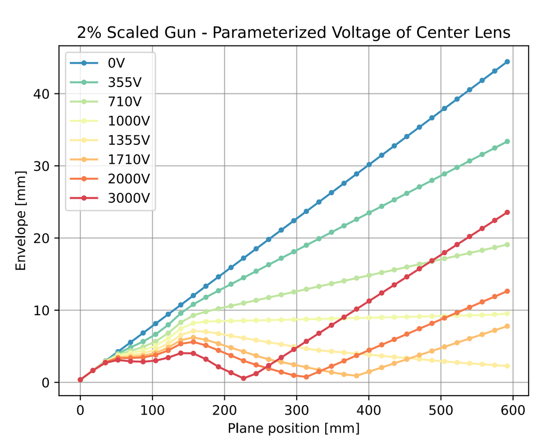

Electric Field between CNT-Sample and Grid 1

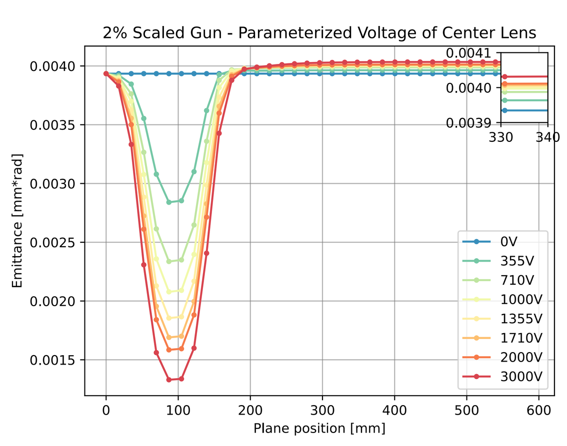
Electron trajectories near the CNT-Sample

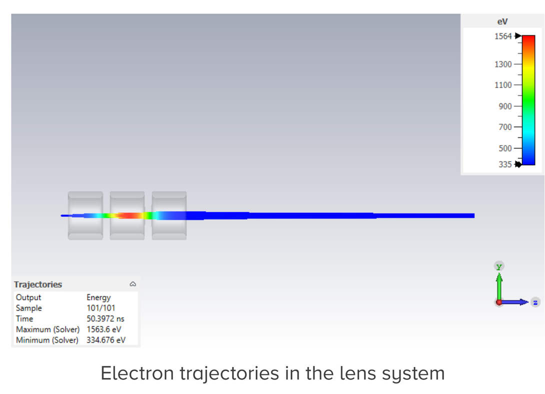
Spot Size

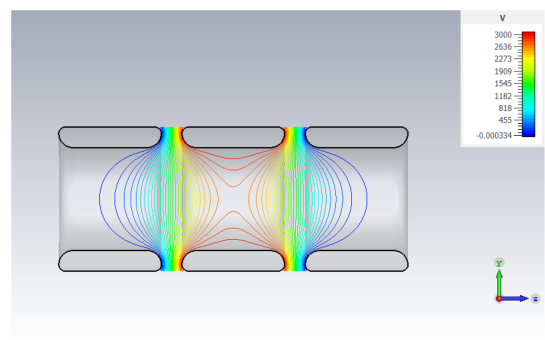


Beam Transport through Einzel-Lenses






Electron trajectories in the lens system


Fringe fields in a cross section close to the electrodes.

Main observations:

1. Mean electron **beam energy remains stable** before and after lens passage, aligning with theoretical expectations.
2. Below a 1000V threshold, no significant focusing effect is observed due to insufficient electric field strength, while beyond this threshold, **increasing voltage results in a reduced focal length.**
3. Optimal **voltage setting for minimized beam radius** at the detector distance: 1355V. For the 1% simulation, the beam envelope at the detector is 2.38 mm, thus scaling the beam with a factor of 4.43.

Future Outlook

Our future research will focus on refining our simulation modeling 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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