Optimization of the electron emission from carbon nanotubes for electron cooling in ELENA

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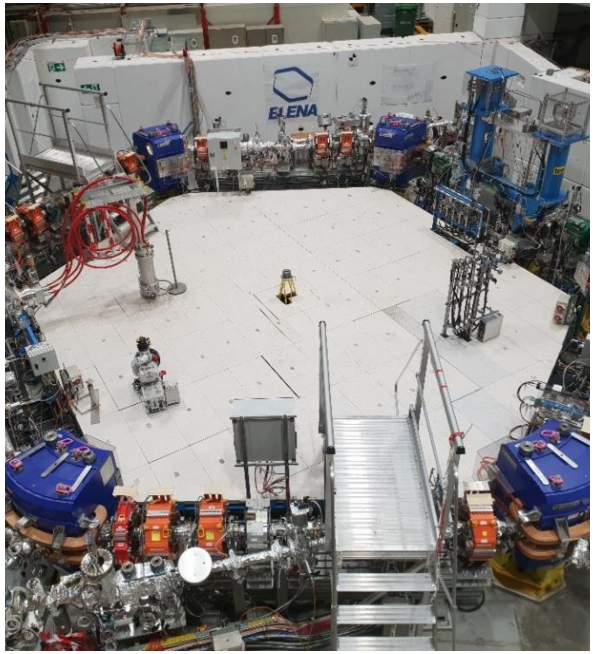
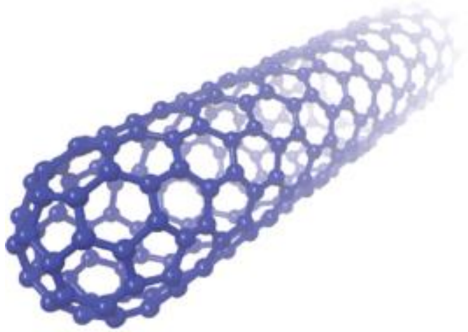




Introduction

Electron cooling is a vital process to guarantee beam quality in low energy antimatter facilities. Low energy: 100 keV.
It permits to reduce the emittance blow-up of the antiproton beam → deliver focused and bright beam to the experiments.

Electron gun must emit a mono-energetic and relatively intense electron beam.

Optimization: cold cathode with carbon nanotubes as electron field emitters.

In order to use carbon nanotubes, there is the need to assess whether they are compatible for what concerns **stability and lifetime.**
Furthermore, a **grid** is deemed essential for extraction of the electrons and this must be thoroughly investigated since the passage of the beam through the **grid can significantly alter the beam properties**.

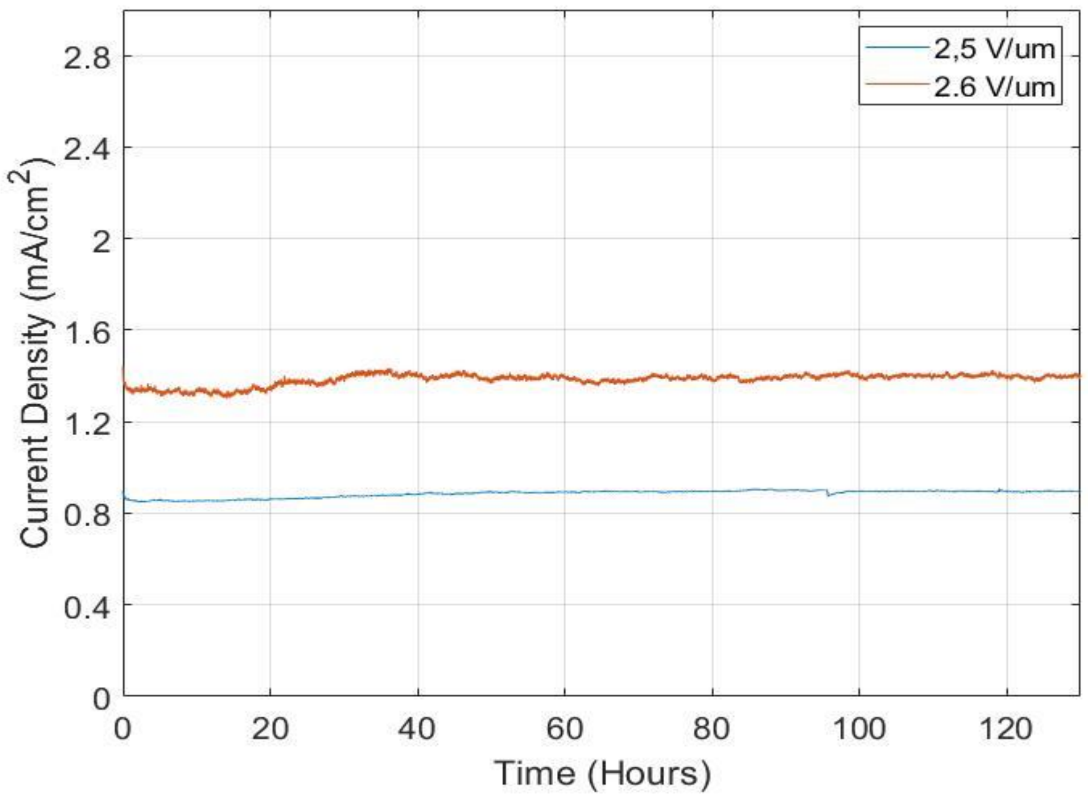
Carbon nanotubes - Stability and Lifetime

Carbon nanotube (CNT) samples tested with optimal environment conditions have shown optimal stability and long lifetime.

Optimal conditions:
- Base pressure in the order of 10^{-8} mbar or less
- Cleaning of the emission region and sample surface (via bake-out)
- Efficient conditioning process

In the diagram beside a CNT sample has been proven to emit for more than 250 hours without clear sign of degradation.

Emission for more than 1500 hours has been proved for CNTs in our previous work [1].



[1] - Carbon nanotubes as cold electron field emitters for electron cooling in the CERN Extra Low ENergy Antiproton (ELENA) ring. -- B. Galante, G. Tranquille, C. P. Welsch, O. Apsimon, J. R. Lopez - doi:10.18429/JACoW-IPAC2021-WEPAB152

Extraction Grid

For field emitting large area cathodes, the grid becomes necessary in order to have homogenous emission along the cathode surface.

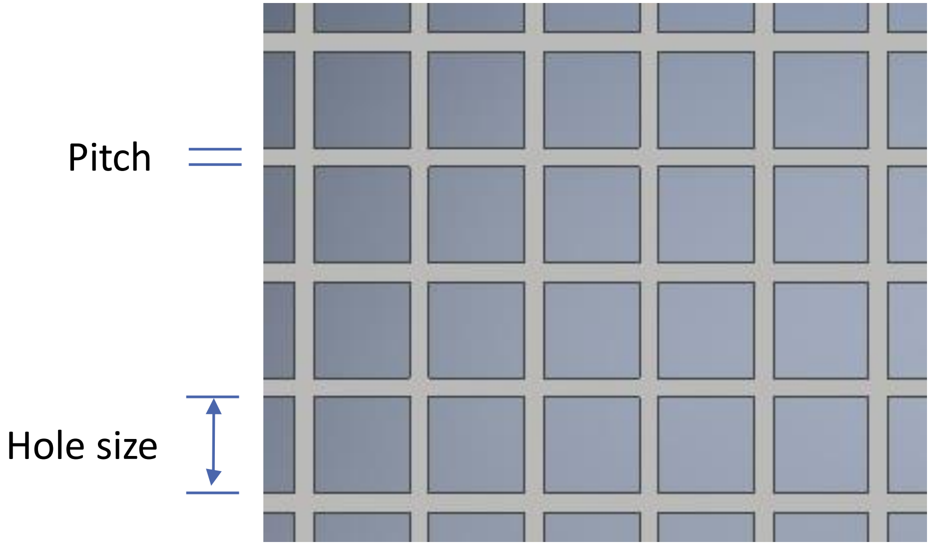
There are many parameters that can affect the grid effect on the beam properties.

- Distance from the cathode → affects voltage applied in order to get the desired electric field.
- Hole size and pitch → The relation between the two affects the transmittance of the grid. The hole size drastically affects the beam properties.
- Hole shape → mainly for transmittance optimization.

The feasibility of making the grid is clearly a factor that also needs to considered.

Grid types (squared holes):

- Hole size: 25 μm – Pitch: 5 μm
- Hole size: 50 μm – Pitch: 10 μm
- Hole size: 100 μm – Pitch: 20 μm
- Hole size: 150 μm – Pitch: 30 μm
- Hole size: 200 μm – Pitch: 40 μm
- Hole size: 250 μm – Pitch: 50 μm



Distance from the cathode

The CST simulation design allows for perfectly straight field lines in all regions. **The only source of field misalignments is thus the grid.**

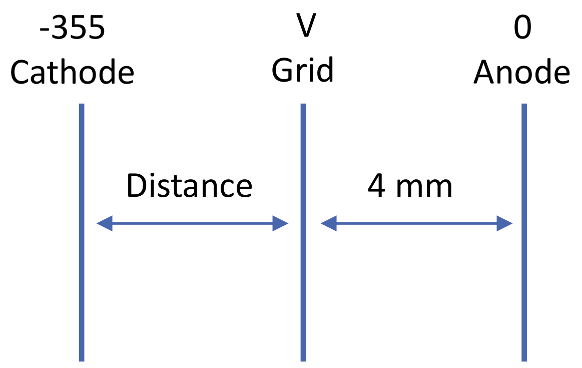
The simulation is applied to all grid types mentioned while keeping a constant electric field of 2 V/µm. The electron source is defined to be field-induced. The parameters “a” and “b” of the Fowler-Nordheim formula are taken from experimental studies of CNTs.

Fowler-Nordheim formula: $J = aE^2 \exp\left(-\frac{b}{E}\right)$

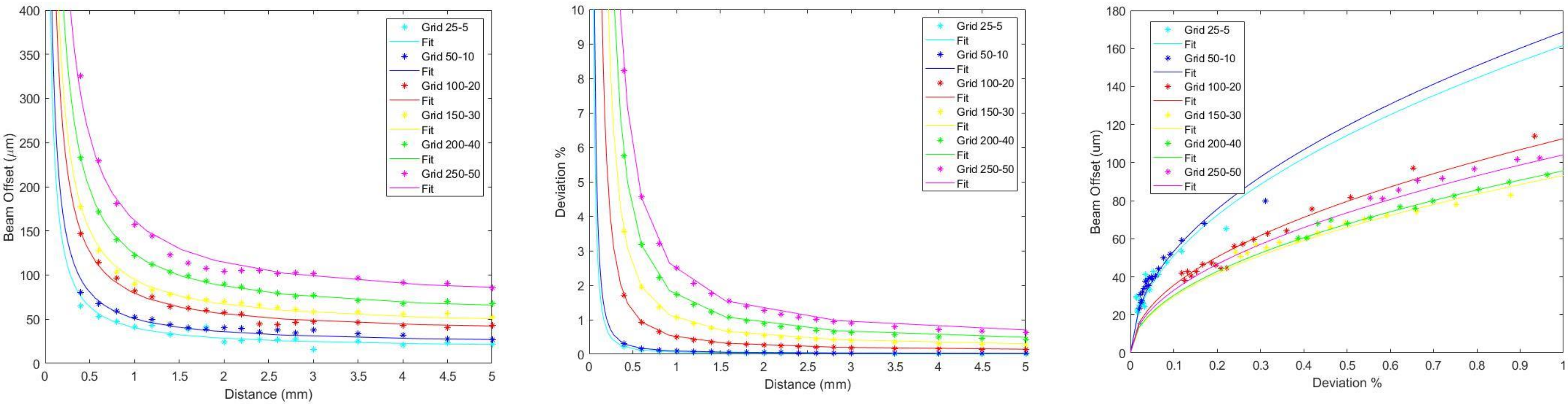
Parametric simulation → changing the cathode-grid distance at every iteration, from 0.4 mm to 5 mm.
Parametric simulation → changing initial beam energy, from 0 eV to 0.1 eV.

Analysing the simulations, we got several info:

- Deviation percent of the voltage V on the grid (maximum deviation in the middle of the hole)
- Cathode - grid distance
- Beam offset calculated with the Envelope option
- Emitted current
- Current value after passing through the grid



Distance from the cathode



Initial beam energy = 0.1 eV. Set within the simulation.
We chose this value in order to study the grid effect with a condition that would be critical for our goal. This is also the beam transverse energy of the beam emitted by the thermionic cathode used in the ELENA e-cooler.

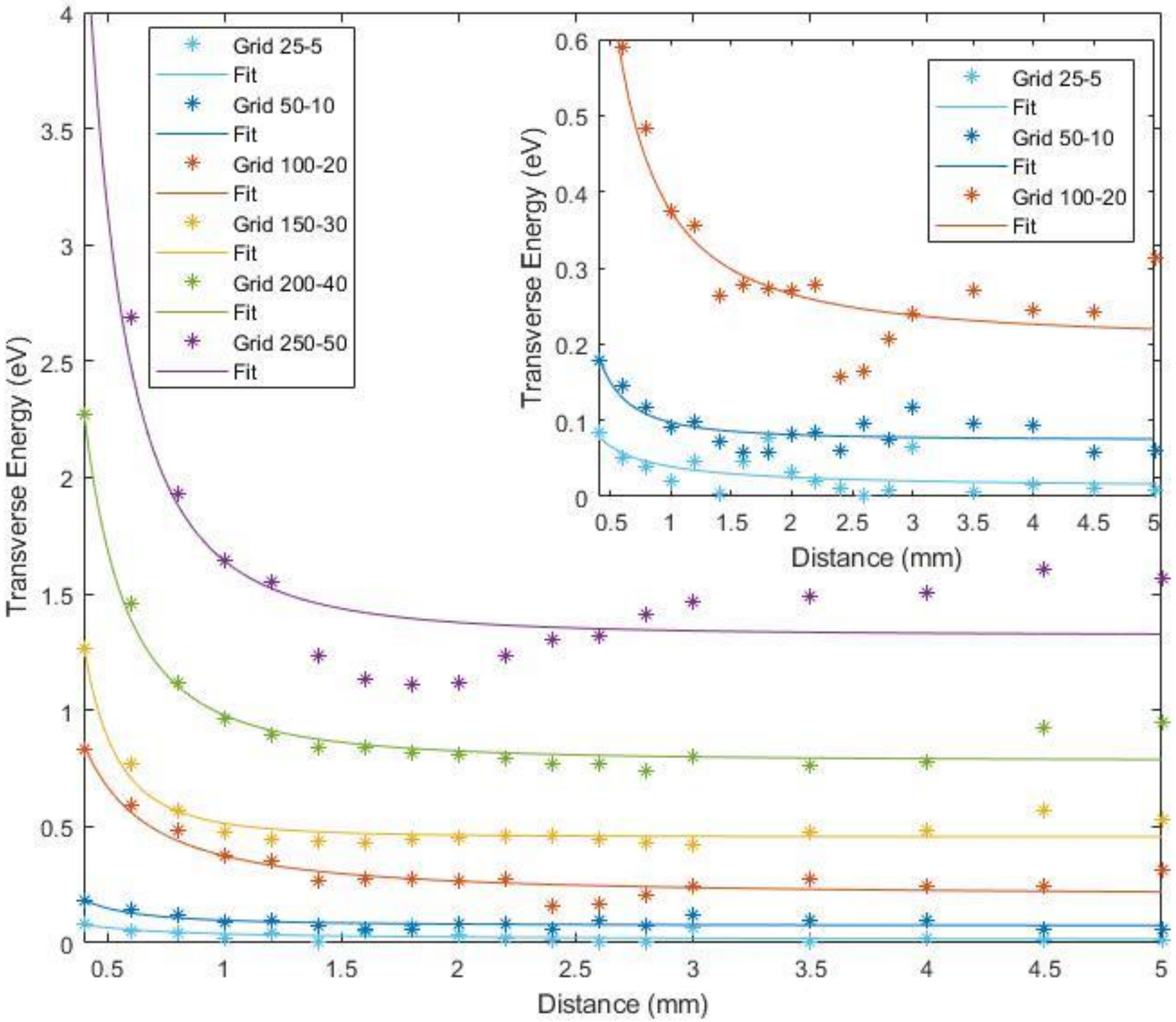
It is clear how the beam offset as well as the overall potential deviation along the grid are strictly dependent on the distance between cathode and grid. However, long distances also imply an increase of the longitudinal beam energy which would require to be then further reduced in a second stage
→ It is vital to find a balance and define the best distance depending on the final goal.

Transverse Energy

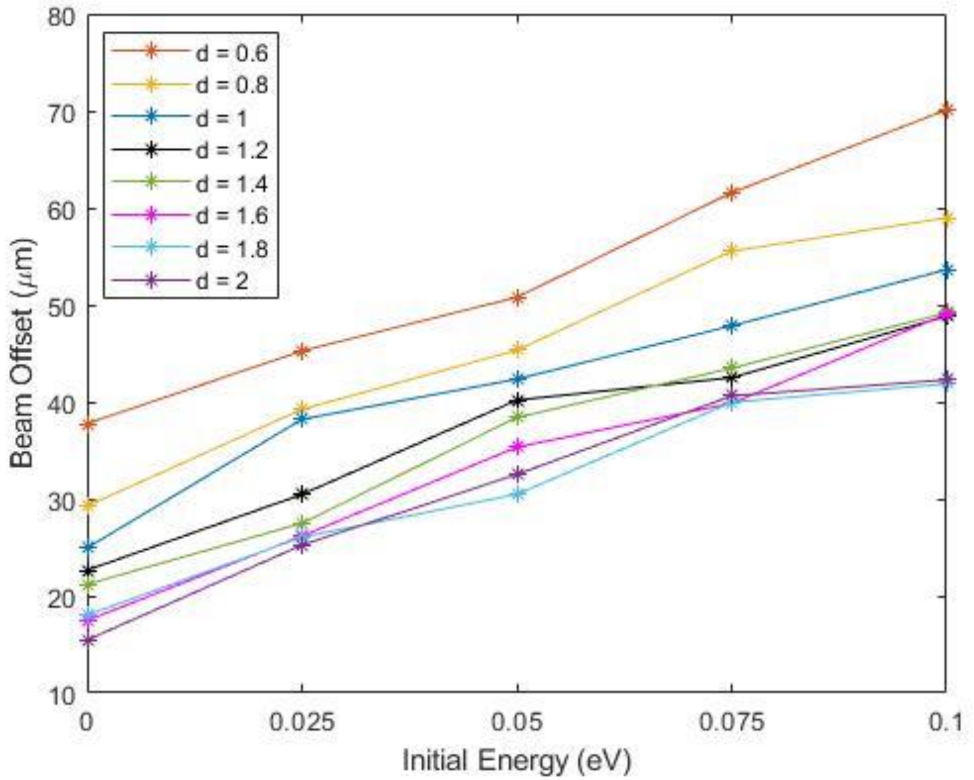
This is the additional transverse energy only due to the grid.

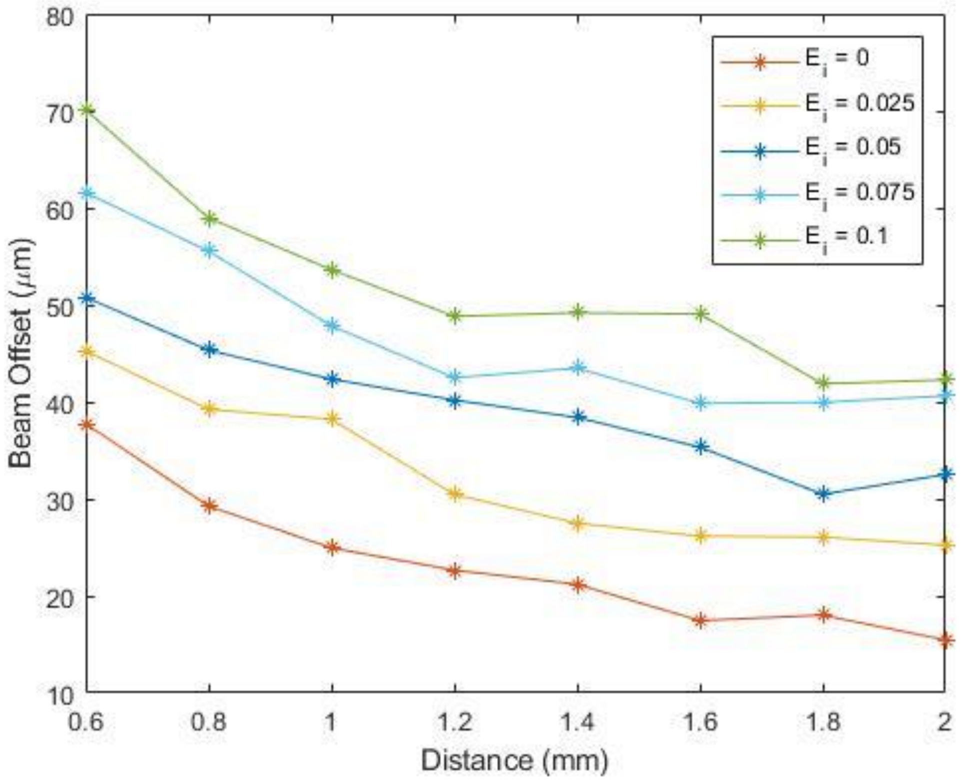
The initial 0.1 transverse energy of the beam has been subtracted in order to solely highlight the grid contribution.

The inset represents a magnification between 0 and 0.6 eV in order to better resolve the behavior of the grids 100-20, 50-10 and 25-5 at low energy.



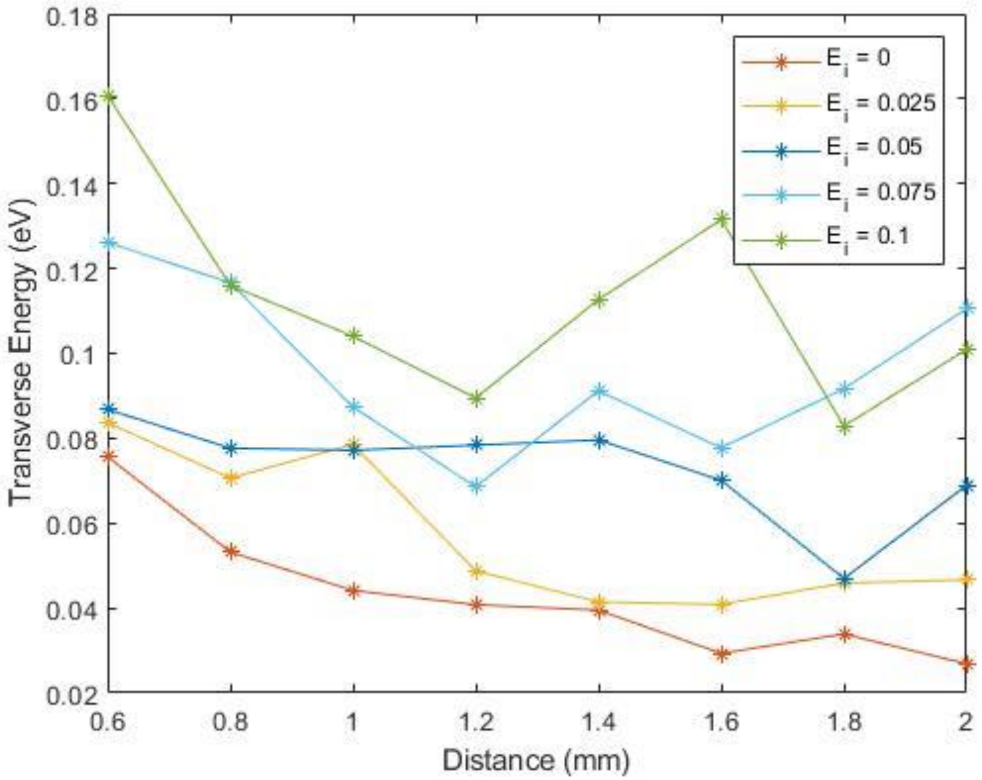
Initial Beam Energy Variations

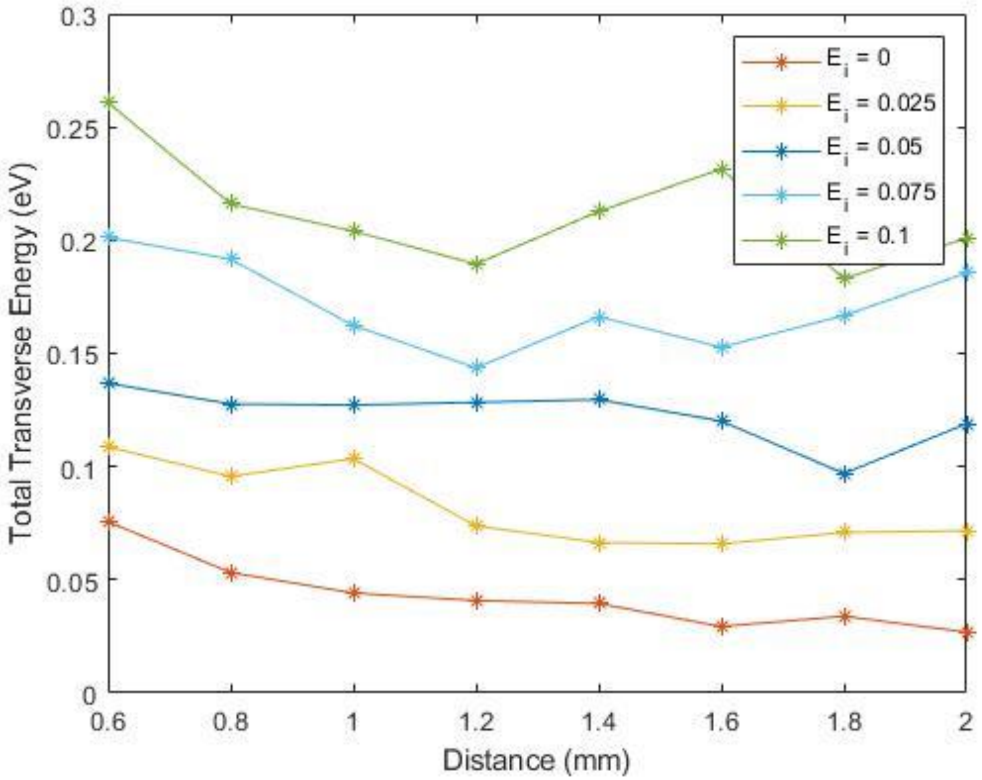




The beam offset due to the grid increases if the initial beam energy is higher.
As already observed earlier, it also increases if the distance between cathode and grid reduces.

Transverse Energy





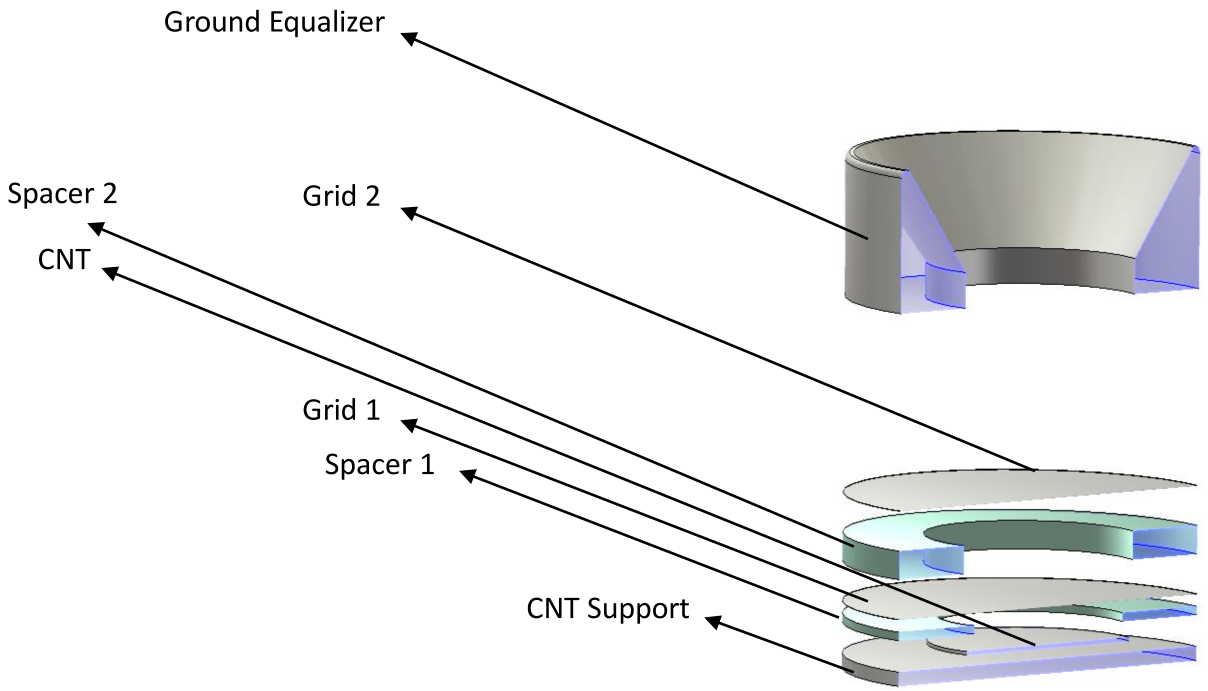
The same behavior translates to the transverse energy.
In order to keep the total transverse energy below 0.1 eV with a 50-10 grid there is the need for an electron source with no more than 0.025 eV initial energy and with a cathode-grid distance of at least 1 – 1.2 mm.

Final Gun Layout

- Simulation of gun components in order to minimize transverse kicks due to initial beam energy and alteration due to passage through grids.

- Final layout includes 2 grids:
  - Extracting Grid (Grid 1)
  - Decelerating Grid (Grid 2)

- Optimization of:
  - Grid Distance
  - Spacers thicknesses
  - Ground Equalizer Shape
  - Addition of Einzel Lens



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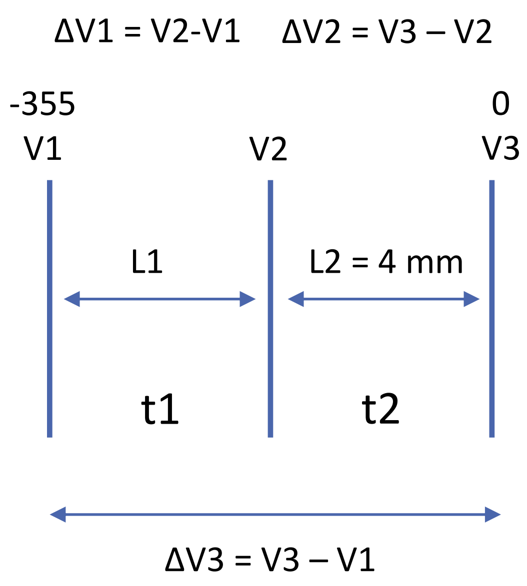
Thank you

Transverse Energy Calculation

$$E = \frac{1}{2}mv^2 \qquad r = vt + \frac{1}{2}at^2 \qquad F = ma;\; a = \frac{F}{m} = \frac{eE}{m} = \frac{e\,\Delta V}{L\,m}$$



$$In\ the\ transverse\ plane\ E = 0\ hence\ a = 0. \;\Rightarrow\; r = vt = \sqrt{\frac{2E_{tr}}{m}}\,t_2$$

$$v = v_0 + at = \sqrt{\frac{2\Delta V_1}{m}} + \frac{e\Delta V_2}{L_2 m}t_2; \quad \sqrt{\frac{2\Delta V_3}{m}} = \sqrt{\frac{2\Delta V_1}{m}} + \frac{e\Delta V_2}{L_2 m}t_2$$

$$\Rightarrow t_2 = \left(\sqrt{\frac{2(V_2+355)}{m}} - \sqrt{\frac{710}{m}}\right)\frac{L_2 m}{V_2}$$

$$E_{tr} = \frac{V_2^2 r^2}{2L_2^2\left(\sqrt{2(V_2+355)} - 26.646\right)^2}$$