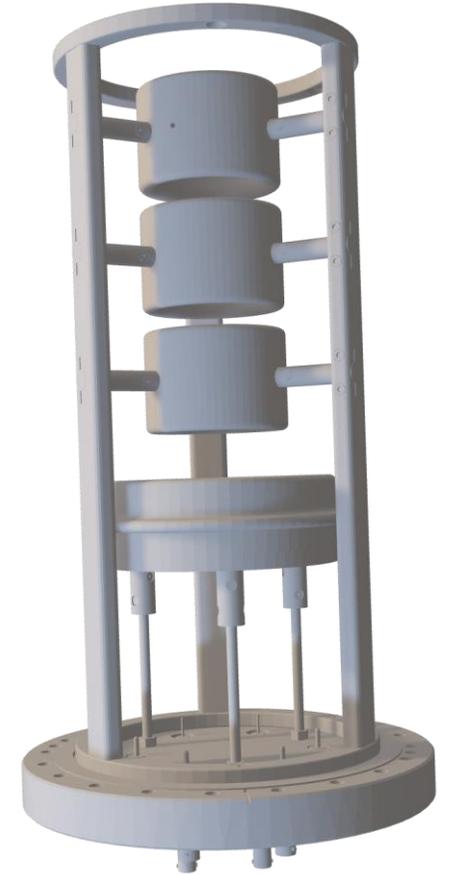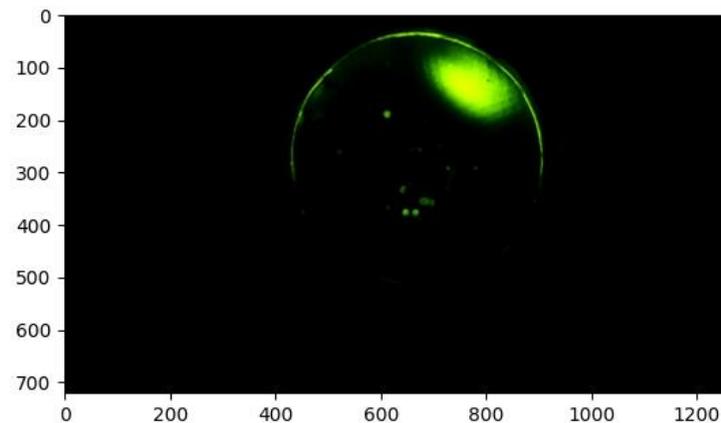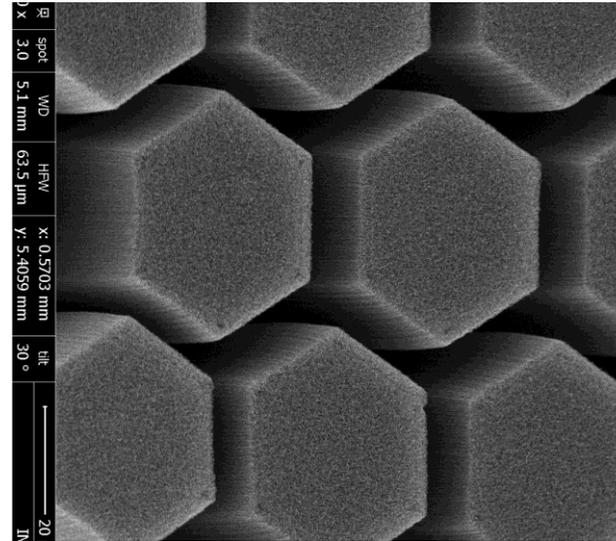# Progress Towards a Field Emission Electron Gun for ELENA

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MOTIVATION

- Generation of a "cold" electron beam for cooling at ELENA energies

- Simplicity for operation
  - no filament heating
  - faster electron emission
  - Lower energy spread

Item	Value	Dimension
Momentum	35 / 13.7	MeV/c
Electron Beam Energy	355 / 55	eV
Electron Current	5 / 1	mA
B Gun	1000	G
B Drift	100	G
Toroid Bending Radius	0.25	m
Cathode Radius	8	mm
Electron beam Radius	(25)	mm
Cooling (drift) Length	1.0	m
Total Cooler Length	1.93	m

- Could also serve as a source for an electron beam scanner

Presentation Outline

- Fundamentals of Field Emission (FE) and Carbon Nanotube (CNT) Characterisation

- FECNT Gun Design and Testbench
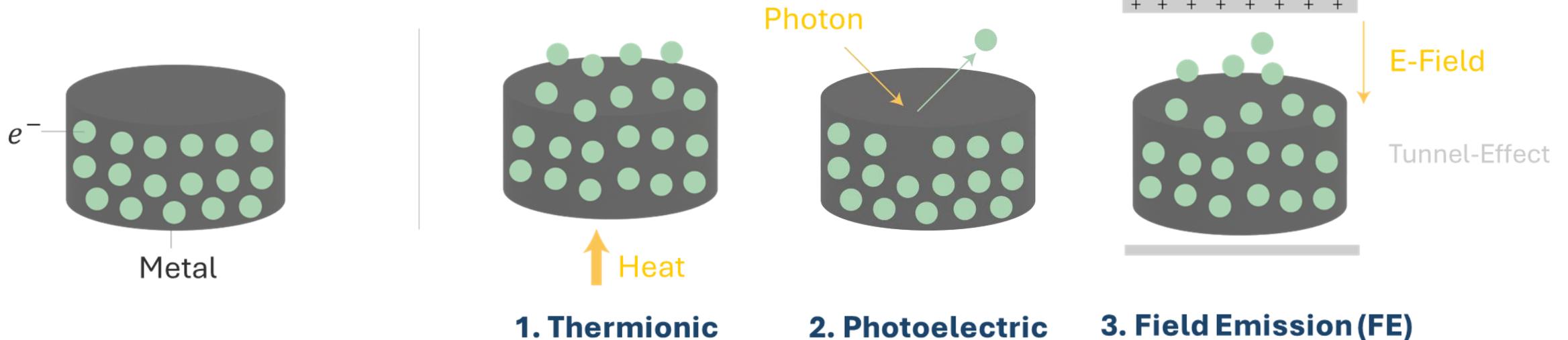
- Cold Cathode Testbench Measurements

Fundamentals of Field Emission

Field Emission

Efficiency of Cooling relies on **transverse energy spread of emitted** e^-!

➔ <u>Goal</u>: Lowest cathode Temperature possible!

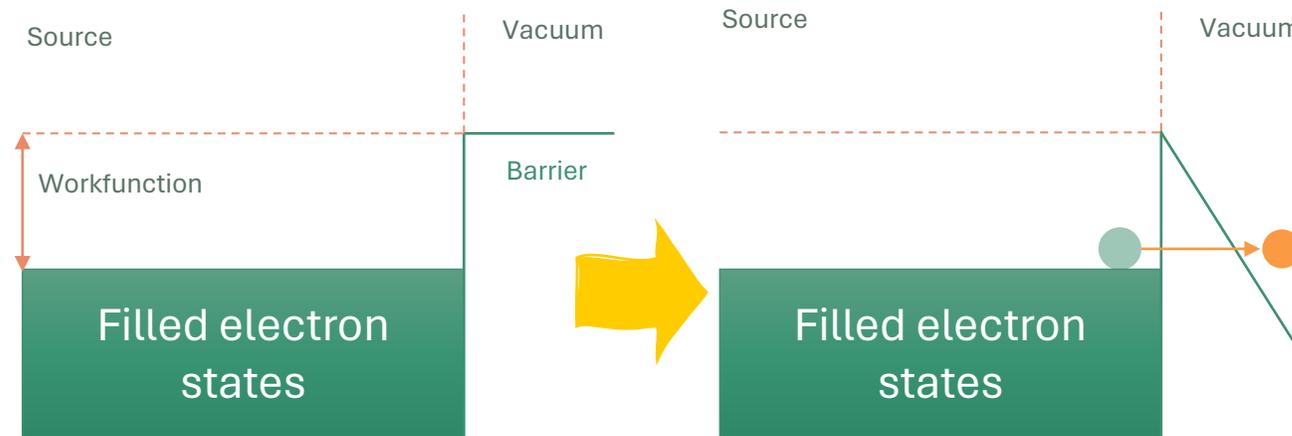**3 ways of extracting electrons** from the surface of a metal:

Anode

+ + + + + + + +

Photon

E-Field

Tunnel-Effect

e^-

Metal

Heat

1. Thermionic

2. Photoelectric

3. Field Emission (FE)

Currently used
BUT: T=1200 °C
➔ high transverse Energy E_T

+ Room-Temp. "Cold-Cathodes"
+ **reduced E_T !**
+ promising alternative

- Thermionic Emission, Photoemission: Generation of electrons once the electrons have energy enough to overtake the potential barrier.

- Field Emission: Tunnelling of electrons through the barrier applying a very large electric field (~ 10^7 *V/cm*). emitted current depends directly on the local electric field at the emitting surface, and on its work function φ (Constants *A* & *B* depend on material)

$$J = AE^2 \exp(-\frac{B}{E})$$

Source   Vacuum   Source   Vacuum

Workfunction   Barrier

Filled electron states   Filled electron states

Effect of applied electric field on potential barrier.

Carbon Nanotubes (CNT)

- For flat surfaces the required electric field is too strong.

- Possible solution: Field Enhancement with tips

PROS:
- High aspect ratio -> High enhancement
- Emit at low field, in order of some V/µm
- Scalable production techniques
- Chemical inertness and stable structure

CONS:
- Small emitted current per tip
- Screening effects
- Impurities and defects

Multi-Wall carbon NanoTube (MWNT)

$$I = aV^2 e^{(-b/v)}$$

$$a = 1.5x10^{-6} n \alpha b^2 \left(\frac{e^{10.4/f^{1/2}}}{f} \right) amps/volt^2$$

$$b = 6.44x10^{-7} \left(\frac{f^{3/2}}{b} \right) volts$$

$$F = bV \, volts/cm$$

I = emission current (amps)

n = the number of tips

α = emitting area per tip (cm^2)

β = field-forming factor (E= βV)

V = applied voltage (volts)

ϕ = work function (eV)

Single-Wall NanoTube (SWNT)

Single CNT
• Strongest E-field
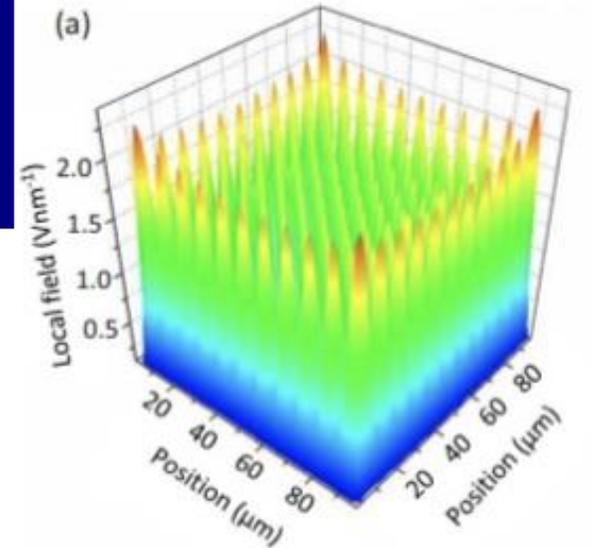• Complete electrostatic field penetration

3 CNTs
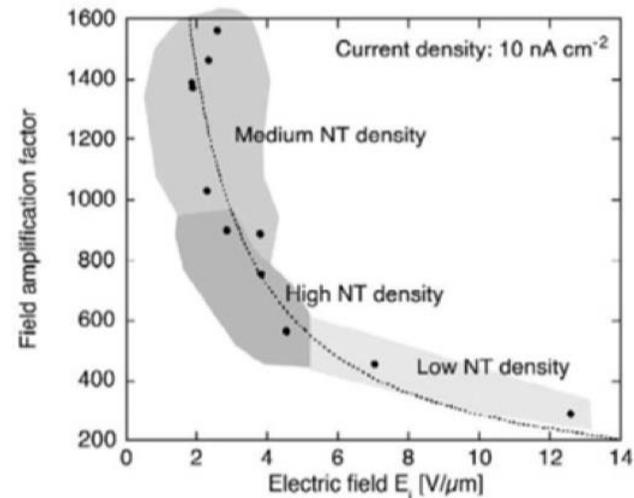• Significantly reduced E-field penetration
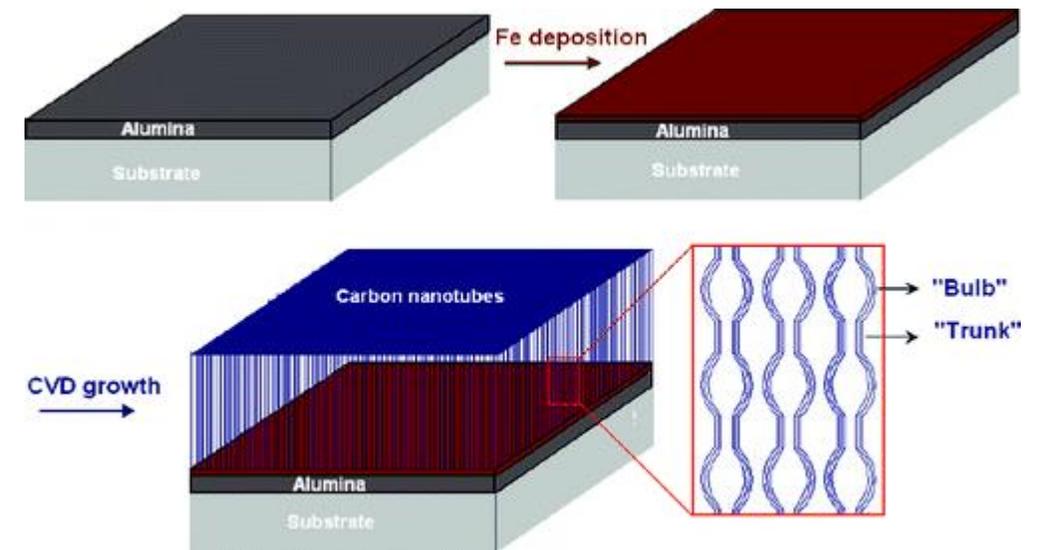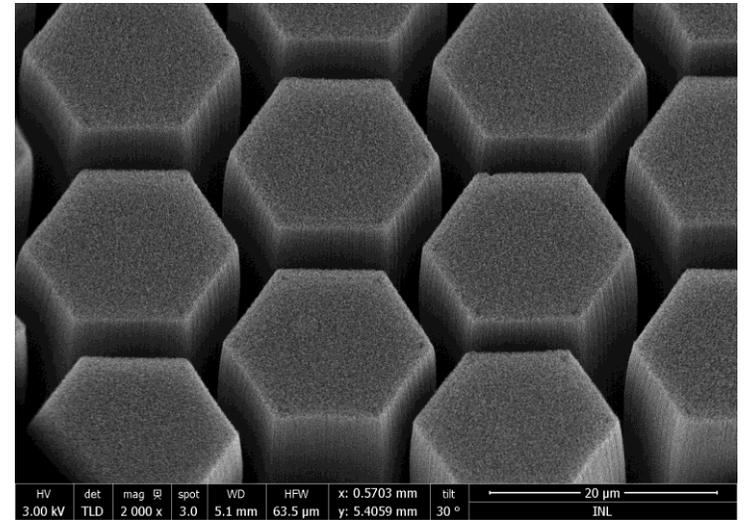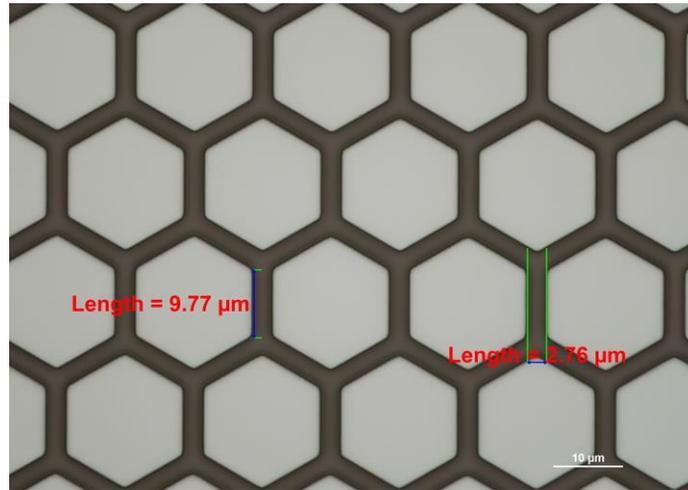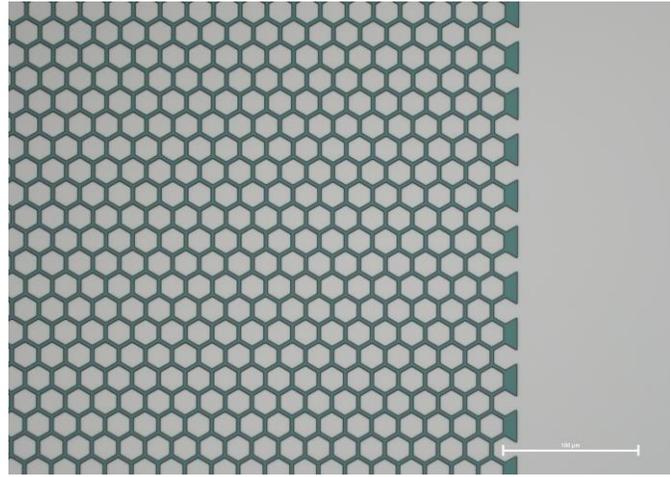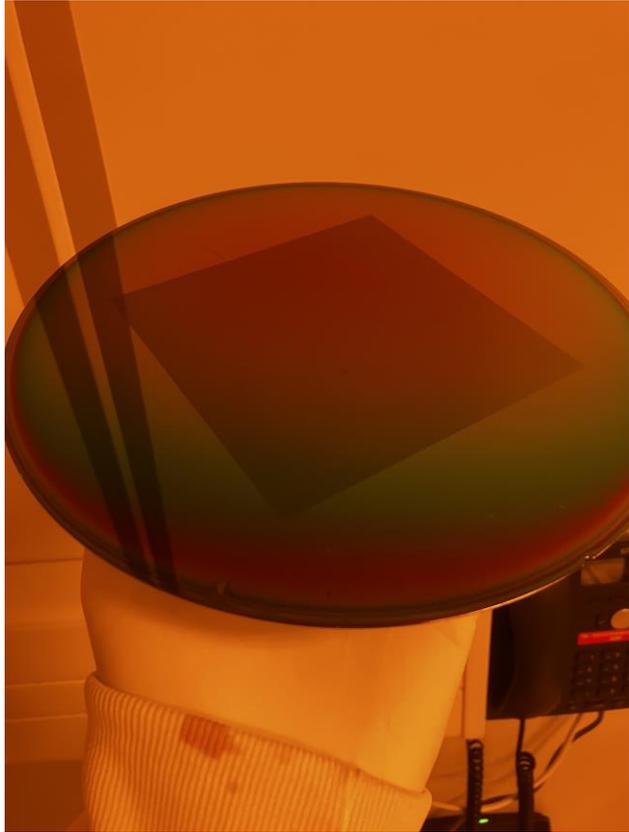
CNT array
• Screening effects are significant

➔ when the nanotubes are densely packed, the field lines cannot fully penetrate, therefore limiting the field enhancement.
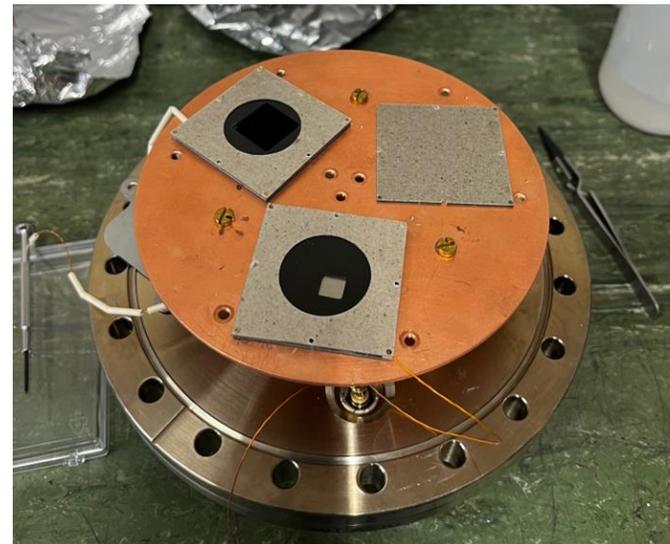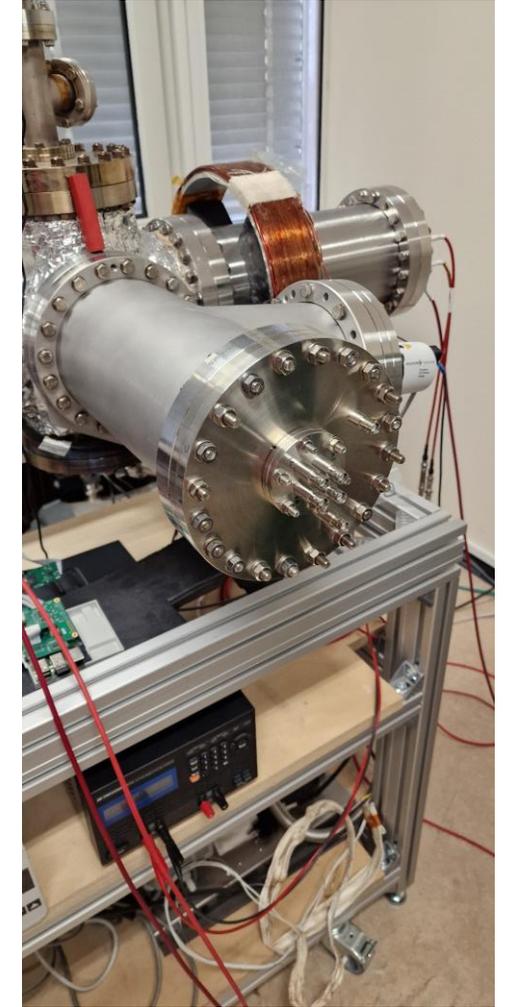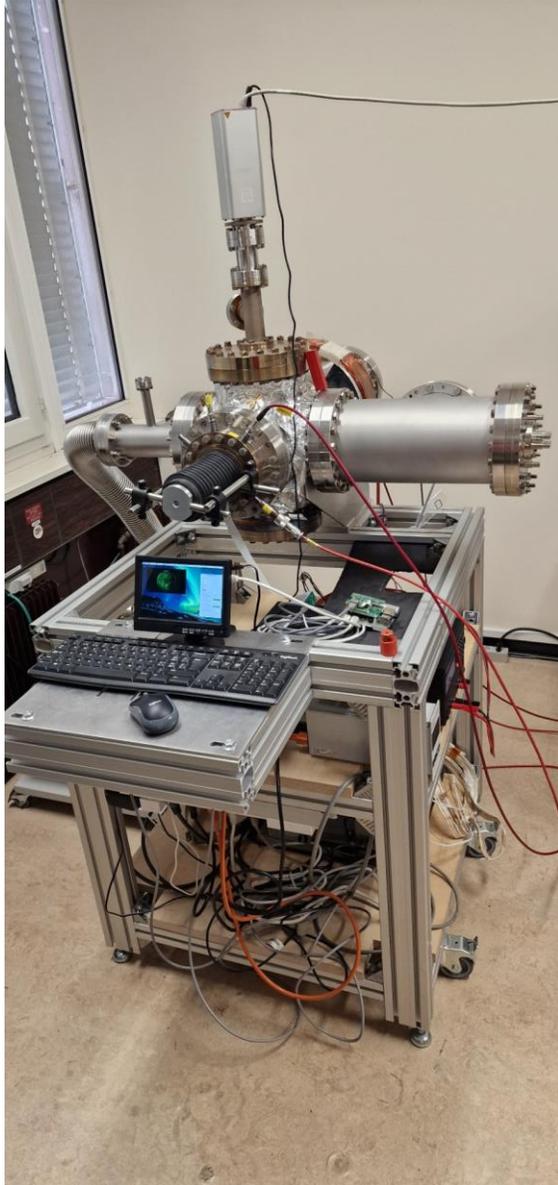
CNT synthesis by chemical vapor deposition (CVD)

- Substrate Si wafer

- Deposition of catalyst-support film (~10 nm of aluminium oxide (Al_2O_3))

- Deposition of active metal catalyst film (0.5–3 nm of Fe) ➜ catalyst layer acts as nucleation sites for CNT growth

- **CNT synthesis** by chemical vapor deposition (CVD)
  - The substrate with the catalyst is placed inside a reaction chamber with controlled environmental conditions.
  - The chamber is evacuated to remove any impurities and then filled with a precursor hydrocarbon gas (e.g., methane, ethylene, or acetylene) and a carrier gas (e.g., hydrogen).
  - The reaction chamber is heated => the carbon precursor gas decomposes into atomic carbon
  - **Carbon Nanotube Growth:** atomic carbons diffuse towards the catalyst particles on the substrate surface. => CNTs grow vertically aligned on the substrate due to the catalytic action of the metal particles.

Length = 9.77 μm

Length = 2.76 μm

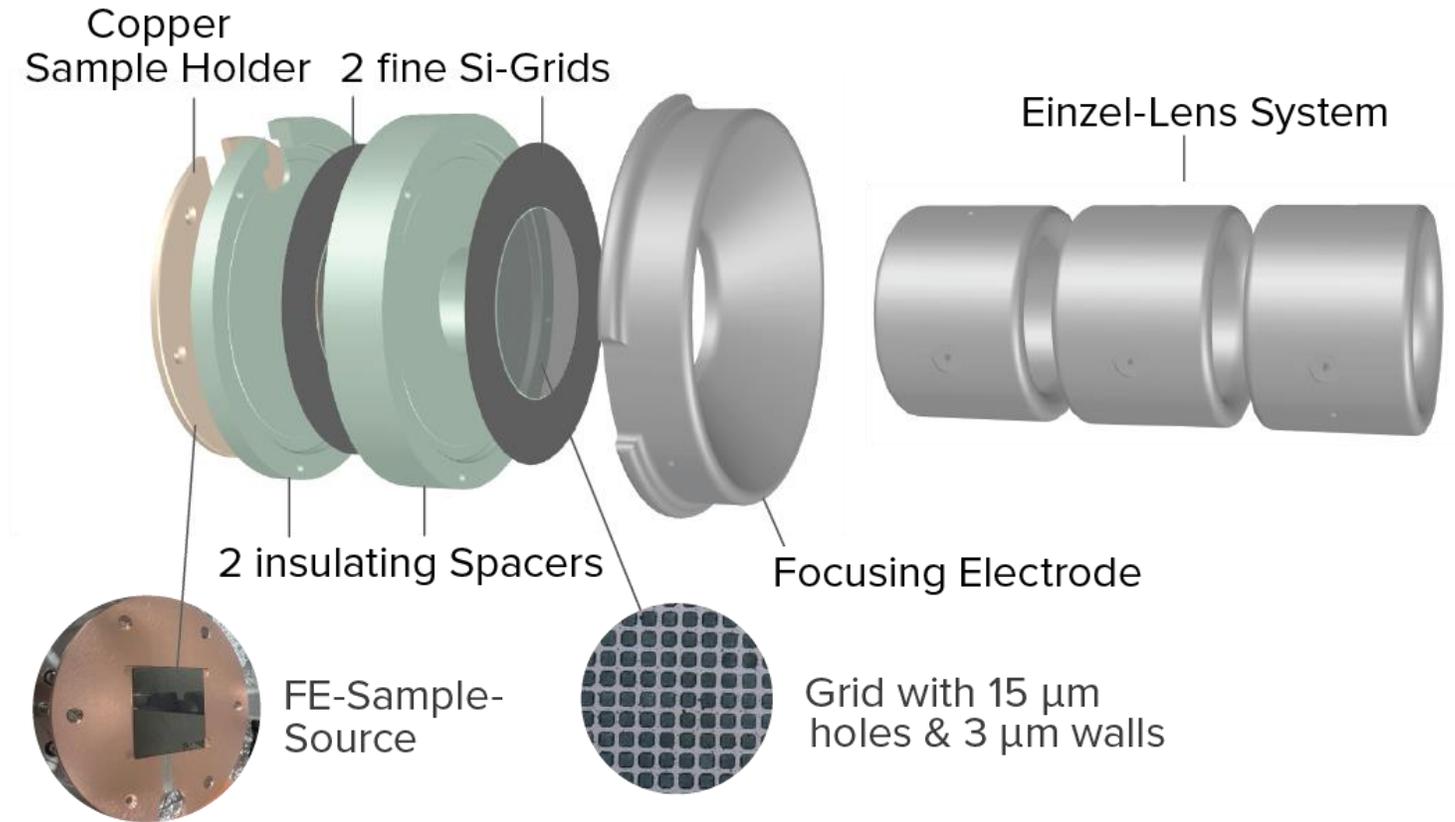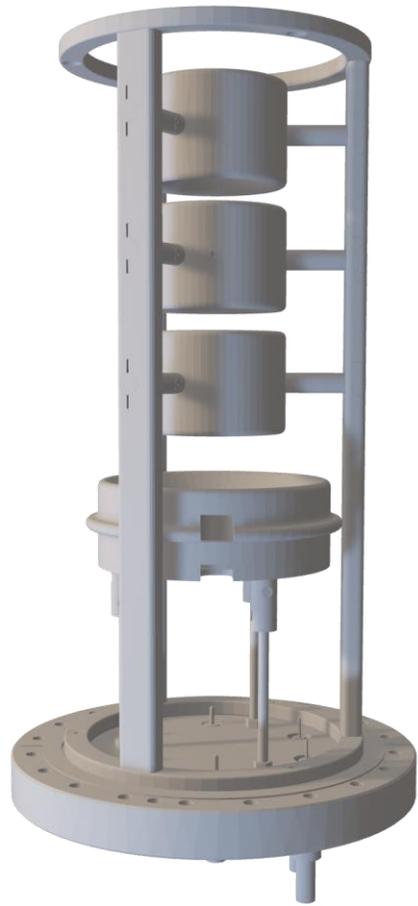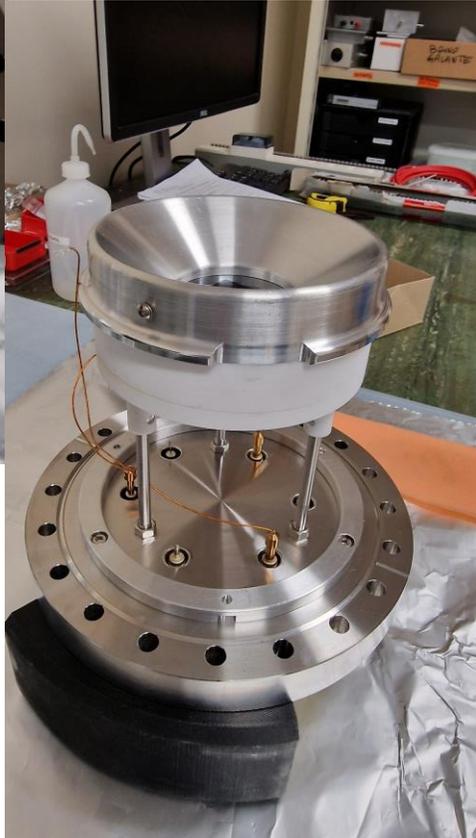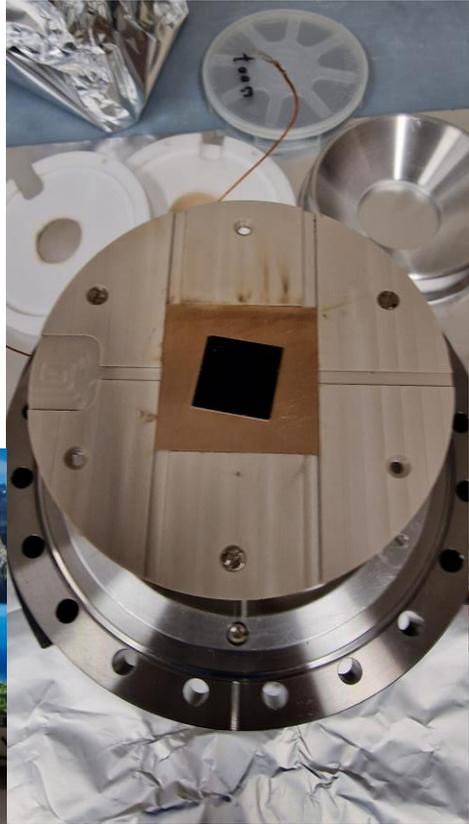| HV | det | mag ⊞ | spot | WD | HFW | x: 0.5703 mm | tilt | 20 μm |
| 3.00 kV | TLD | 2 000 x | 3.0 | 5.1 mm | 63.5 μm | y: 5.4059 mm | 30 ° | INL |

FECNT Gun Design and Test Bench

Cold Cathode Test Bench

FECNT Design

Copper Sample Holder

2 fine Si-Grids

Einzel-Lens System
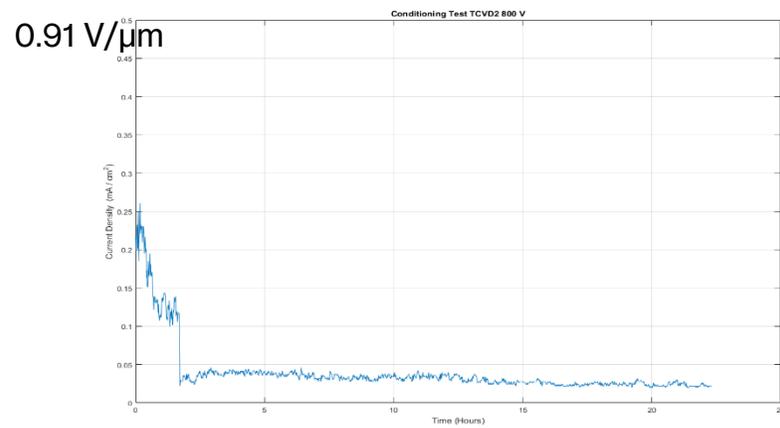
2 insulating Spacers

Focusing Electrode

FE-Sample-Source

Grid with 15 µm holes & 3 µm walls

Cold Cathode Testbench Measurements

Conditioning Test

Hexagonal (CNT1) array

0.91 V/μm

1.94 V/μm

2.51 V/μm

Square (CNT2) array

1.48 V/μm

2.4 V/μm

2.63 V/μm

Fowler-Nordheim Plot

Determination of material parameters and enhancement factor:
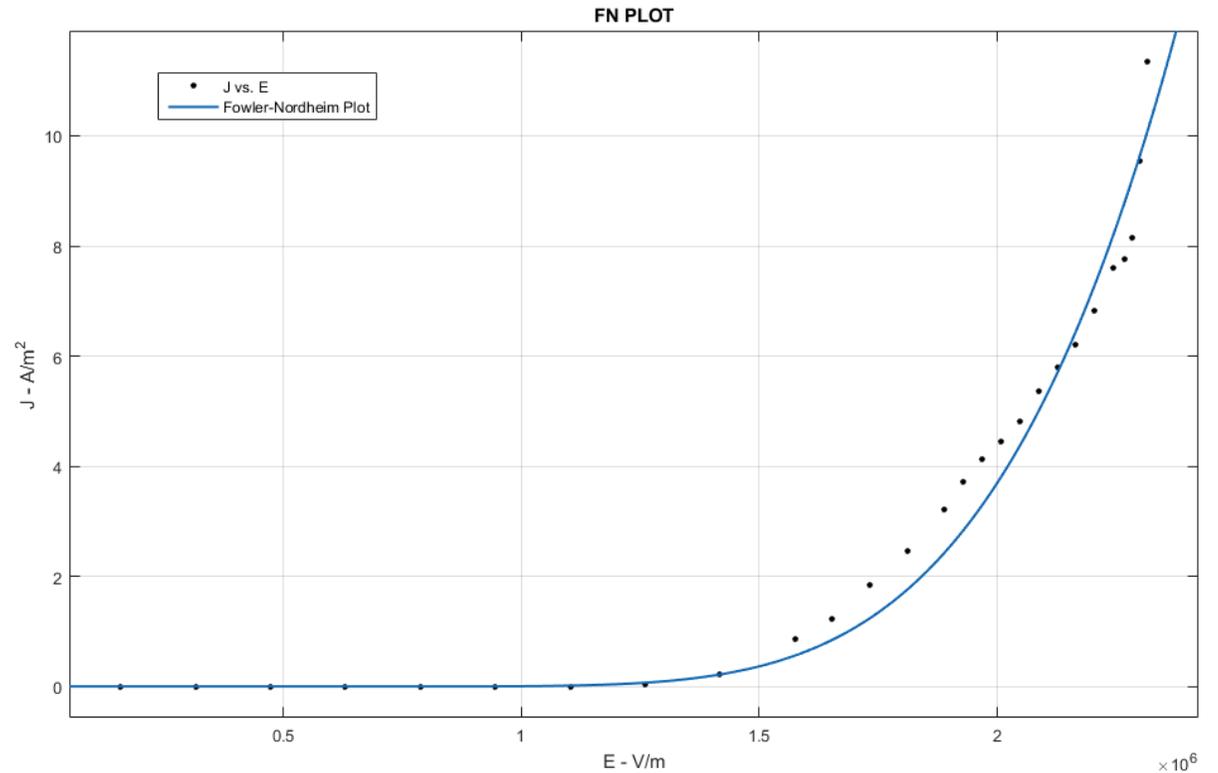
$$f(x) = a(x^2) \exp\left(-\frac{b}{x}\right)$$
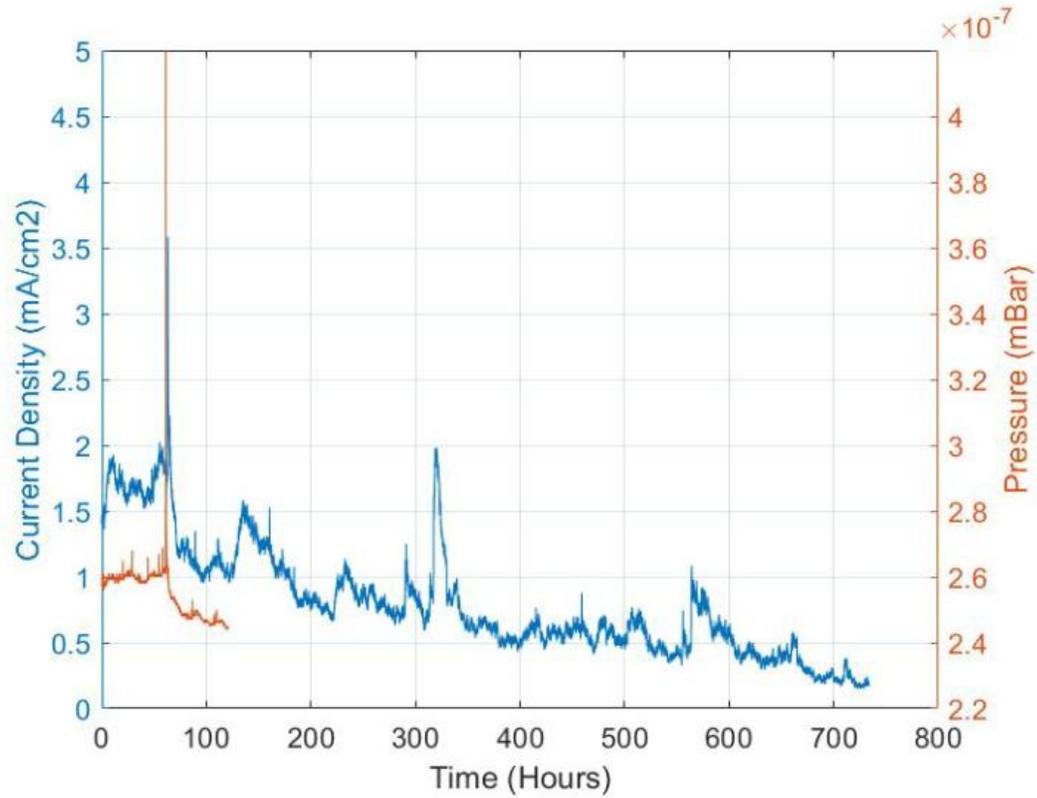
$a = 1.693e^{-10}$

$b = 1.042e^7$

"a" and "b" are necessary parameters for simulation of field emission.

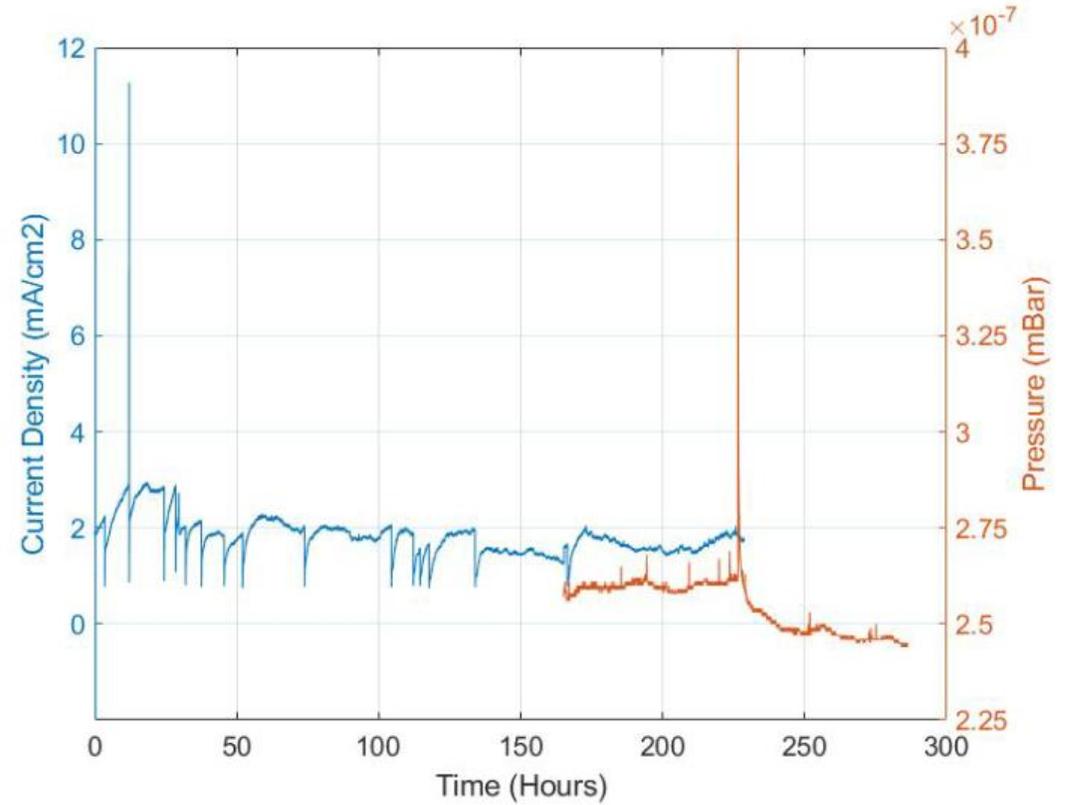$$J = AE^2 \exp\left(-\frac{2.1 * 10^8 \, \phi^{3/2}}{\beta E}\right)$$

$\beta = 225.3$
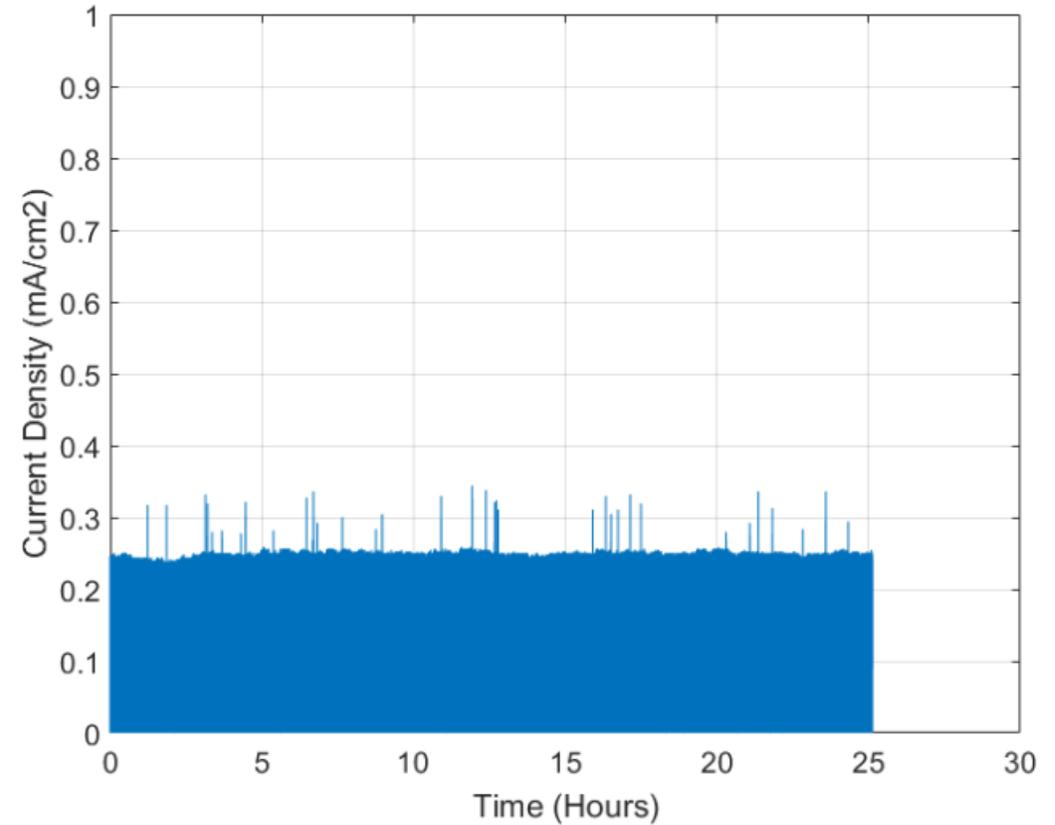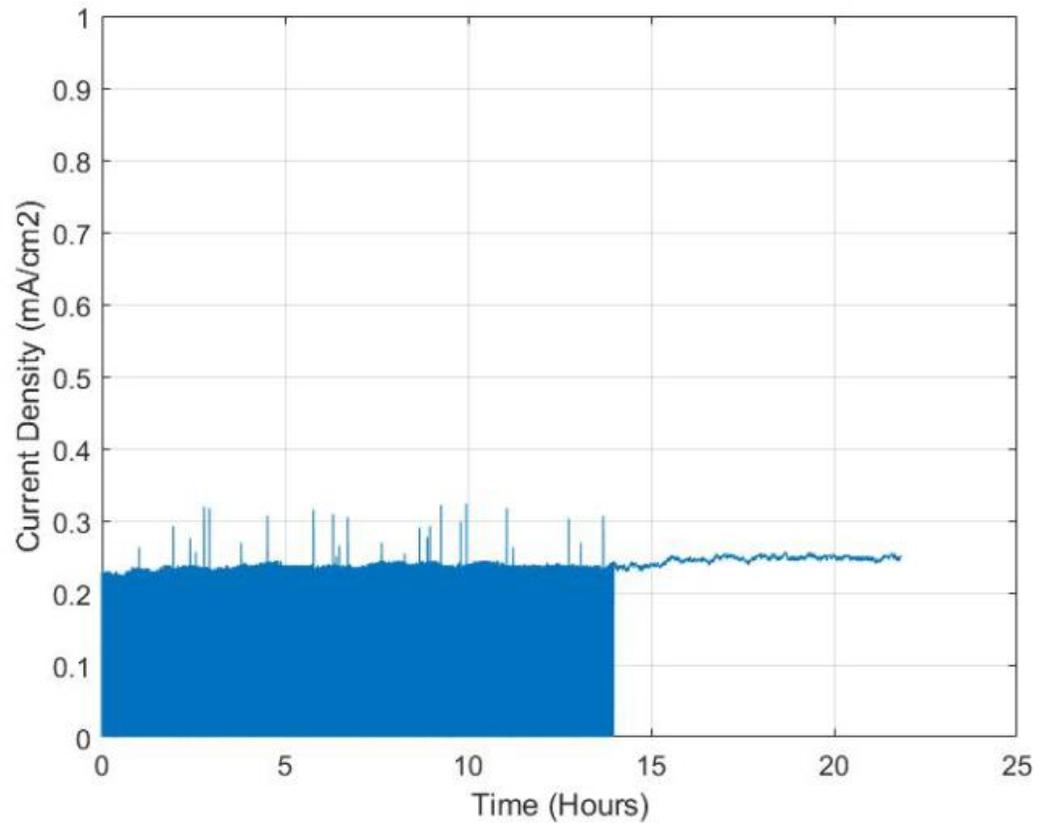
Lifetime test for CNT1 (a) and CNT2 (b)

(a) $E = 3$ V/μm

(b) $E = 3.9$ V/μm

Emission Stability Test for Switching Mode for a CNT1-type Array. E = 2 V/μm

FN analysis of 7.1 cm² sample

IV plot

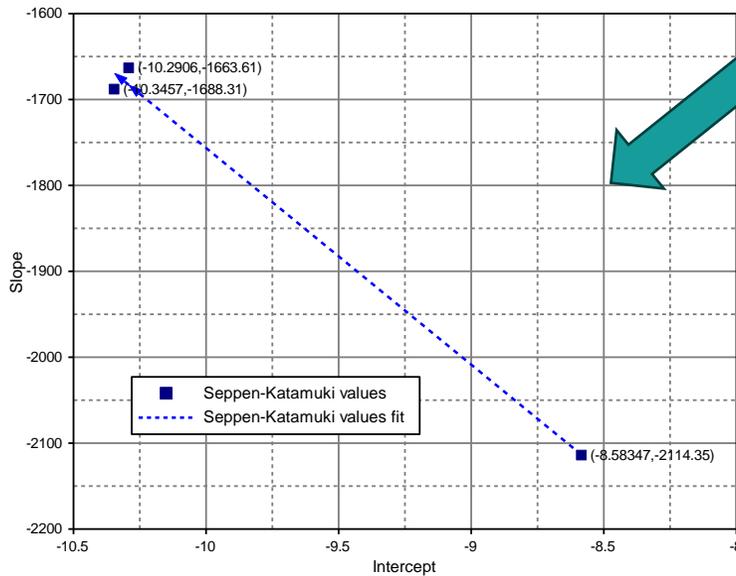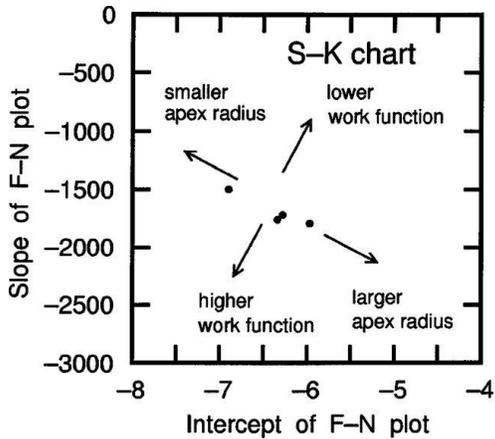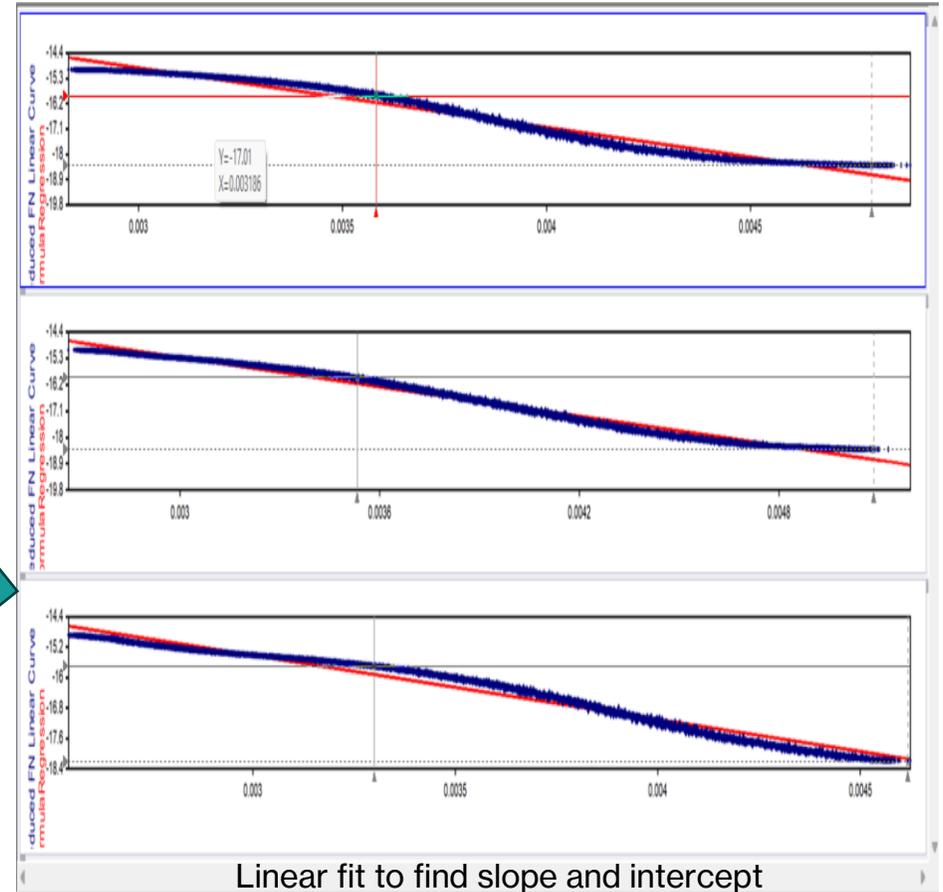# Ln(I/E²) vs 1/E

Linear fit to find slope and intercept

S–K chart
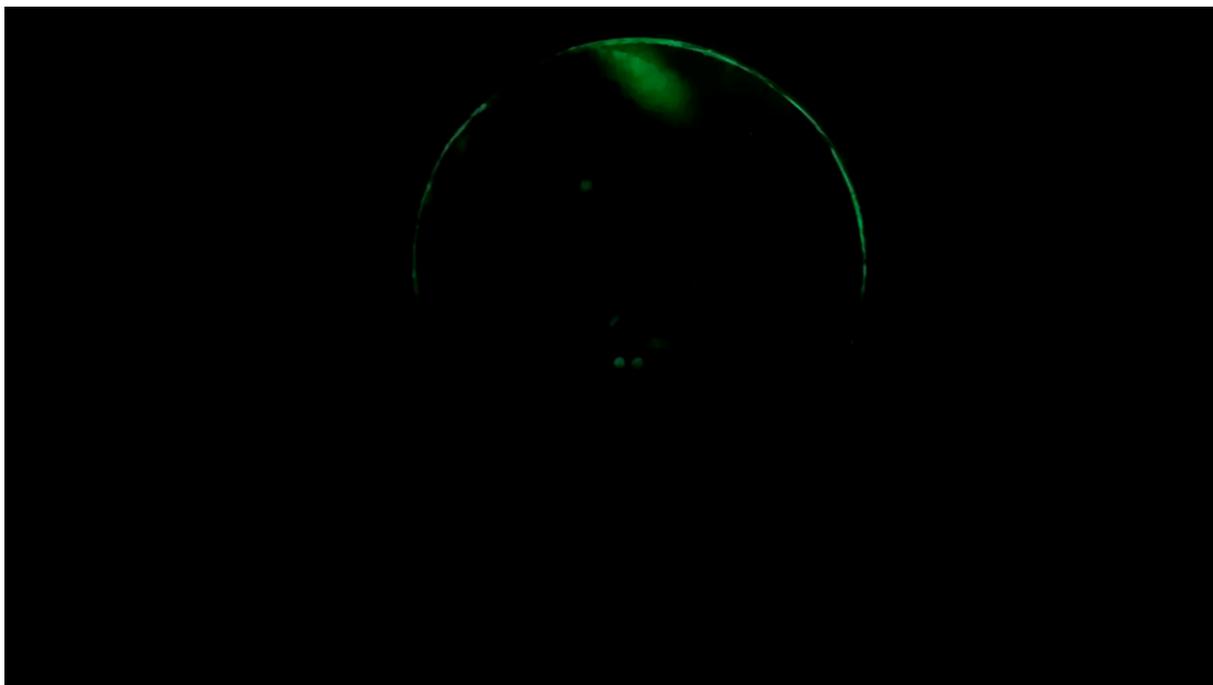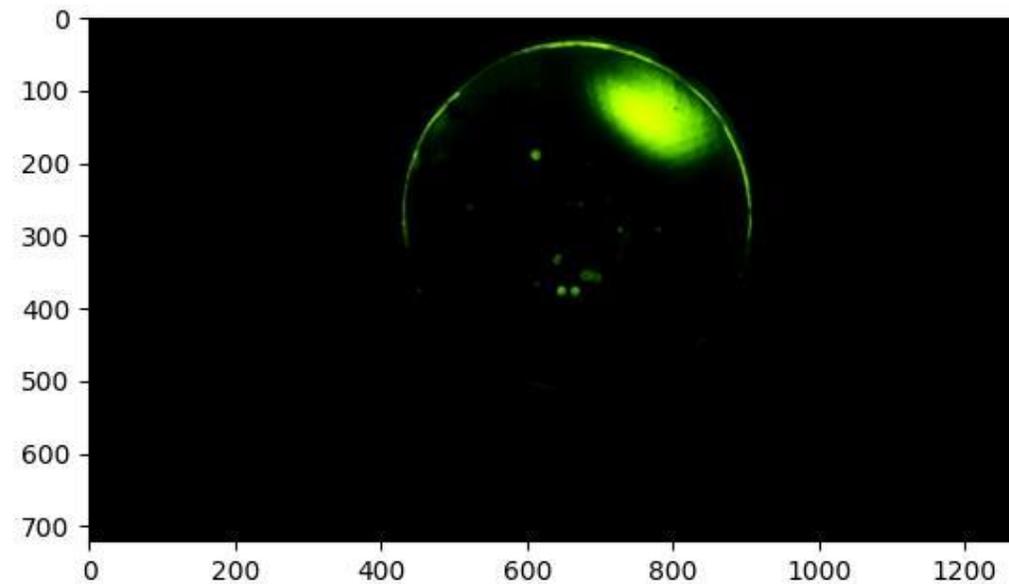
Seppen-Katamuki(SK) chart

The change in the SK values between the ramps indicate significant structural damage to the tips
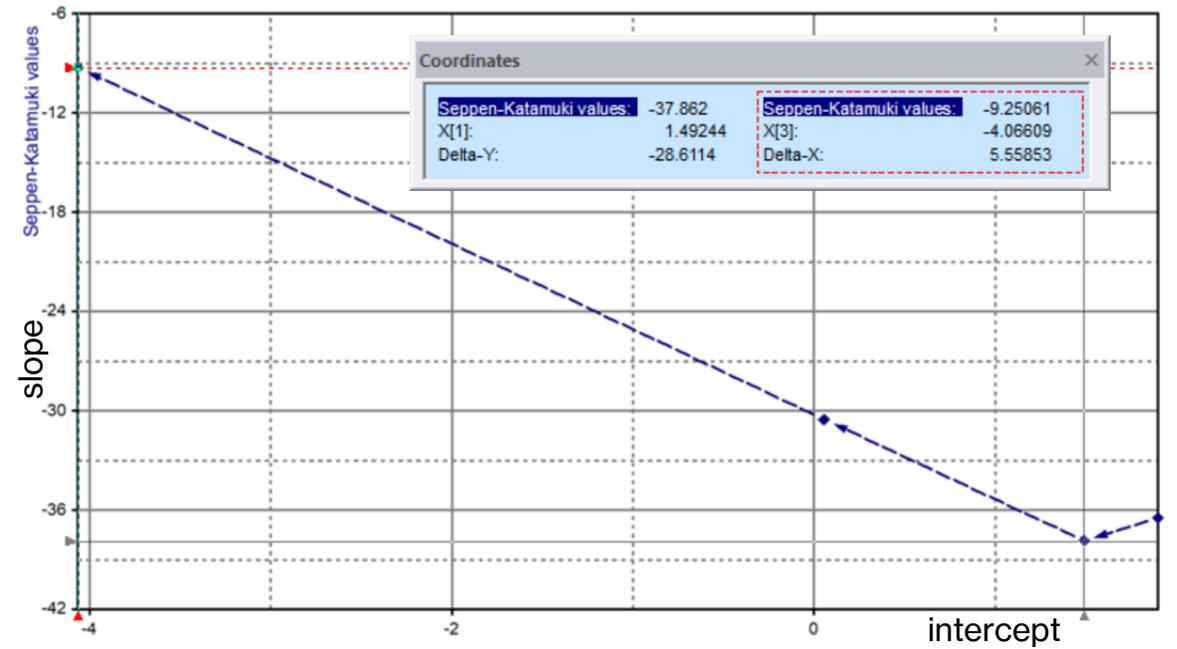
- Joule Heating:
    - The primary cause of rapid degradation at high currents is joule heating, worsened by the low inter-tube spacing within the VACNT array.
    - This leads to poor heat dissipation and thermal stress.
- Electrostatic Screening:
    - In closely packed VACNT arrays, neighboring CNTs shield each other, reducing the effective emission area and the field enhancement factor (β)
    - As fewer VACNTs actively emit, localized heating increases, weakening the bond between VACNTs and the substrate.
    - This results in peeling of VACNTs from the substrate surface.

0.36 mA beam with Einzel lens and
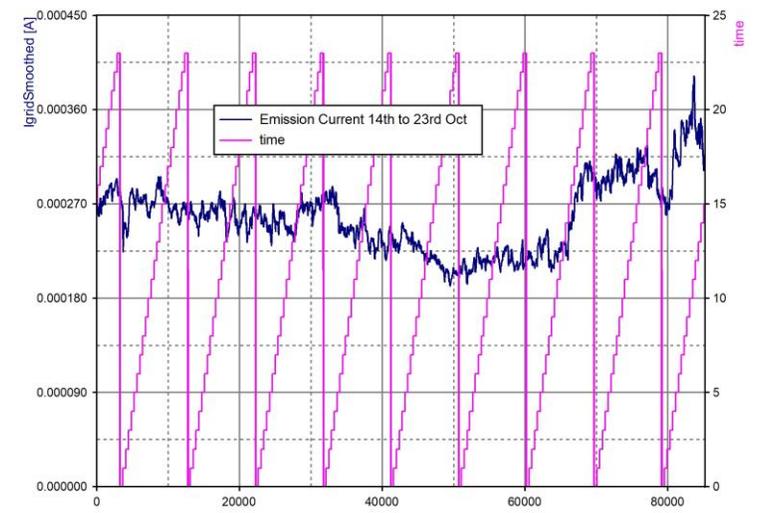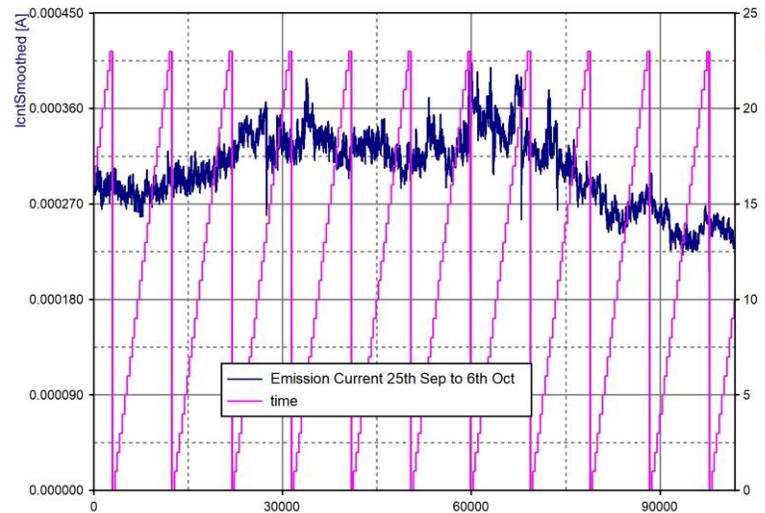magnetic steering

0.520 mA beam with a 0.64 cm² sample
(no Einzel lens)

0.25 mA emission from a 0.64 cm² sample

FN curves for 0.64 cm² sample

SK chart

Longterm stability run 25th September to 23rd October for 0.64 cm² sample

Preliminary Conclusions

CNTs have been shown to be an attractive alternative to thermionic sources for the generation of electron beams

Conditioning of the CNT sample is important to obtain high emission current densities

Patterned arrays can reduce the screening effect and help avoid excess tip burn off

CNTs have a long lifetime but their long-term stability is questionable

Production of large area CNTs is difficult

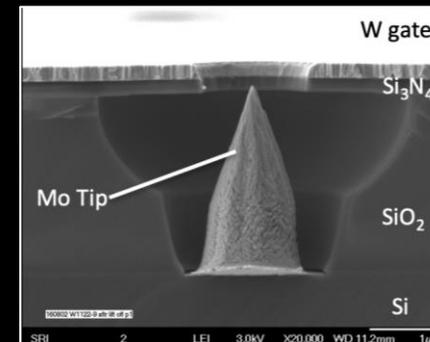The double-gridded electron gun has (finally) shown some promising results

Future Developments

Find a reliable supplier of large area patterned CNT samples

Revisit the gun design to move the focus electrode and extraction grid closer to the source

Investigate the use of Spindt cathodes
- 3 mA per tip, single emitters in pulsed mode
- 100 μA per emitter from small arrays routine
- 2000 A/cm^2 from small areas (few mA total)
- 330 mA total current from 50K emitters from 1 mm^2 area

Spindt Cathode Architecture