Characterization of carbon nanotubes as cold electron field emitters for electron cooling in ELENA

Bruno Galante
NanoAc 2022 – 22-23 November

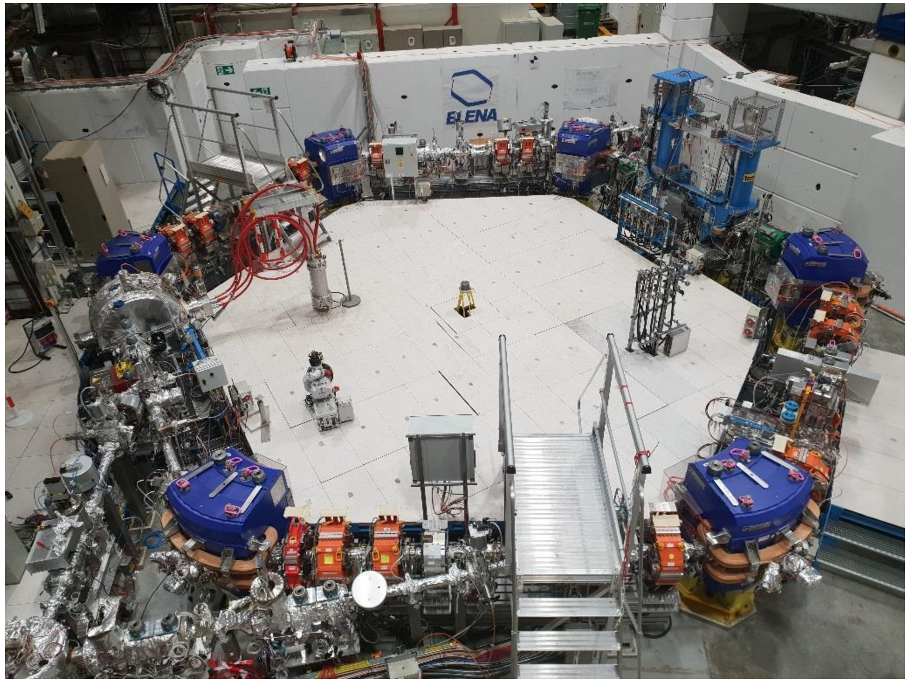
Table of contents

bgalante91@gmail.com

ELENA

ELENA

Item	Value	Dimension
Circumference	30.4	m
Beam Momenta max/min	100 / 13.7	MeV / c
Energy Range max/min	5.3 / 0.1	MeV
Ring Acceptance	75	π mm mrad
Number of extracted bunches	≤ 4	
Emittances of extracted bunches	4 / 4	π mm mrad
Required (dynamic) vacuum	$3\ 10^{-12}$	Torr



Electron Cooling

Electron Cooling

However, emittance blow-up is caused by:

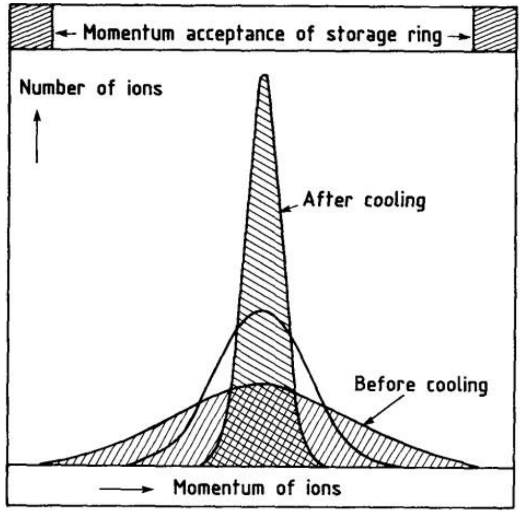
- Intra-beam scattering
- Scattering with residual gases
- Deceleration process.

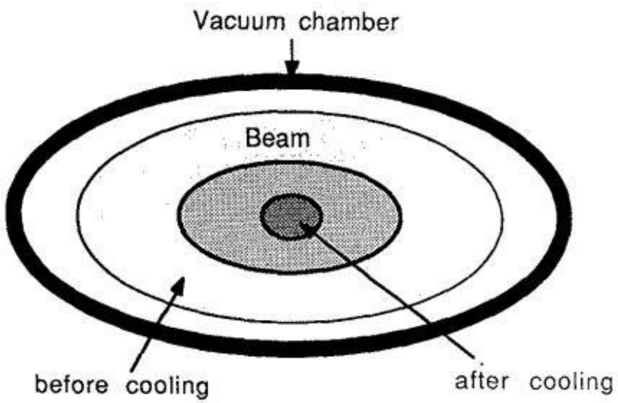
Electron cooling reduces:

- Longitudinal and transverse energy spreads (reduce the beam temperature)
- Size of the beam
- Divergence of the ions

Reaching thermal equilibrium between electrons and ions (e.g. antiprotons) in a time in the order of seconds.

Result: A very intense and brilliant beam can be delivered to the experiments.



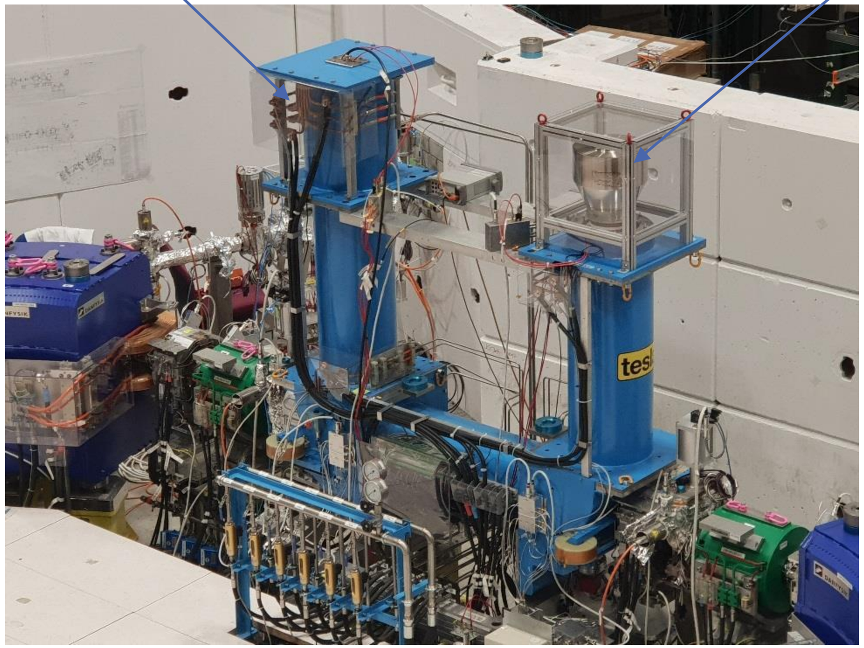


ELENA’s Electron Cooler

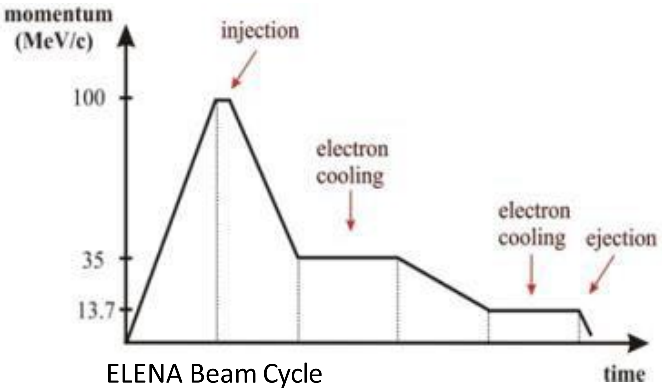
ELENA e-Cooler

Electron Gun

Collector



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

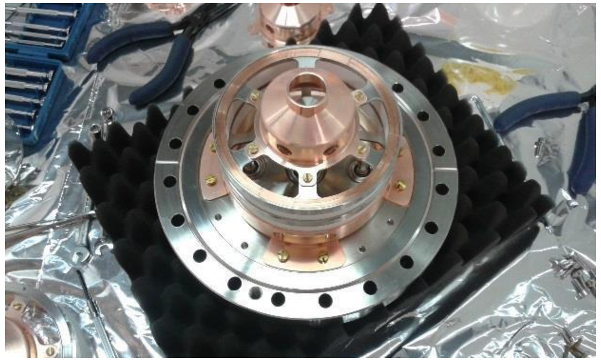


ELENA Beam Cycle

Electron Gun

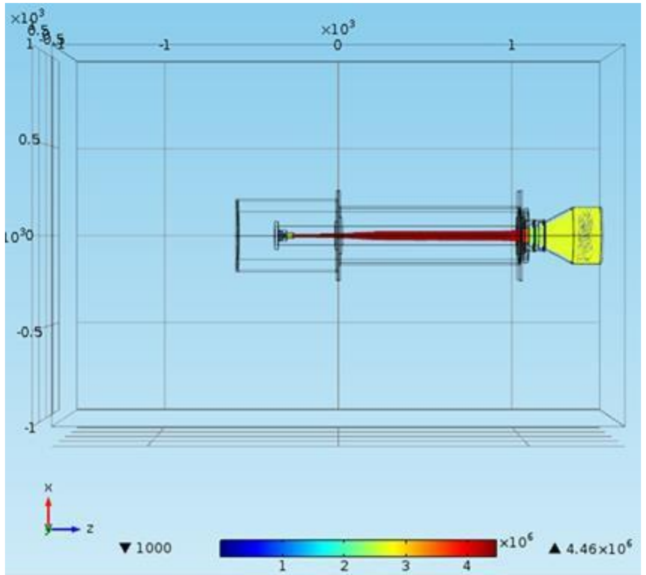
It must produce a

- Cold ($T_{\perp} < 0.1$eV)
- Relatively intense electron beam ($n_e \approx 1.5\text{x}10^{12}$ cm^{-3}).



Thermionic cathodes limit electron cooling performance due to the emitted beam's high $T_{\perp}$.
➔ **Adiabatic expansion**. Requires additional solenoid to generate a larger magnetic field at the gun.

Photocathodes suffer from a usually quite low lifetime, and stability issues and are quite
complicated to operate.



Alternative solution: **Field Emission.**

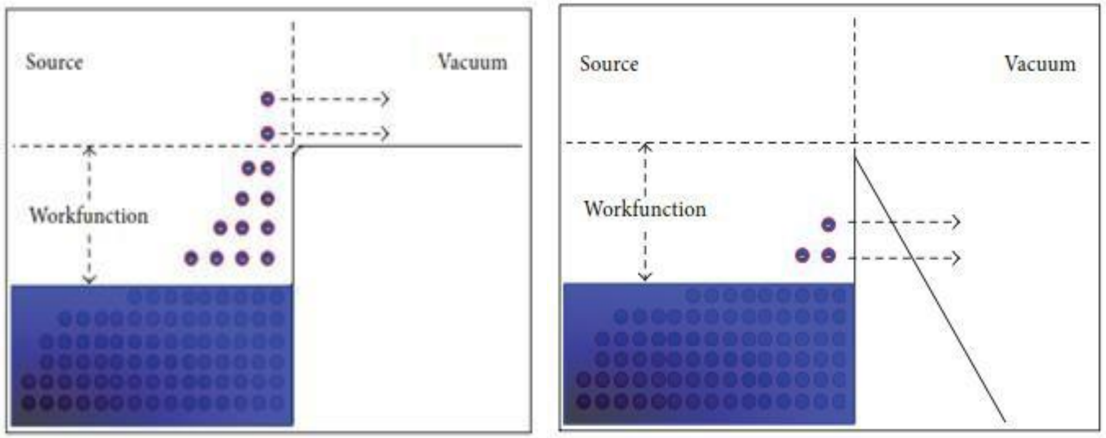
Field Emission

Thermionic Emission, Photoemission: Generation of electrons once the electrons have energy enough to overtake the potential barrier between the material's surface and vacuum.

Field Emission: Tunneling of electrons through the barrier applying a very large electric field (*> 10^7 V/cm*).

Fowler-Nordheim Theory.

$$J = aE^2 \exp(-\frac{b}{E})$$



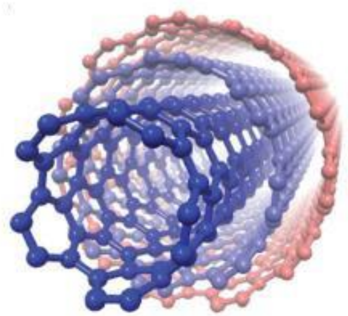
Carbon Nanotubes

Carbon Nanotubes

For flat surfaces, the required electric field is too strong (> 10^7 V/cm).

Possible solution: Field Enhancement with tips. Carbon nanotubes (CNT).

$$J = AE_a^2 \exp(\frac{-B\Phi^{3/2}}{\beta E_a})$$



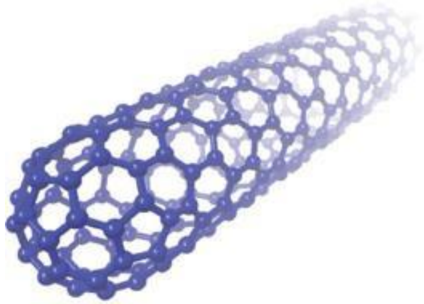
Multi-Walled carbon NanoTube (MWNT)

PRO:

- 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.



Single-Walled NanoTube (SWNT)

Vertically Aligned CNTs

Best field emission performances have been achieved with **perfectly aligned CNTs.**

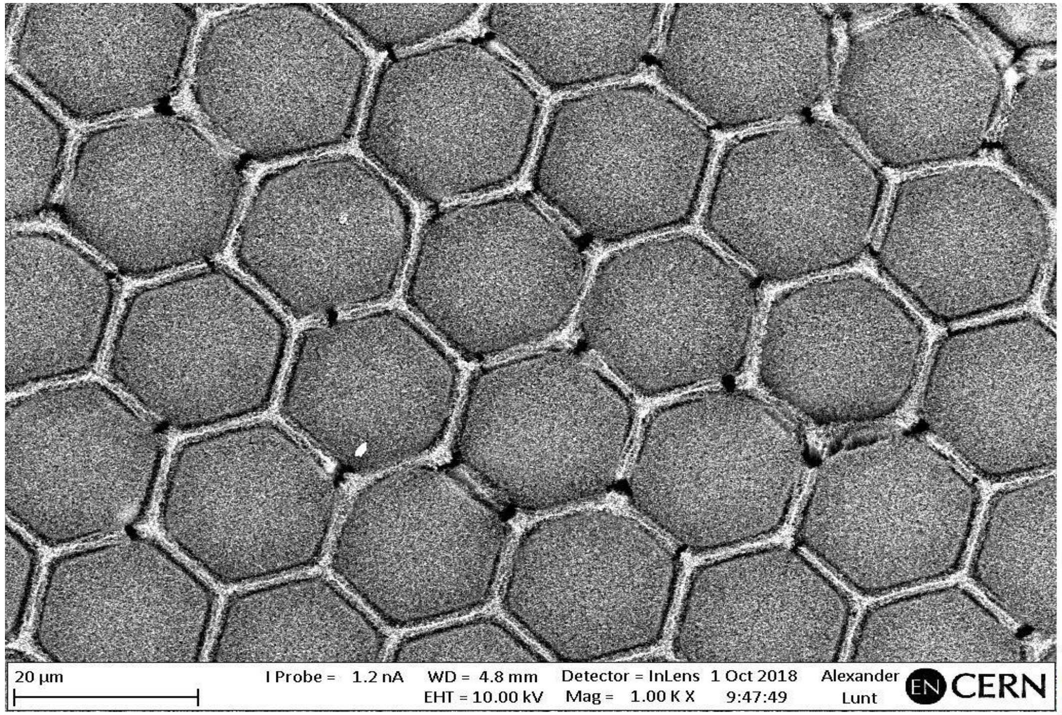
However, several parameters must be considered:

- **Screening Effect**: Uniform penetration of the electric field is complicated for high-density forests.

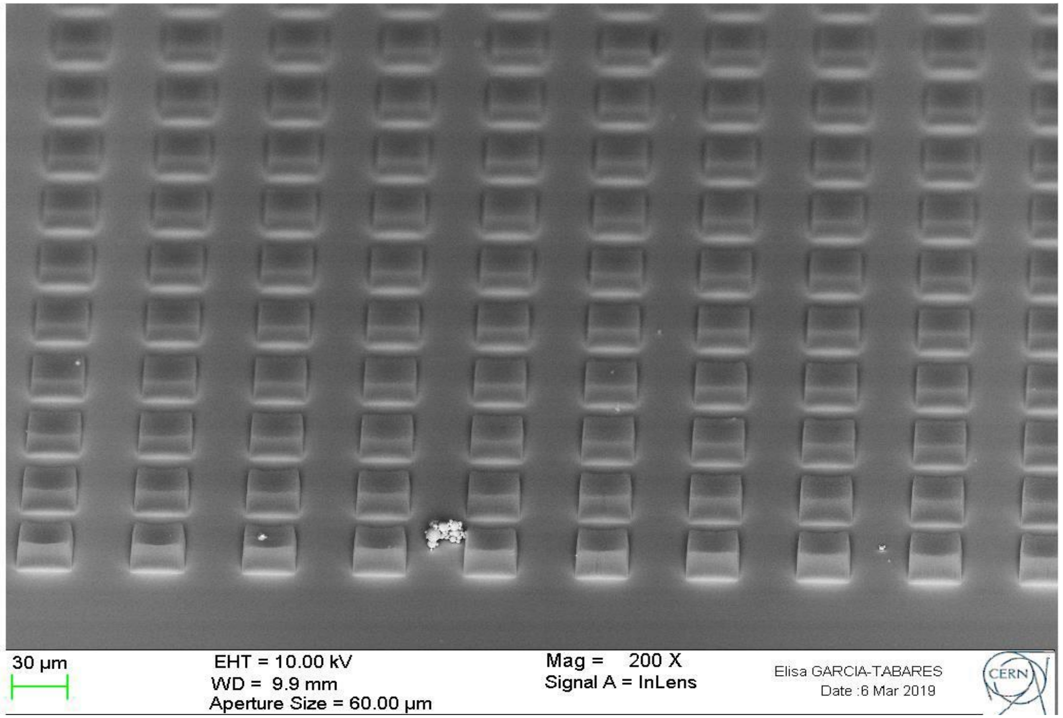
- Length distribution and burn-out
  → **Conditioning process.**

CNT Samples

CNT Array 1



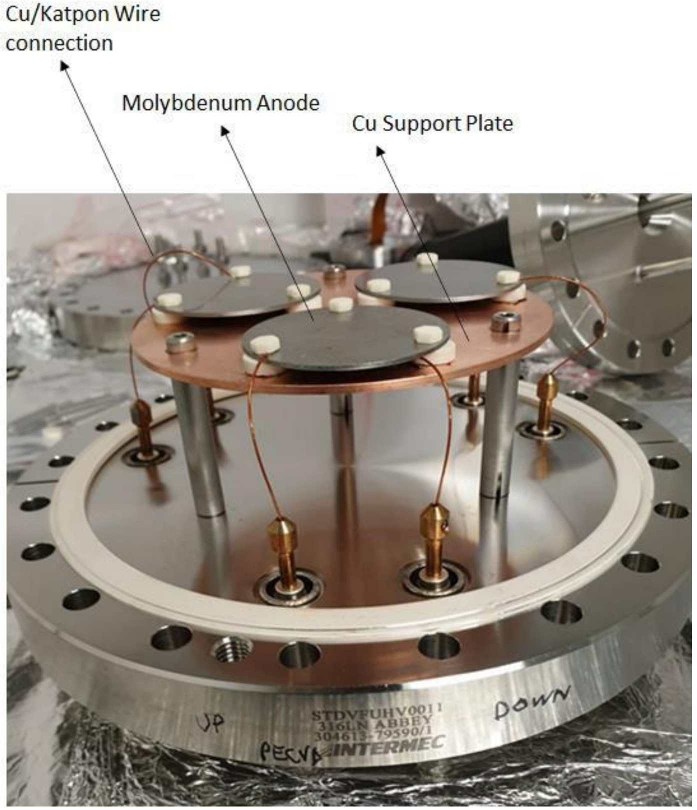
CNT Array 2

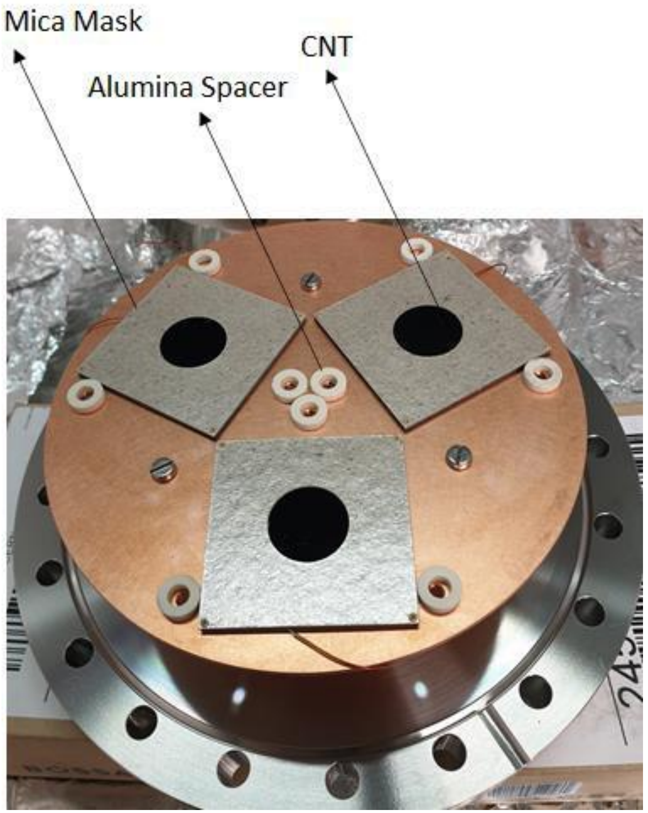


SEM analysis in collaboration with Ana Teresa Perez Fontenla, Elisa Garcia-Tabares Valdivieso and Alexander Lunt, CERN EN-MME-MM.

Cold Cathode Test Bench

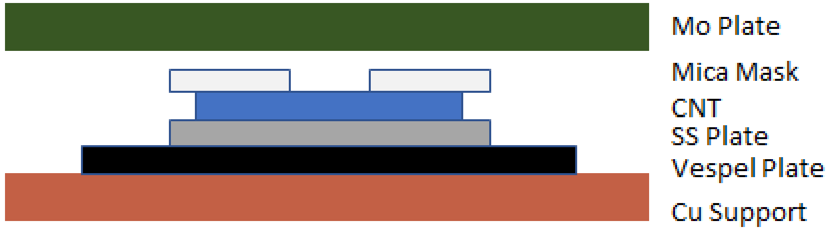
Cold Cathode Test Bench





The test bench has been designed to characterize:

- Conditioning process
- Emitted current in function of E_a
- Stability of the emitted current
- Lifetime.



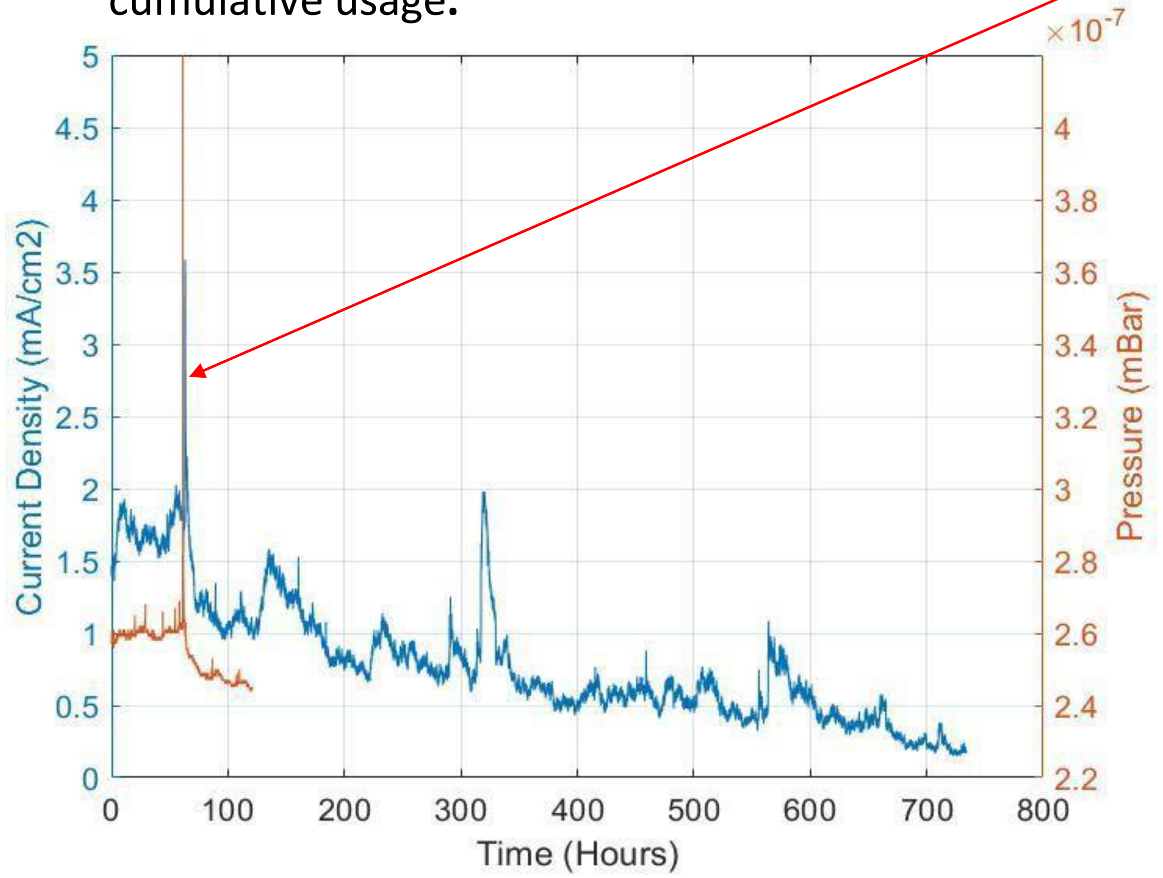
bgalante91@gmail.com

Lifetime and Stability Measurements

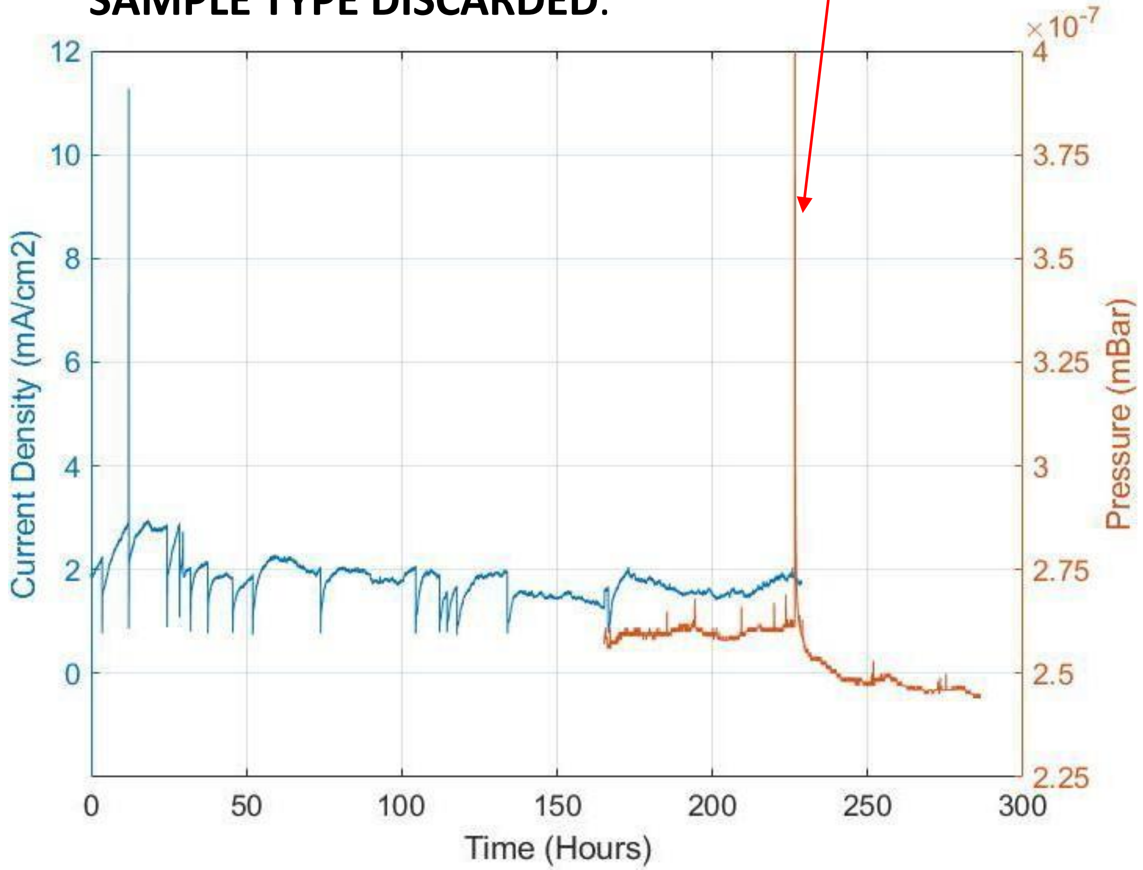
Lifetime Measurements

Vacuum Peak. CNT2 Burnout Time.

CNT1: Total of more than **1500 hours** of cumulative usage.



CNT2: Best sample up to 500 hours. **SAMPLE TYPE DISCARDED**.

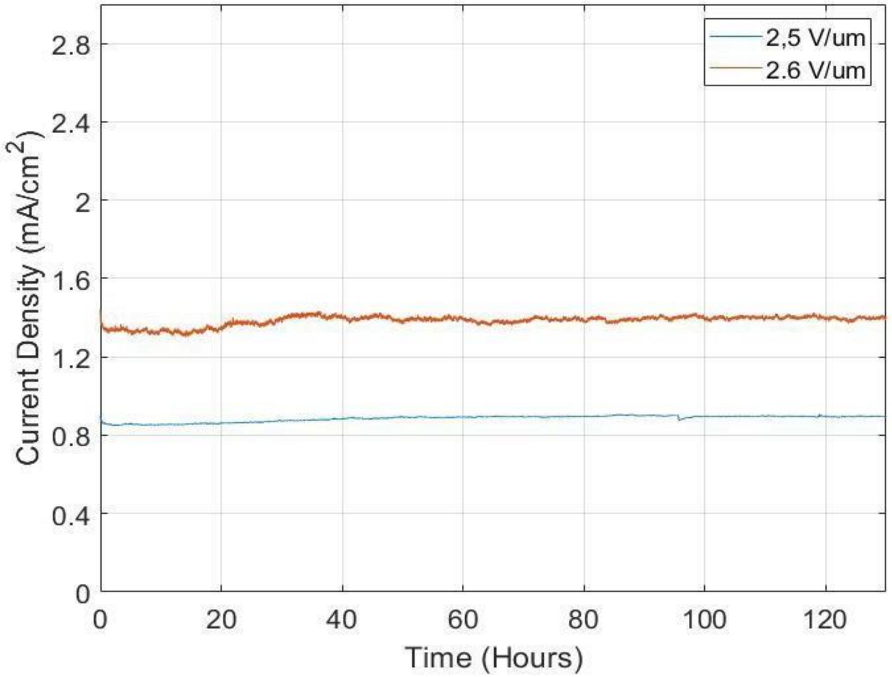


Lifetime Measurements (CNT1-2)

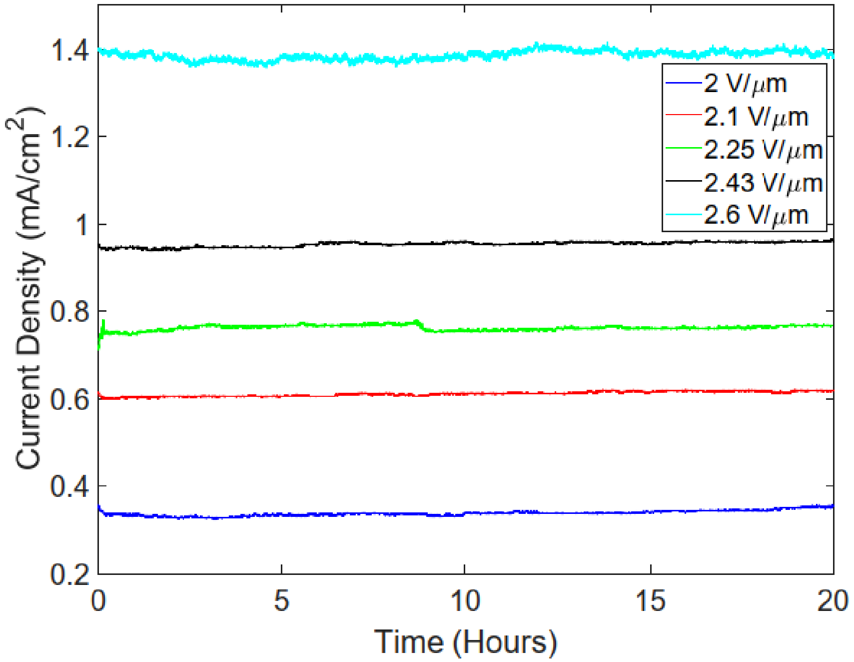
New CNT1 sample tested with optimal environment conditions:

- Pressure below 10^{-8} mbar.
- Bake-out at 220 °C.
- Several voltage ramps before lifetime measurements.

More than 250 hours of emission with no degradation.

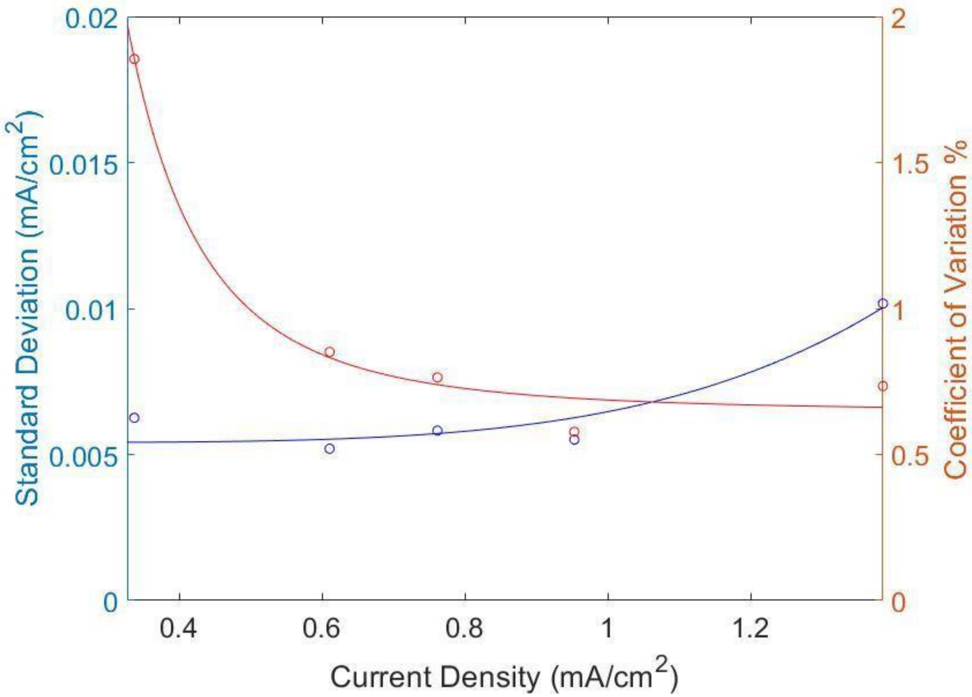


Stability test of the CNT2 sample at 5 different applied electric fields for 20 hours.
The emitted current density was then studied in order to investigate the stability over time in terms of absolute standard deviation and coefficient of variation.



Coefficient of variation (or relative standard deviation):

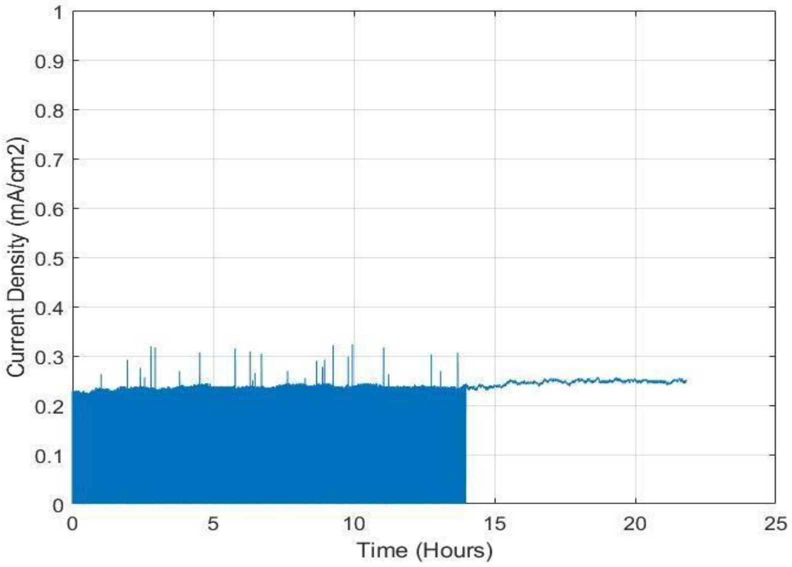
$$c_v = \frac{\sigma}{\langle J \rangle} \times 100$$

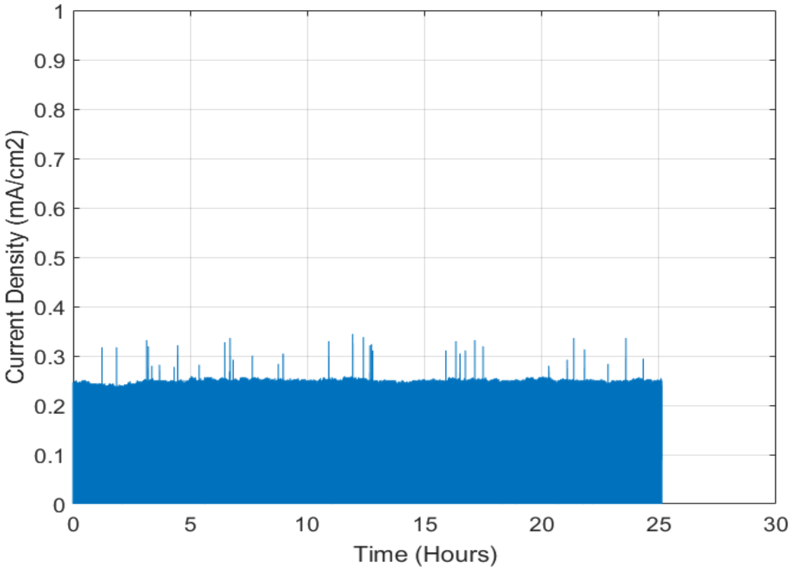


Stability Measurements (CNT1)

The same CNT1 sample that was previously used.
Measurement performed in **pulse mode** following the ELENA beam cycle ➔ assess stability during current switching.

→ Stability improved thanks to proper conditioning.





Work Function Measurements

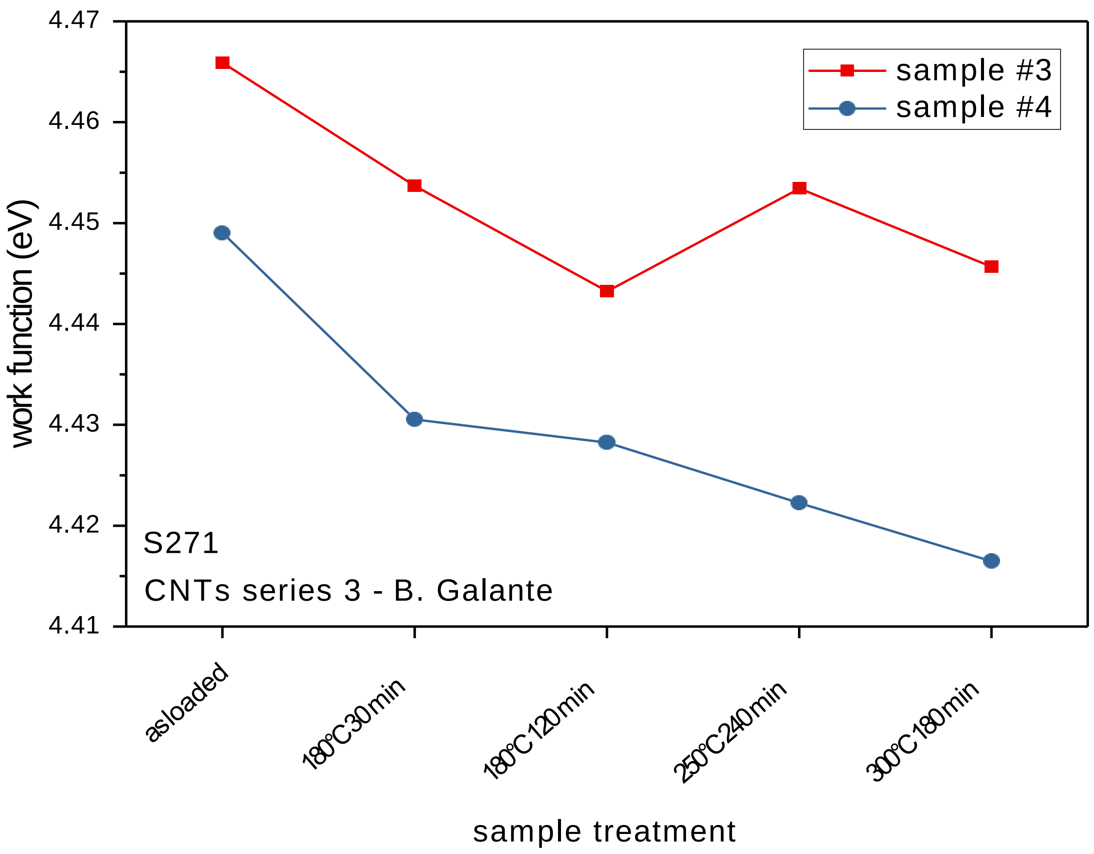
Work Function

Annealing process on 2 samples.

The process was composed of 4 steps:

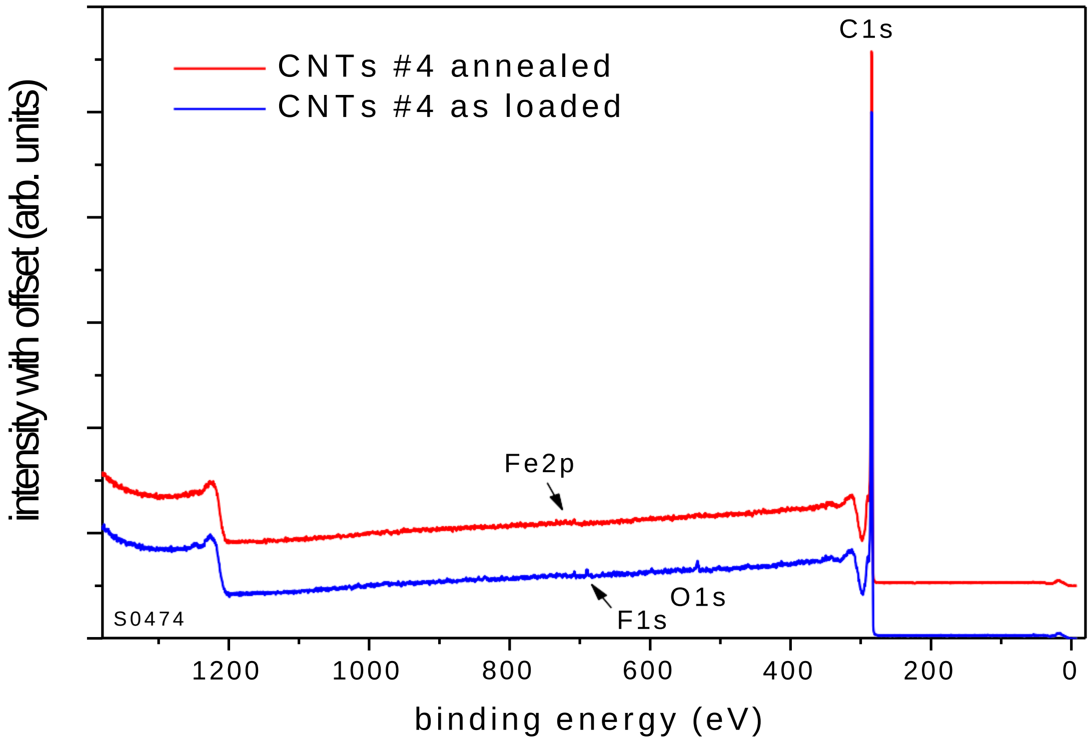
- 180 C degrees for 30 mins,
- 180 C degrees for 120 mins,
- 250 C degrees for 240 mins,
- 300 C degrees for 180 mins.

After each step, the work function of the samples was measured (at RT).



XPS

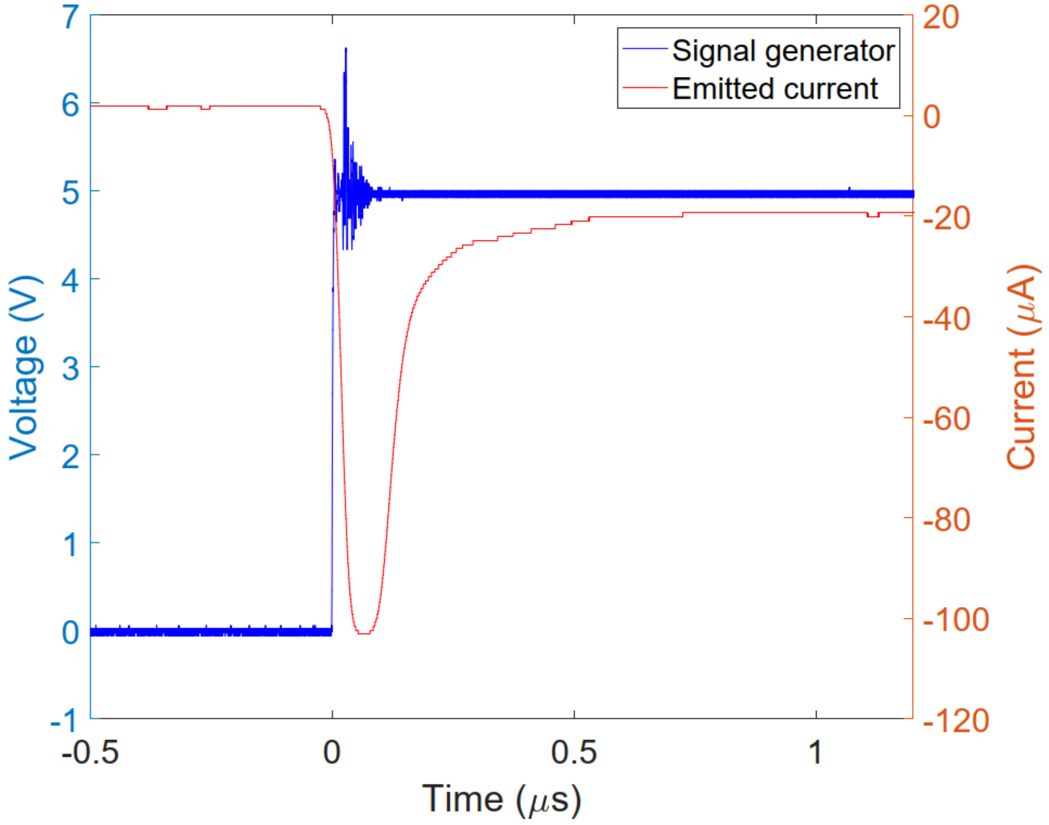
XPS. The impurity level of oxygen was very low and even reduced after the thermal treatment in UHV. Furthermore, the minor Fe signal detected is most likely connected to impurities from the CNT growth using a Fe-based catalyst.

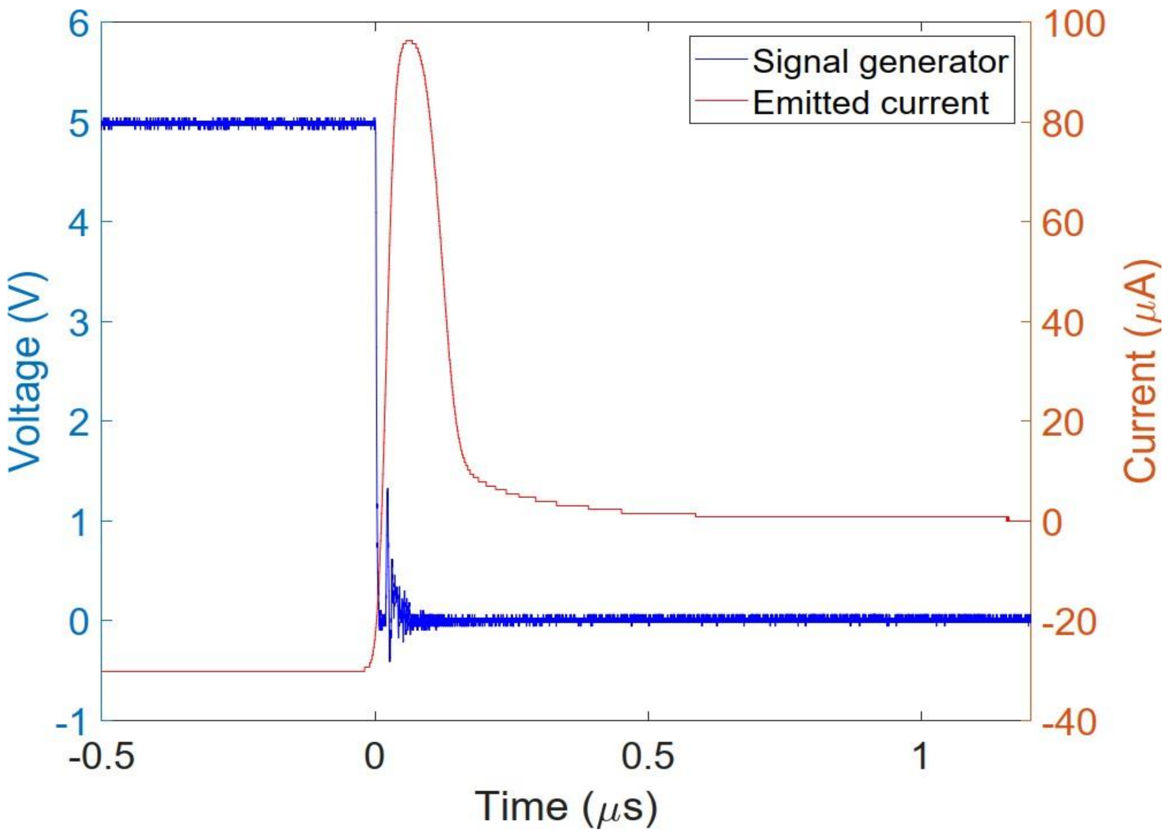


- B. Galante, G. Tranquille, M. Himmerlich, C. P. Welsch, J. Resta Lopez, Stability and lifetime study of carbon nanotubes as cold electron field emitters for electron cooling in the CERN extra low energy antiproton ring, PhysRevAccelBeams.24.113401.

Current Switching

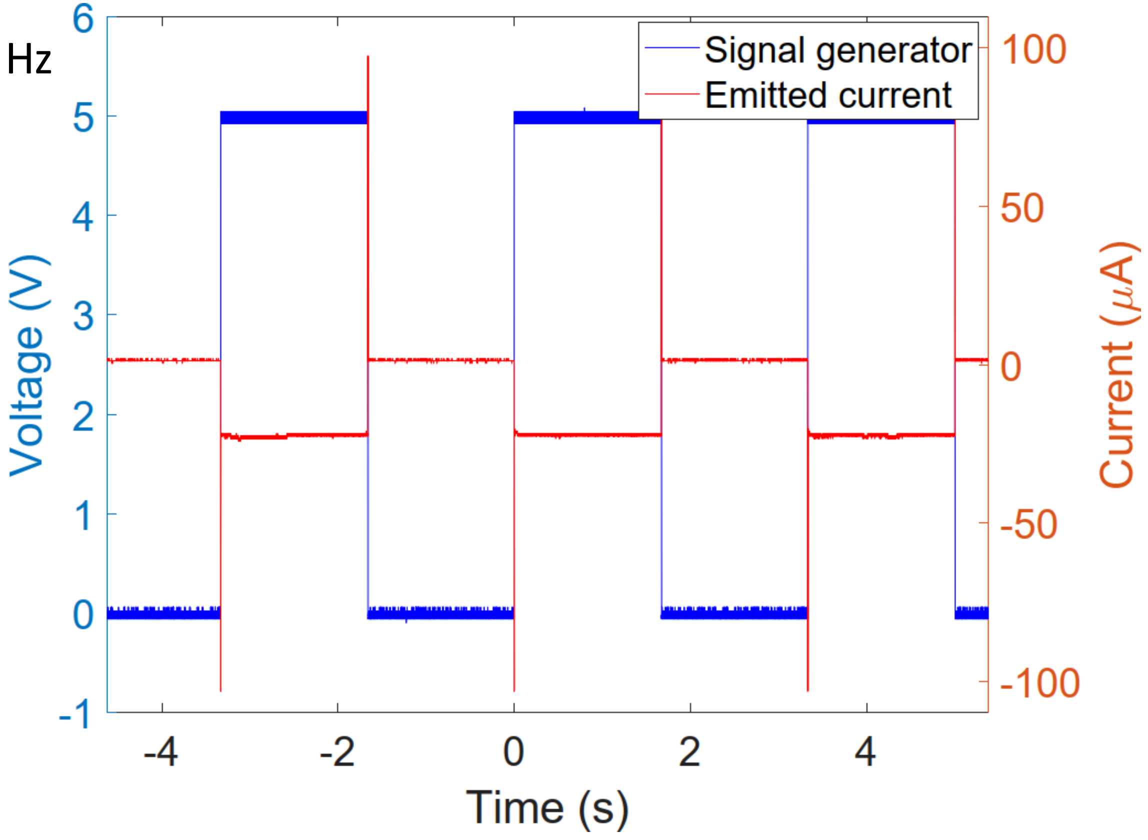
Rise and fall time



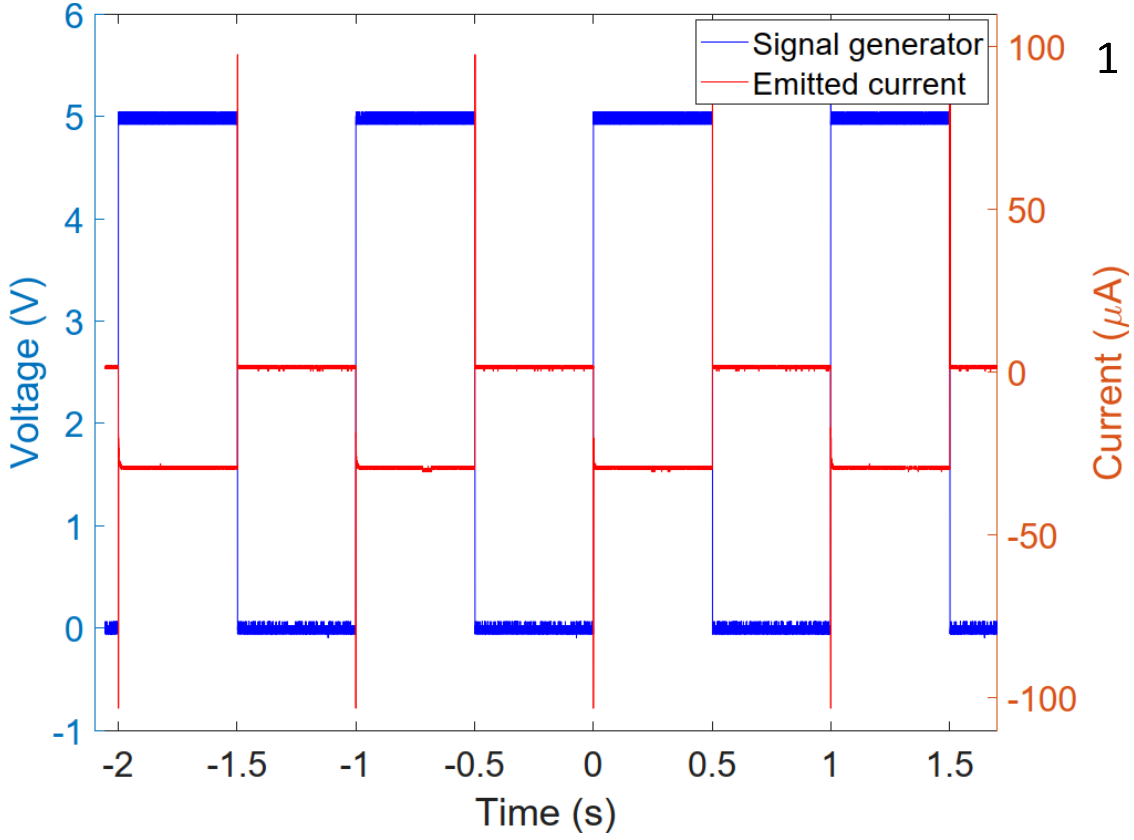


Stability examples

0.3 Hz



1 Hz



bgalante91@gmail.com

Conclusions

- Carbon nanotubes have proved to have promising stability and lifetime after a suitable conditioning process.

- The emitted current can easily match the requirements at a relatively low electric field.

- Beam current switching has been successfully tested via software and hardware. Rise and fall times below 1 μs have been proven.

Thank you

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

Electron Cooling

Let's consider an ion beam (in our case an antiproton beam) and an electron beam as 2 plasmas of different T.

High T Plasma: Ion beam - **Low T Plasma:** Electron beam.

If there is a **big density of electrons** and they are **continuously generated**, after a certain time
➔ Ion Beam T = Electron Beam T.

Electron-Ion interactions: Series of small-angle Rutherford scatterings via Coulomb interactions where little momentum and energy is transferred.

Adiabatic Expansion

Single electron case. If:
- axially symmetric field geometry, $B = B_{||}(z)$
- electron moves slowly enough

We can consider the following adiabatic invariance: $$\frac{E_\perp}{B} = const$$

When the field is reduced from the value B_i to a value B: $$E_\perp = \frac{B}{B_i} E_{\perp i}$$

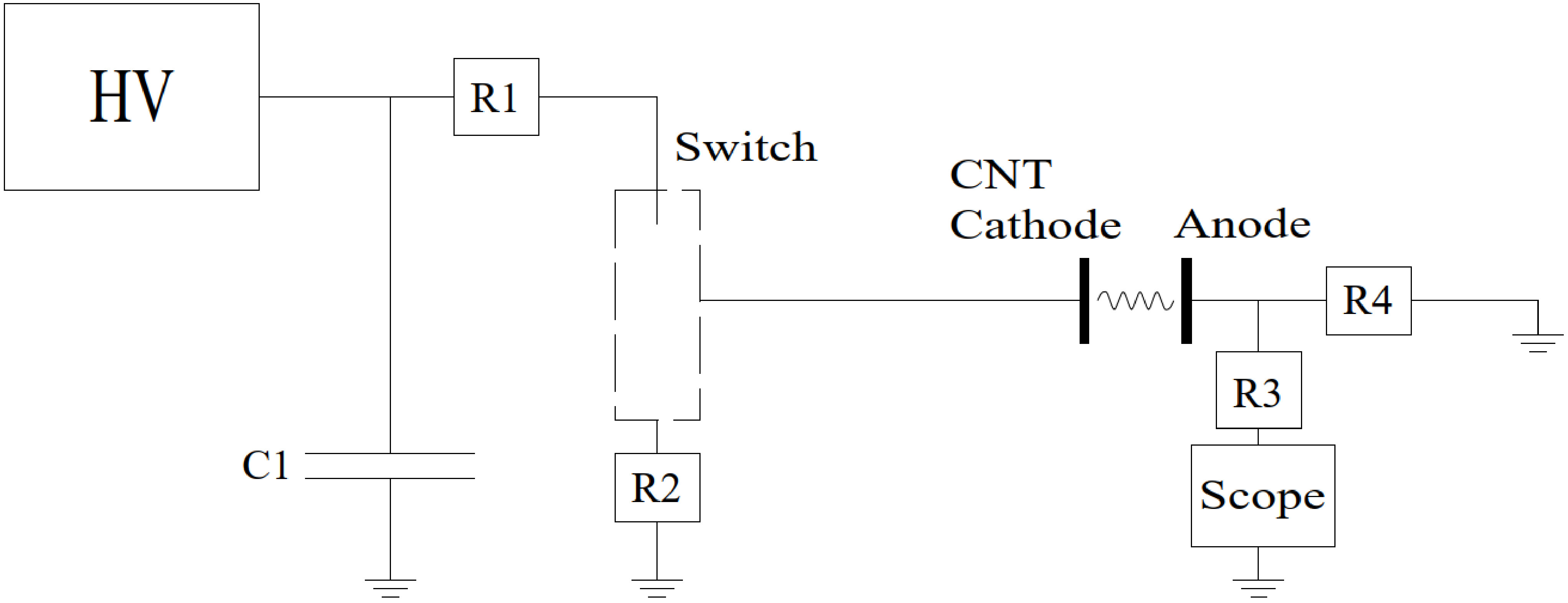
Also, the magnetic flux contained in the cross section of the assumed cylindrical electron beam is an adiabatic invariant, therefore it will increase when the B decreases: $$R = \sqrt{\frac{B_i}{B}} R_i$$

Multiple electrons. For multiple, not independent electrons, the Coulomb interaction breaks the invariance. However, the invariance stands for the average transverse energy: $$\frac{\langle E_\perp \rangle}{B} = const$$

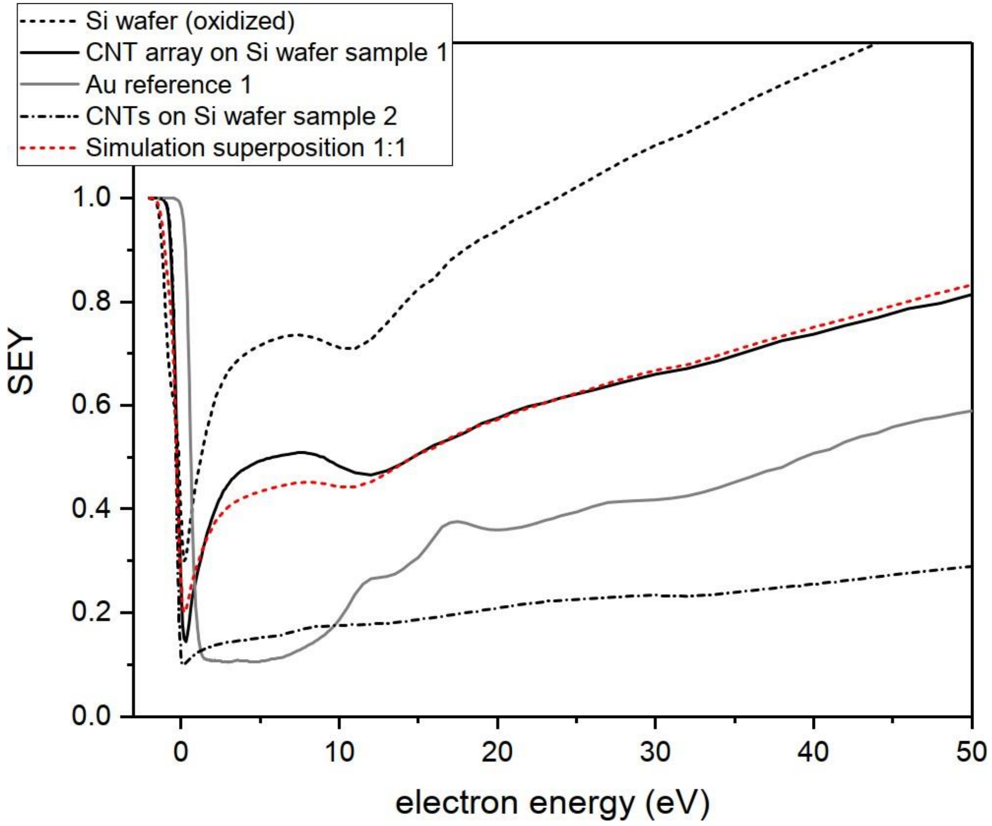
Therefore: $$k_B T_\perp = \frac{B}{B_i} k_B T_{\perp i}$$

Electron cooling and recombination experiments with an adiabatically expanded electron beam – S.Pastuszka, U.Schramm, M.Grieser, C.Broude, R.Grimm, D.Habs, J.Kenntner, H.-J.Miesner, T.Schussler, D.Schwalm, A.Wolf

Circuit



SEY



Method:

SEY and has been measured in CERNs surface analysis from SPECS.
Chamber pressure during measurement 9×10^{-10} mbar, sample at room temperature

The SEY setup consists in an electron gun (ELG-2/EGPS-1022 from Kimball Physics) and a sample holder, on which the sample current I_{sample} is measured.
The SEY is measured using the following approach:
1. A positive voltage is applied to the sample. All primary electrons (PE) impinging on the sample surface are collected by the sample and the emitted secondary electrons are recaptured.
→ I_{sample} can be therefore assumed to be the primary current I_{PE} from the electron gun.
2. A negative voltage V is applied to the sample. All emitted secondary electrons (SE) are accelerated to leave the sample surface, i.e., I_{sample} measures the flux of electrons through the sample.
→The current of secondary electrons is $I_{SE} = I_{PE} - I_{sample}$.
3. The secondary electron yield SEY is $\delta = I_{SE} / I_{PE}$ can be calculated from those two measurements.

Further relevant experimental conditions of the SPECS system:
- Sample is biased (±45V);
- if not otherwise specified, the primary electrons impinge the sample at normal incidence