Vertically aligned multi-walled carbon nanotube (MWCNT) arrays for X-ray sources applications

M. TRUJILLO ARREDONDO
P.L GAUTHERIN

IVeSC 2026

www.thalesgroup.com

Table of contents

THALES MICROWAVE & IMAGING SUB-SYSTEMS

DEFENSE

Protecting citizens and armed forces

Power transmitters for missile seekers

Electromagnetic directed-energy weapons **for anti-drone warfare**

SPACE

Promoting access to information, exploring space

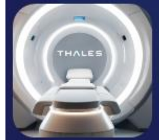
Travelling wave tubes (TWT) for **satellites**

Space qualified thrusters serving **Orbit Raising and Station Keeping** missions

SCIENCE

Designing sustainable heating solutions and power for therapeutic purpose

Gyrotrons and Diacrodes for plasma heating in nuclear **fusion reactors**



Klystron electron tubes for **linear particle acceleration** also used for **FlashTherapy**

HEALTHCARE

Delivering advanced digital imaging for more than 25 years

Innovative range of **X-ray detectors and imaging solutions**

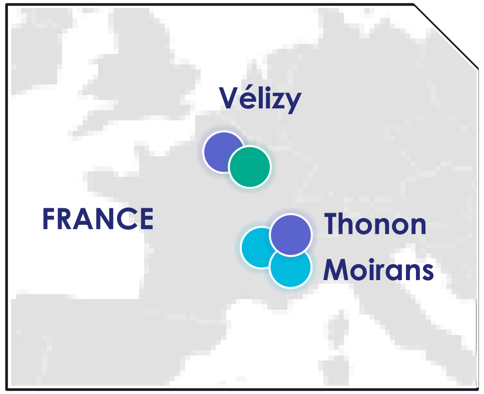
Complete **portable radiography systems**

SECURITY

Ensure the safety of people and people in public places

**Airport checkpoint : ** 3D scanner for hand luggage screening

X- Ray based detection of explosives (ex : abandoned luggage)



Vélizy

Thonon

Moirans

Ulm

- Radiofrequency manufacturing sites
- Radiology manufacturing sites
- Sales

02 Introduction to CNT electron sources : Field emission (cold cathodes)

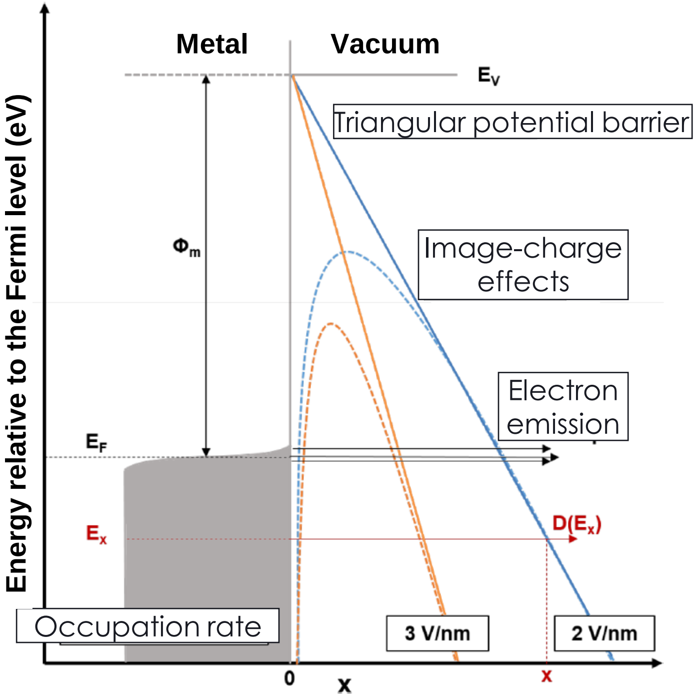
CNT : Carbon nanotubes

We are developing X-ray tubes for applications requiring pulsed operation, with pulse widths on the order of a few hundred microseconds.

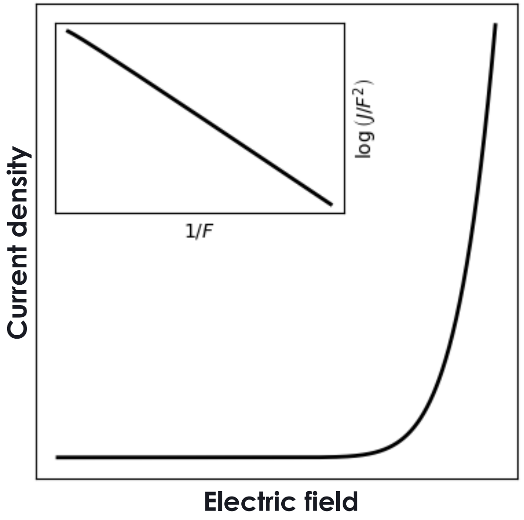
Commutability

Cold cathodes

Field emission



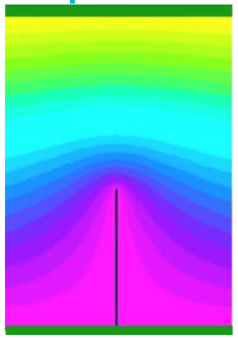
Exponential



Obtaining significant emission current density (J) on metallic surface imposes to induce an extremely high electric field E **(~V/nm)**

Introduction to CNT electron sources : Carbon nanotubes as field emitters

Tip effect

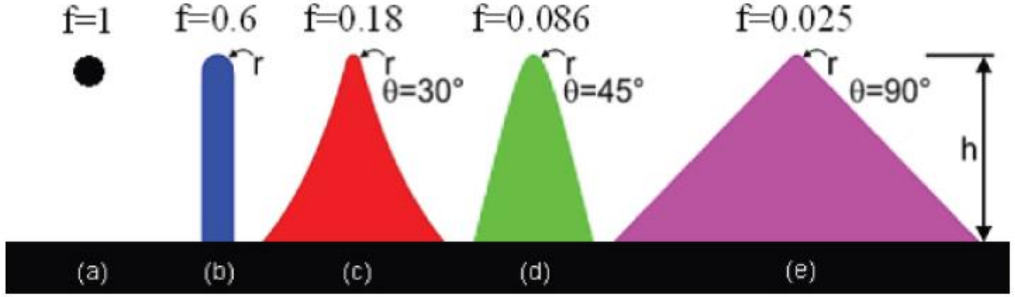


$$F_{tip} = \beta F_{ext}$$

F : *electric Field*

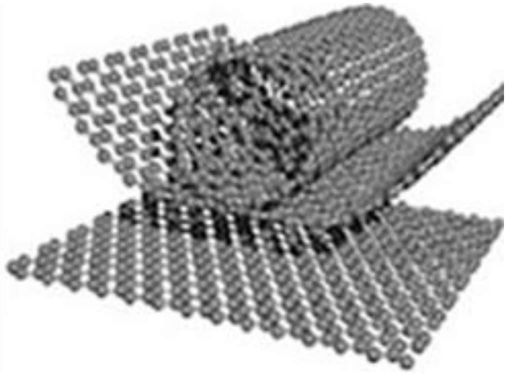
β : *enhancement fator*

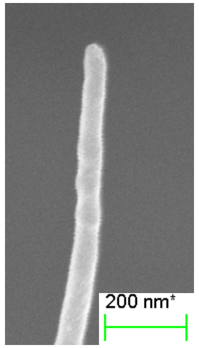
Ideal field emitter described by Utsumi



[Utsumi1991]

Multi-wall carbon nanotubes : Metallic tips with a high aspect ratio



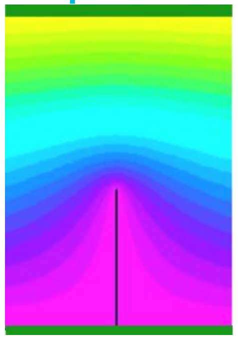


One single MWCNT : ~100 µA

[Minoux2005]

Introduction to CNT electron sources : Carbon nanotubes as field emitters

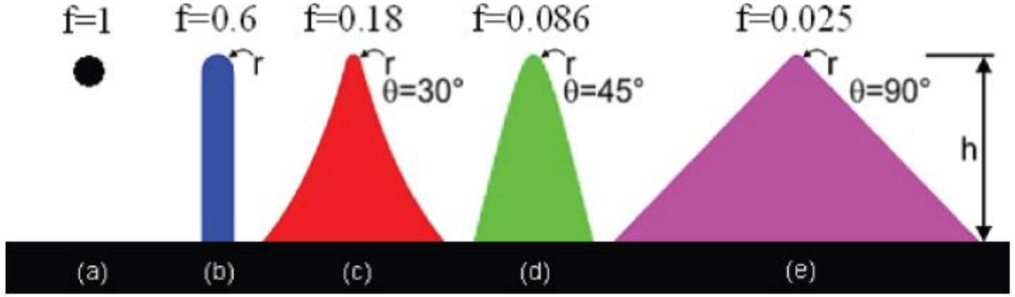
Tip effect



$$F_{tip} = \beta F_{ext}$$

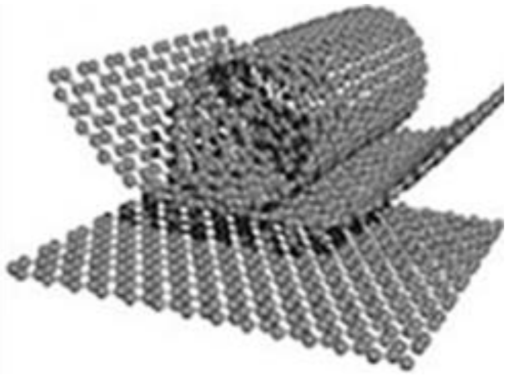
F : *electric Field*
β : *enhancement fator*

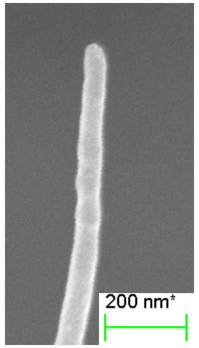
Ideal field emitter described by Utsumi



[Utsumi1991]

Multi-wall carbon nanotubes : Metallic tips with a high aspect ratio

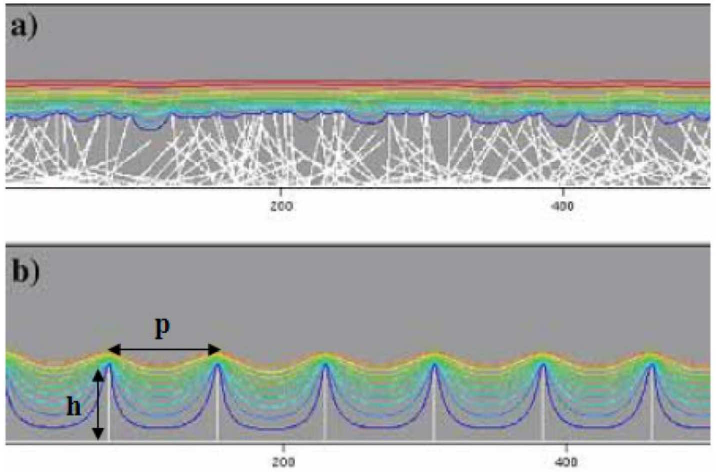




One single MWCNT : ~100 µA

[Minoux2005]

Need of CNT array to obtain useful cathode current densities : electrostatic screening



[Milne and al.2004]

Ideal CNT array

- MWCNT
- Carbon nanotubes vertically aligned → PECVD
- Diameter and height controlled
- Balance between the number of emitters and the effective field-enhancement factor

emitter density

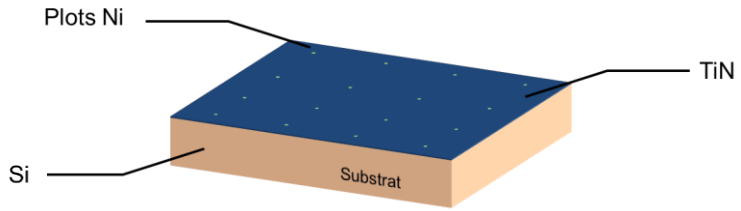
effective field-enhancement factor

[Utsumi1991]: T. Utsumi, IEEE Transactions on Electron Devices, 38(10), 2276-2283 (1991)
[Milne and al. 2004]: J. Mater. Chem. (2004) 14 (6): 933–943
[Minouxand al. 2005]: Nano Lett., 5(11), 2135-2138 (2005)

03 Cathode fabrication and I(V) characterization → > 1 A / cm^2

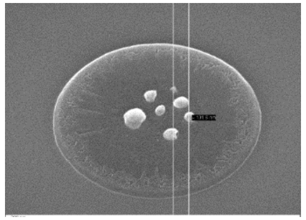
> Fabrication

The substrate
Emission surface : few mm^2

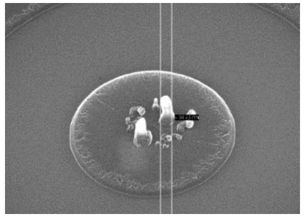


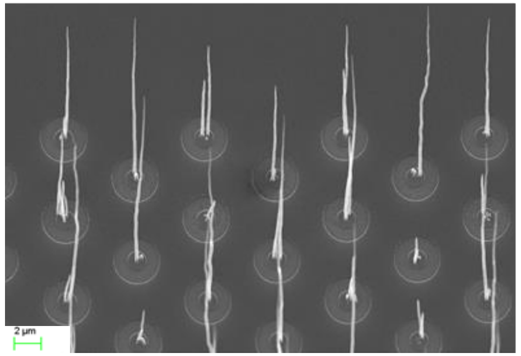
Plasma-enhanced chemical vapor deposition (PECVD)

Ni



Nucleation



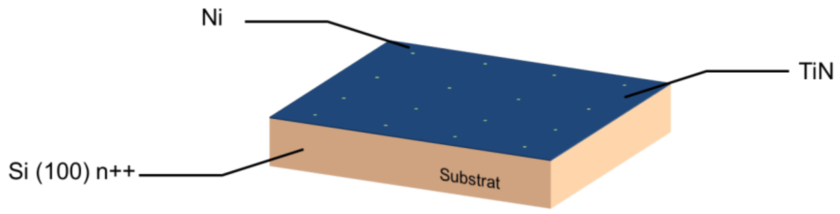


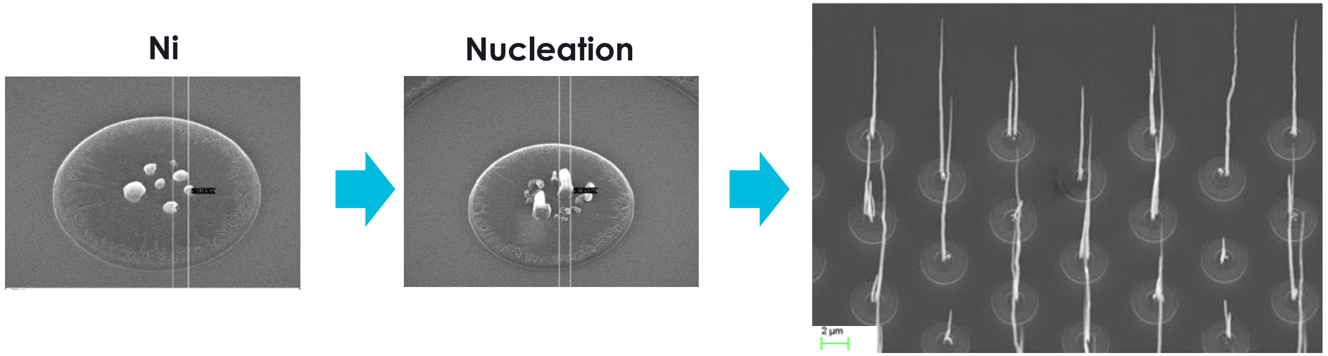
03 Cathode fabrication and I(V) characterization → > 1 A / cm²

> Fabrication

Plasma-enhanced chemical vapor deposition (PECVD)

The substrate
Emission surface : few mm^2





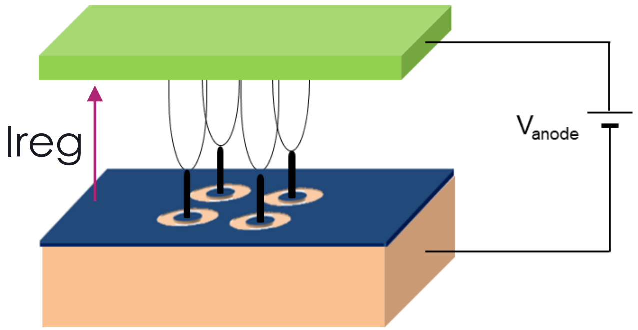
> Characterization

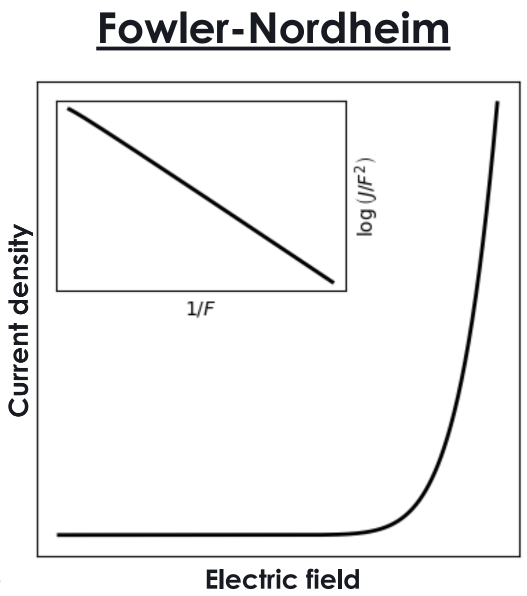
Current regulation mode : Bias adapted to correct the current setpoint

Dynamic Vacuum conditions : ultra-high vacuum (UHV) ~1 × 10^{-9} mbar

Distance between cathode-anode : few hundreds µm

Pulses widths : hundred µs

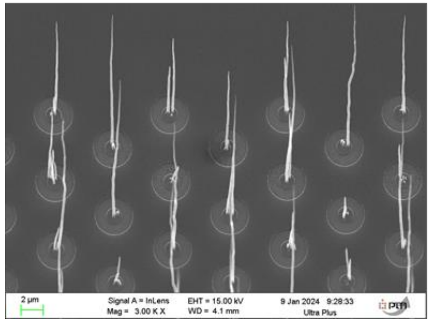




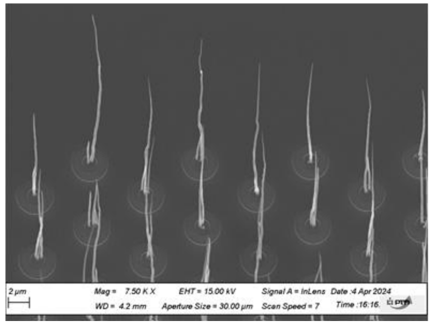
Cathode fabrication and I(V) characterization → > 1 A / cm²

Plasma-enhanced chemical vapor deposition (PECVD) enables precise control over the growth, morphology, and electrical emission properties of CNT arrays

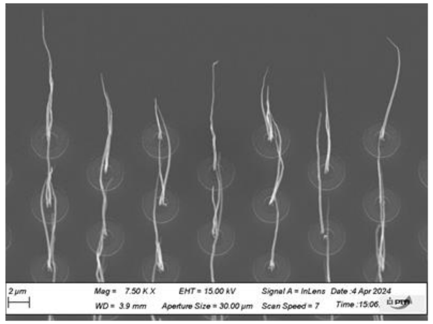
Cathode 1



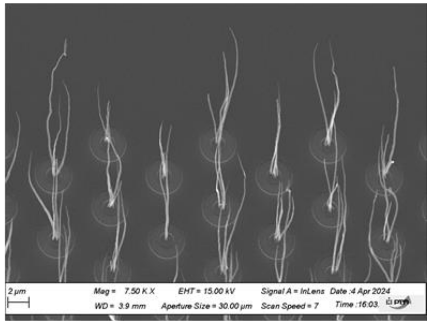
Cathode 2



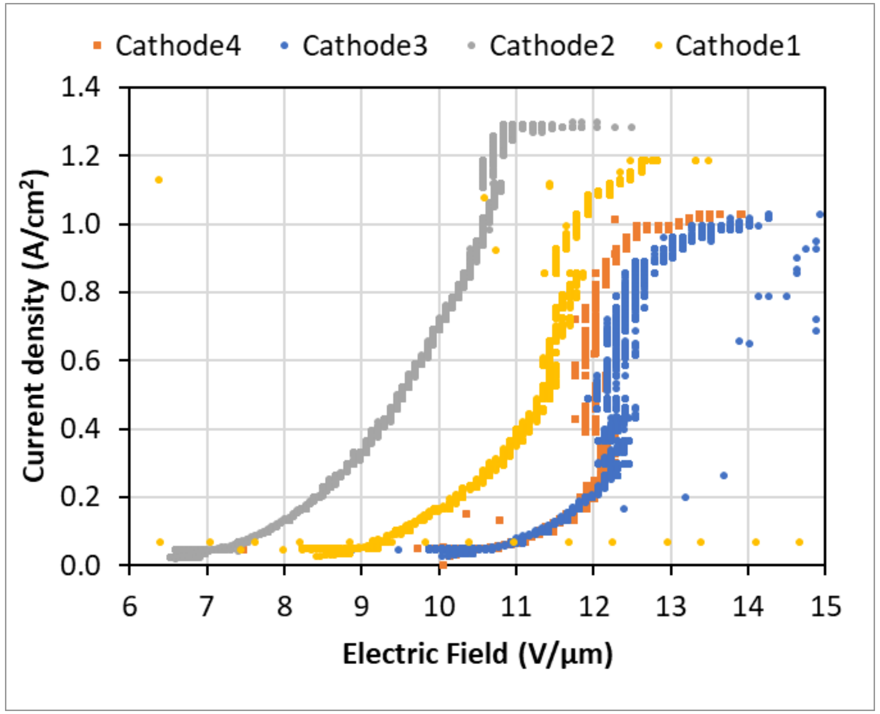
Cathode 3



Cathode 4



Maximal Current Measurements until cathode failure



The fabrication process from substrate to characterization allows us to obtain density currents above 1 A/cm²

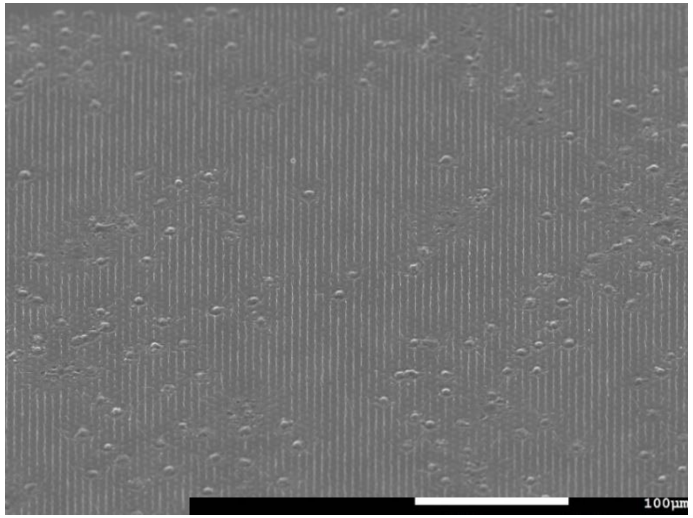
Failure modes

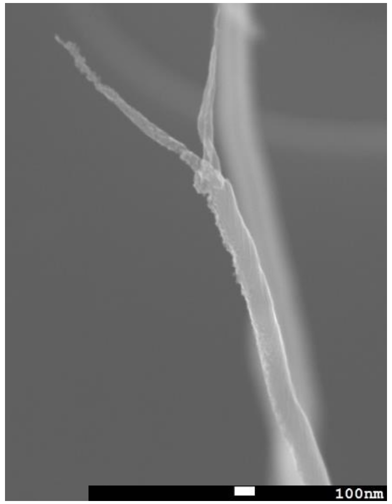
> **Failure modes observed after emission**

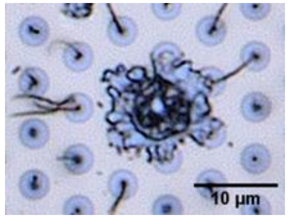
- Joule heating
- Electrical arcing and discharge

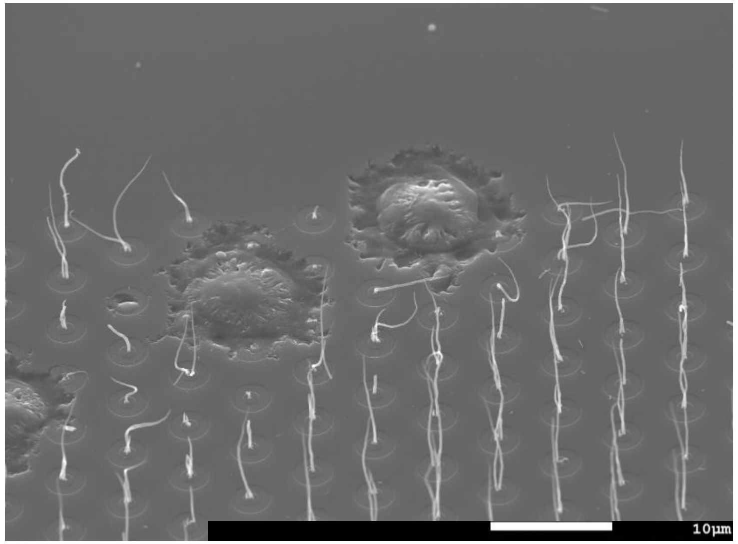
> **Defaults**

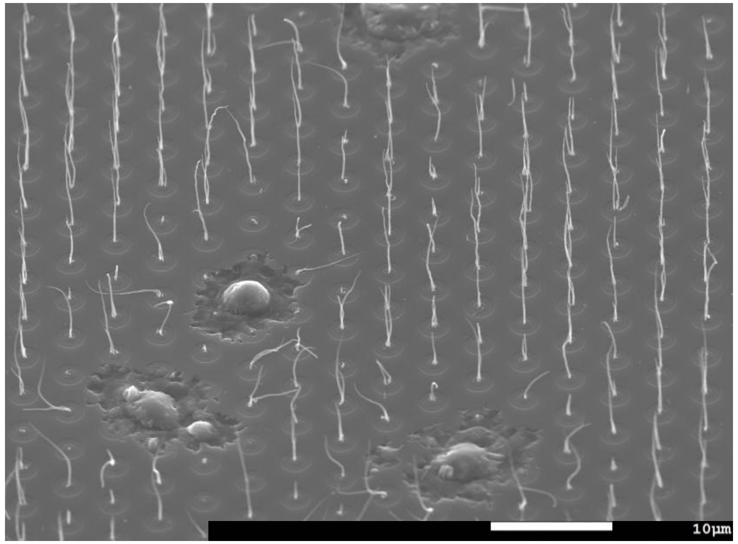
- Contact failure between CNT and substrate
- Structure imperfections

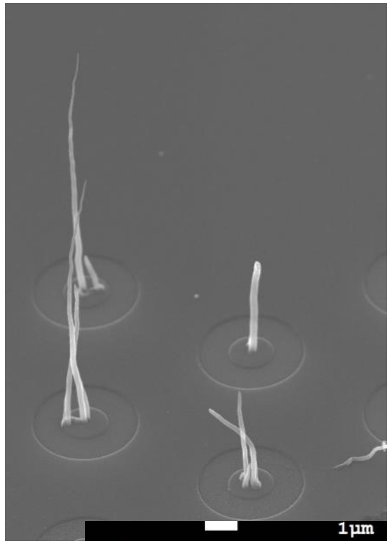










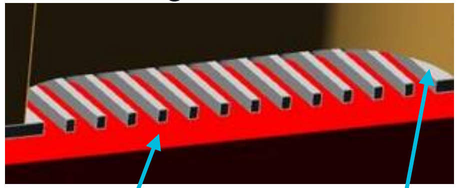


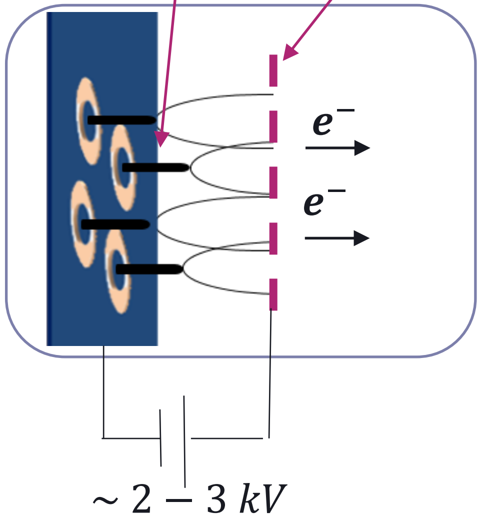
05 Electron gun CNT based : Ageing results

> **CNT integration on an electron gun**

- Grid as electrode extraction

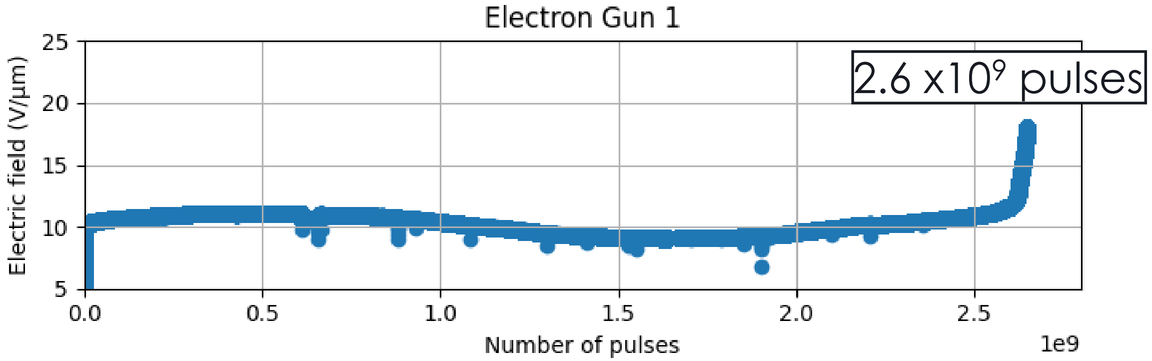
Electron gun cross-section

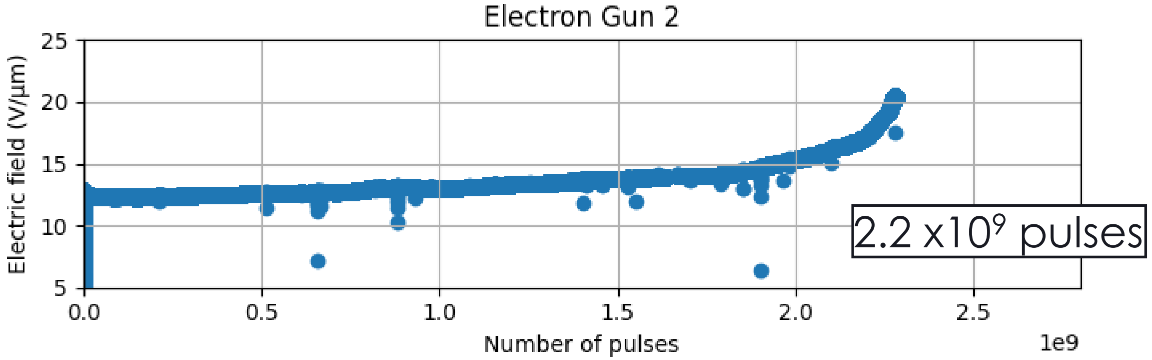




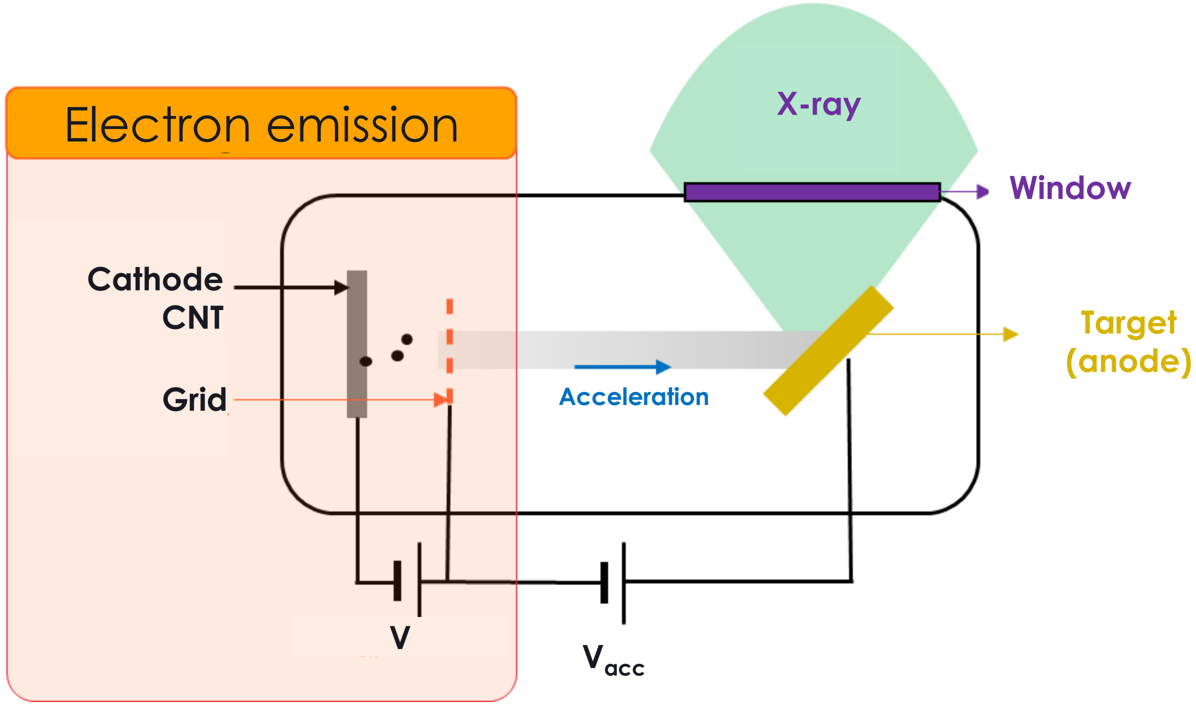
> **Electron gun ageing results**

- Stressful lifetime test : twice product current





Lifetime > 1×10^9 pulses

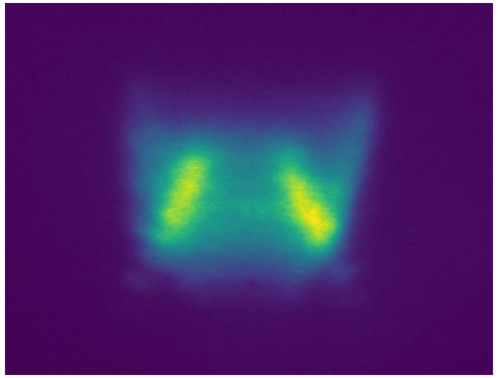


> **Pulsed emission**

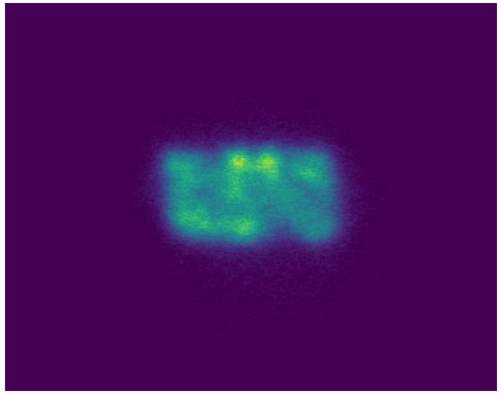
- Emission pulse width : few hundreds µs
- X-ray commutability

> **Focal spot**

- Thermionic cathode :
  - non homogenous focal spot



- Cold cathode : carbon nanotubes
  - Squared top-hat focal spot
  - Improved spatial resolution
  - Pulsed emission



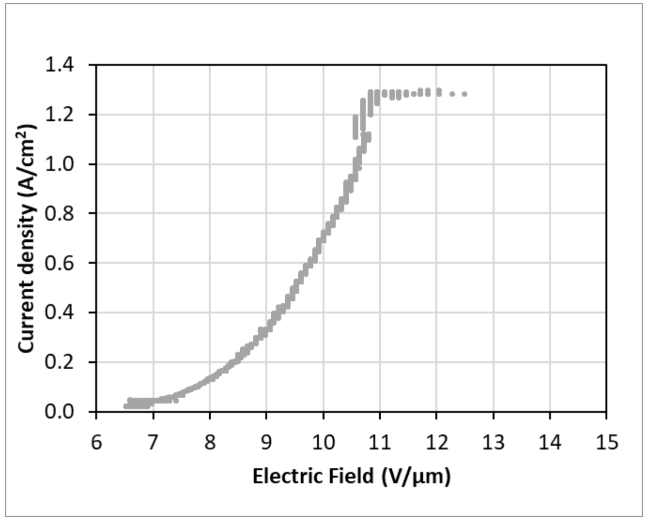
X-rays sources with improved spatial resolution in pulsed emission mode

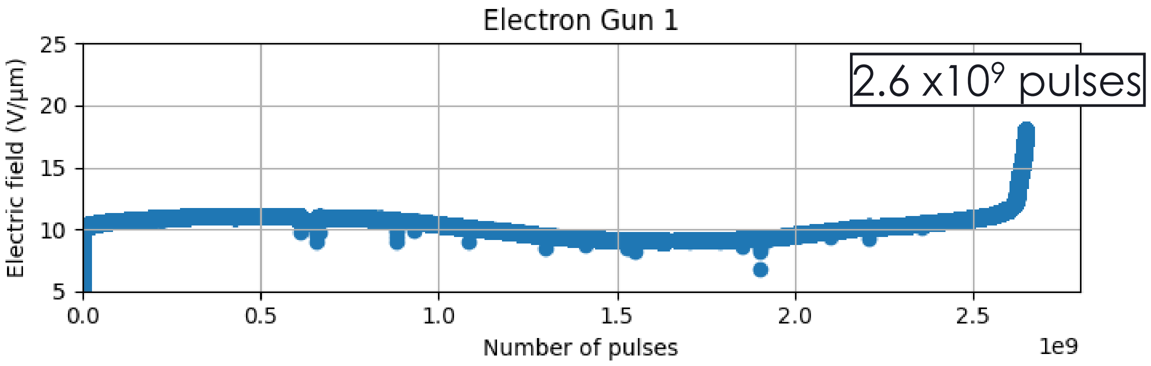
07 Conclusions

> Controlled CNT cathode fabrication enabling current emission above 1 A/cm²

> Lifetime tests exceeding the expected lifetime target > 1×10^9 pulses

> Pulsed X-ray source with improved spatial resolution





THALES
Building a future we can all trust

Thank you

Mariana TRUJILLO

Engineering Development

Mariana.trujilloarredondo@thalesgroup.com