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Thermal simulations for carbon nanotube and carbon fibre as wire scanners targets

Low Density Materials for Beam Instrumentation Workshop 20/06/23 – 21/06/23

Introduction

- Wire scanners are instruments used to measure transverse beam profile, using thin wire of tungsten, molybdenum or carbon fibre because of their good thermal, mechanical, and electrical properties.
- Low-density materials, such as carbon nanotube, can offer advantages.

- Focus on the thermal behavior of the wire:
  - Thermal modeling: PyTT (Python Thin Target) simulation code from A.Navarro and M.Sapinski
    - Physical model
    - Benchmarking
  - Comparison of the thermal behavior of carbon fibre (CF) and carbon nanotube (CNT) wires:
    - 2 different sets of beam parameters :
      - PSI Main ring cyclotron beam
      - HL-LHC beam

I) PyTT code

II) Wire signal benchmarking

III) Comparison of thermal simulation between carbon fibre and carbon nanotube wire scanners for PSI and HL-LHC beam parameters

Thermal modeling: PyTT simulation program

- Modified version of PyTT Package from A.Navarro and M.Sapinski [1,2,3]
- Reproduce the **thermal evolution** of thin target detectors
- When the beam interacts with the wire, the energy deposition leads to a fast increase of the temperature but several cooling process are also taken into account.
- The thermal evolution of the wire is described by the **heat equation**:

$$\left(\frac{\partial T}{\partial t}\right)_{Tot} = \frac{\Phi(x,y,t)}{Cp(T)} \cdot \frac{dE}{dx}$$ ← **Beam heating**

$\Phi(x, y, t)$ [cm^{-2} s^{-1}]: Flux of particles
$\frac{dE}{dx}$ [MeV cm^{2} g^{-1}]: Energy loss from Beth Bloch without δ électrons (conservative)

Radiative cooling → $$- \frac{S \cdot \sigma_{SB} \cdot \epsilon(T) \cdot (T^4 - T_0^4)}{V \cdot Cp(T) \cdot \rho}$$

Conductive cooling → (neglected because it is weak) $$- \frac{k(T)}{Cp(T) \cdot \rho} \cdot \frac{\partial^2 T}{\partial^2 y}$$

Thermionic cooling → $$-S \cdot \left(\phi + \frac{2K_B T}{Q_e}\right) \cdot \frac{J_{Th}(T)}{V \cdot Cp(T) \cdot \rho \cdot Q_e}$$

- The program also allows to compute the wire signal:
  - **Secondary electron emission** current with **Sternglass** formula
  - **Thermionic electron emission** current with **Richardson-Dushman** formula

[1]: A. Navarro, *Understanding Secondary Emission Processes and Beam Matter interactions for Optimization of Diagnostic Wire Grid System in Particle Accelerators*, PhD Thesis, 2022
[2]: M. Sapinski, *Model of Carbon Wire Heating in Accelerator Beam,* CERN-AB-2008-030 BI, 2008
[3]: A. Navarro, *PyTT GitHub*, URL: https://github.com/navarrof/PyTT

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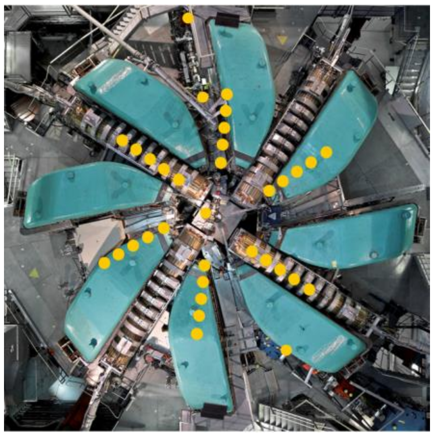
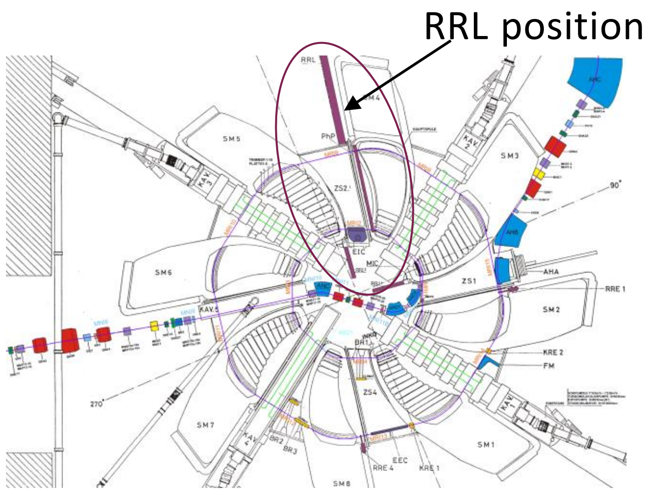
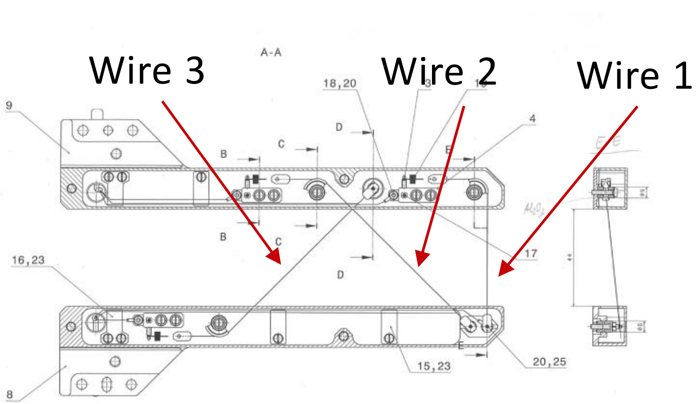
PSI's Main Ring Cyclotron Radial Probe (RRL)

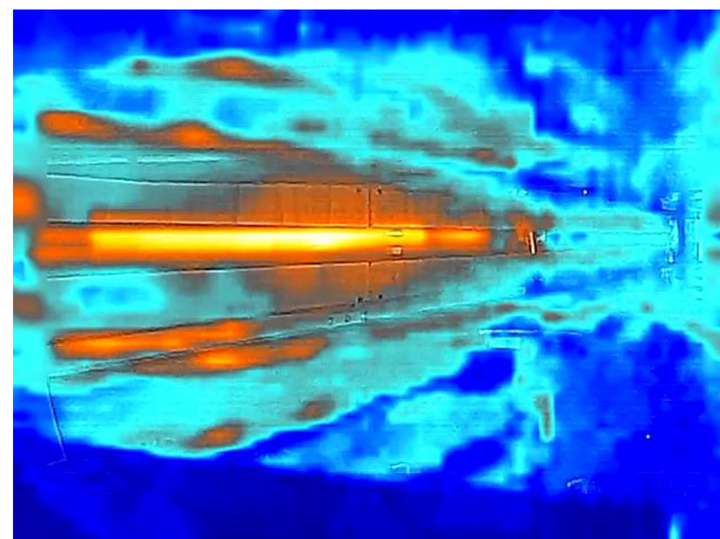
- **PSI's Main Ring Cyclotron Radial Probe** (RRL): wire scanner which is able to scan all the orbits along the cyclotron radius (2.5m) by measuring secondary emission current



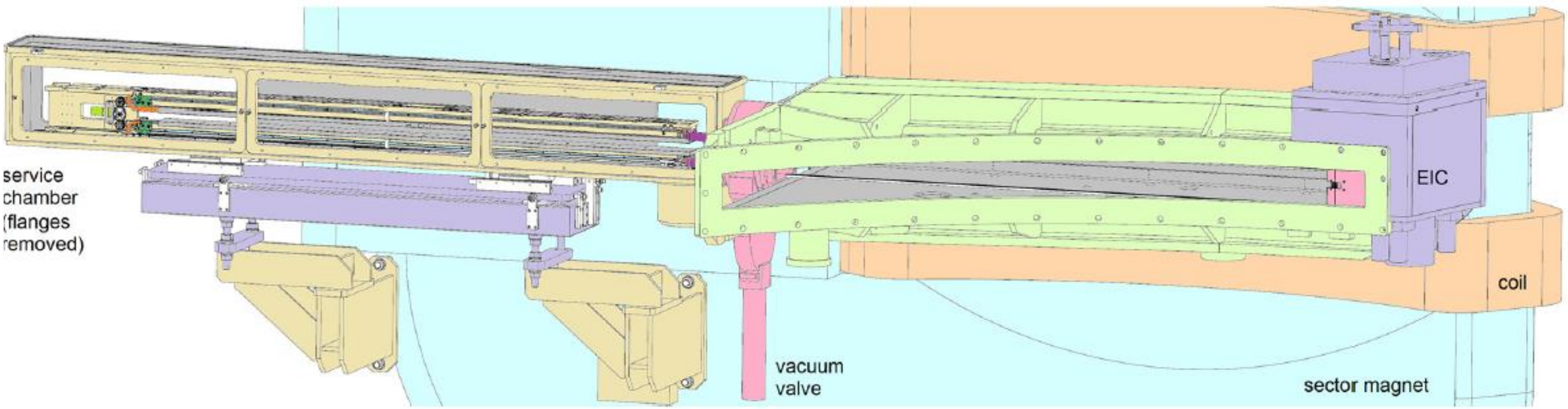




3 wires made of carbon fibre with 2.1 g/cm3 density, 34 µm diameter and 3 cm/s speed

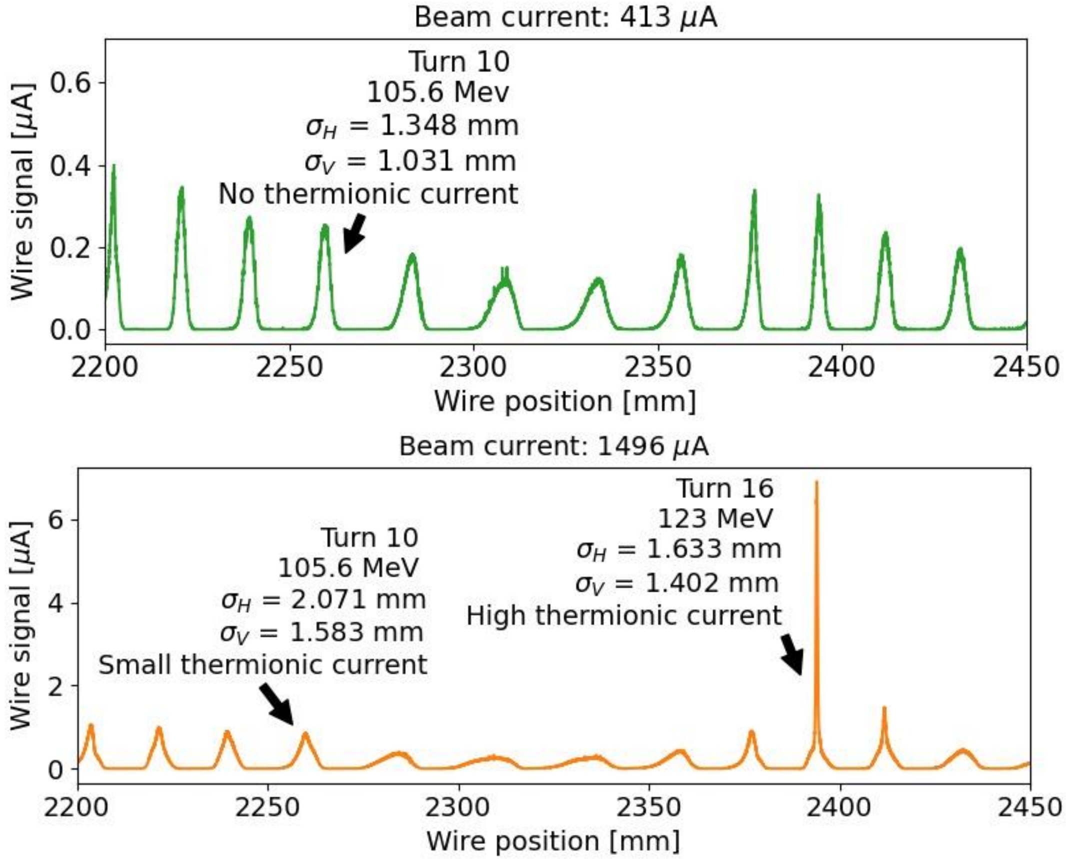


PSI's Main Ring Cyclotron Radial Probe (RRL)



RRL's Measurements

- 3 cases are studied for wire 1 with different thermionic current:



Vertical beam size derived from tilted wires

Assuming the beam sizes as a a function of the beam current goes like [1]:

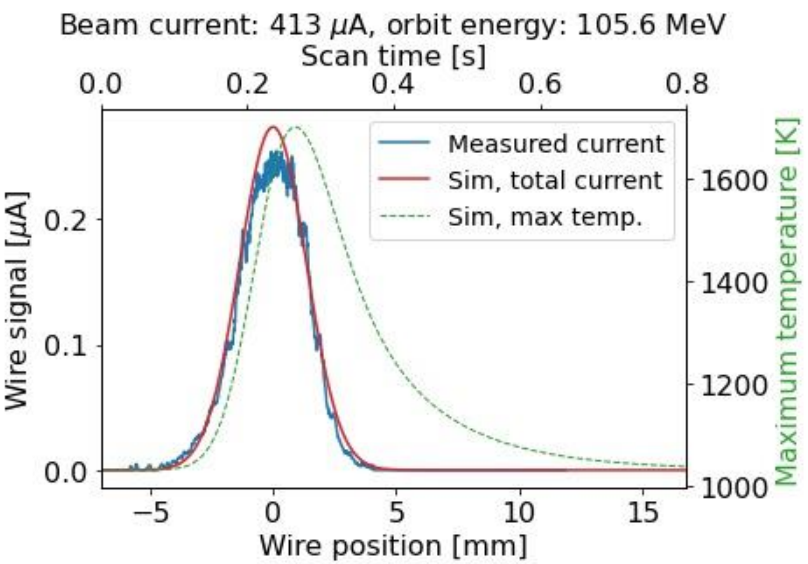
$$\sigma_{H,V}(I_{beam}) = aI_{beam}^{\frac{1}{3}}$$

with a, a constant determined with low current profile

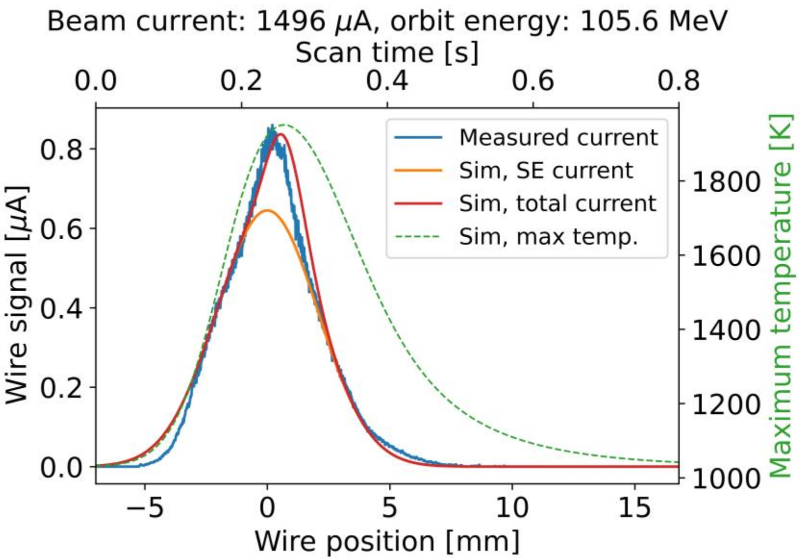
- Comparison of RRL's measurements with simulations
- Benchmark of the wire signal because it is very difficult to benchmark the temperature

[1] C. Baumgarten, H. Zhang, priv. comm

Benchmarking of the wire signal



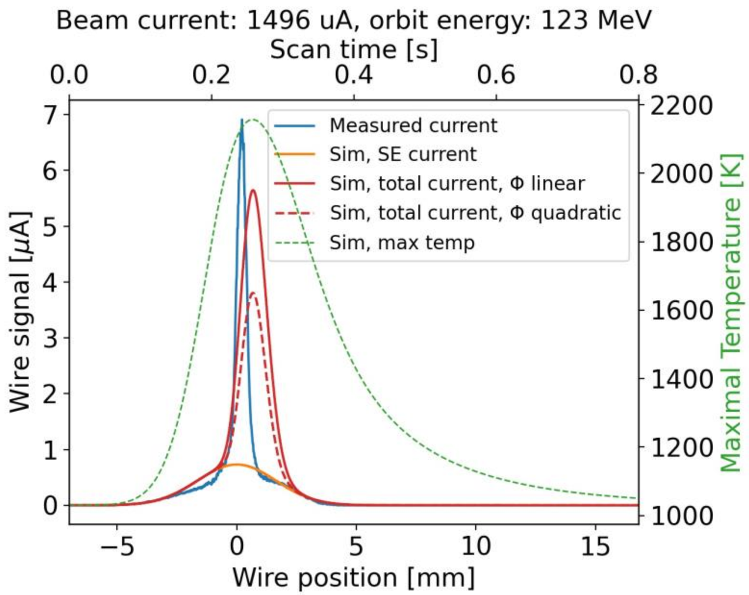
No thermionic current: wire signal well reproduced (slightly higher in simulation)



Small thermionic current: accurately reproduced

More detailed study:
M. Sapinski, M. Boucard, *Dealing with Thermionic Emission in Wire Scanners based on Secondary Electron Emission*, THPL150, in Proc. of International Particle Accelerator Conference (IPAC23), Venice, Italy, May 2023

Benchmarking of the wire signal



Higher thermionic current: discrepancy between simulation and measurements which can come from:

- Sensitivity to parameters like **emissivity** and **work function** for which the temperature dependency is poorly known
- Other phenomena that are not taken into account by PyTT like **build-up of space charge** and **increase of the electron reflection coefficient**

Previous benchmarking has been done in Navarro's thesis [1](see slides in Annexes) for SEM grid but it is more speculative (what is observed could be an effect other than the thermionic current)

More detailed study:
M. Sapinski, M. Boucard, *Dealing with Thermionic Emission in Wire Scanners based on Secondary Electron Emission*, THPL150, in Proc. of International Particle Accelerator Conference (IPAC23), Venice, Italy, May 2023

[1] A. Navarro, *Understanding Secondary Emission Processes and Beam Matter interactions for Optimization of Diagnostic Wire Grid System in Particle Accelerators*, PhD Thesis, Universitat Politècnica De Catalunya and CERN, 2022

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I) PyTT code

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PSI Main Ring Cyclotron and HL-LHC beams parameters

Beam	PSI turn 10	PSI turn 16		HL-LHC at beam injection
Beam energy [MeV]	105.6	123		450000
Energy loss [MeV cm^2 g^{-1}]	6.231	5.575		1.27
Beam current [mA]	1.496	1.496	5.000 (ADS intensity)	270 (25% of the nominal current)
σ_H [mm]	2.071	1.633	2.44	0.645
σ_V [mm]	1.583	1.402	2.09	0.645

PSI plans to reach 3.0 mA.

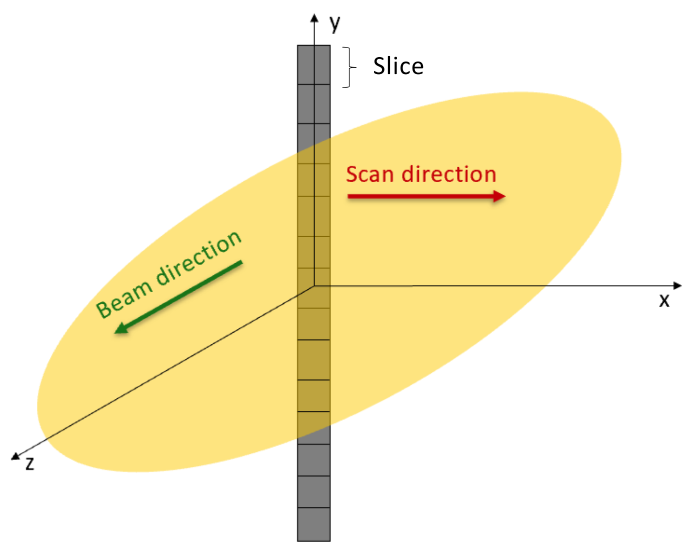
ADS [1]: proton accelerator → high-intensity neutron beam by spallation → transmutes Thorium into Uranium isotopes → release energy

Only short-living nuclear wastes are produced

[1] Accelerator-Driven Nuclear Energy, URL: https://world-nuclear.org/information-library/current-and-future-generation/accelerator-driven-nuclear-energy.aspx World Nuclear Association Website

Wire parameters for thermal simulation

- Simulation parameters:
  - Wire:
    - 2 cm long
    - At PSI main ring cyclotron: **3 cm/s** speed
    - At HL-LHC: **1 m/s speed**
    - 34 µm diameter
    - Materials: carbon fibers or carbon nanotubes wire
  - Resolution of slices:
    - PSI: 0.25 mm
    - HL-LHC: 0.10 mm
  - Number of steps: 10000
- Crucial parameters in thermal simulations for CF and CNT:
  - Density
  - Work function
  - Emissivity
  - Specific heat



•Buyco, E. H.

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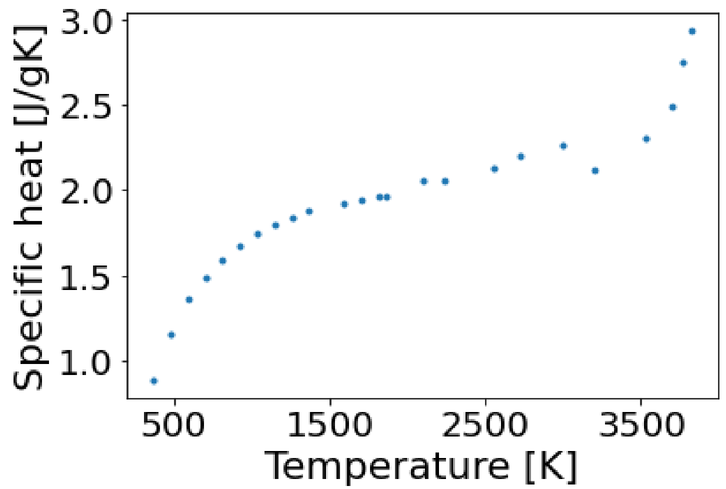
Density and specific heat

- Density:
  – Carbon fibers: 2.1 g/cm^3
  – Carbon Nanotubes:
    – 1.0 g/cm^3 (experiment at CERN [1])
    – 0.2 g/cm^3 (anticipated)

- Specific heat:
  – Should be the same for CF and CNT
  – Depends on the temperature
  – Values are taken from:
  Thermophysical Properties of Matter - the TPRC Data Series. Volume 5. Specific Heat - Nonmetallic Solids, Touloukian, Y. S. Buyco, E. H., 1970



[1] Alexandre Mariet, *Study of the effects of copper-coating and proton irradiation at 440 GeV on the mechanical properties of carbon nanotube wires for particle beam instrumentation at CERN*, PhD thesis, Université de Franche-Comté and femto-st, Besançon, May 2023

Emissivity and work function

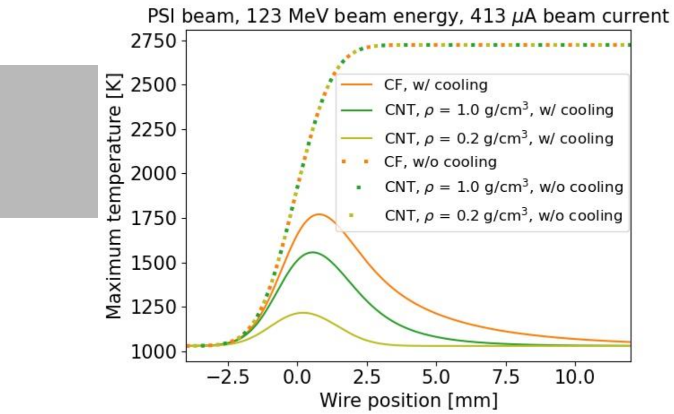
- Emissivity
  - Similar for CF and CNT: around **1**
  - Surface of CNT not really **smooth** → can **lower the emissivity**
  - Lower emissivity → lower radiative cooling

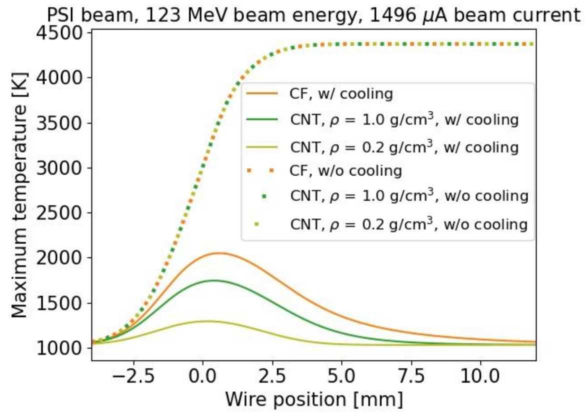
- Work function
  - Similar for CF and CNT: around **5 eV**
  - The **lack of smoothness** of the surface can **lower the work function** of the CNT
  - Lower work function → stronger thermionic current
  - Literature suggests that the work function **decreases with the temperature** [1,2]→ stronger thermionic cooling for high temperature

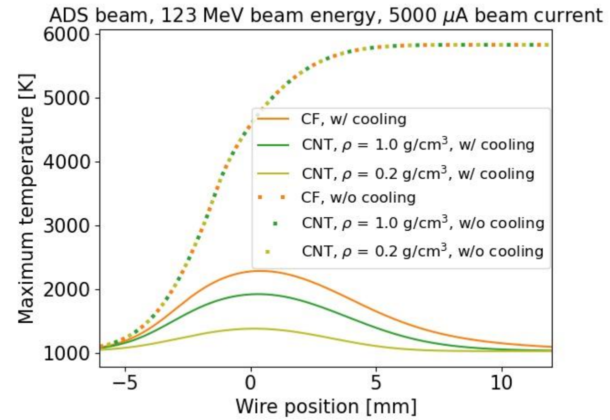
[1]H. Zhu, C. Masarapu, J. Wei, K. Wang, D. Wu, B. Wei, *Temperature dependence of field emission of single-walled carbon nanotube thin films*, Physica E: Low-dimensional Systems and Nanostructures, Volume 41, Issue 7, 2009, Pages 1277-1280
[2]R. Rahemi, D. Li, *Variation in electron work function with temperature and its effect on the Young's modulus of metals*, Scripta Materialia 99, 2015, Pages 41-44

With and without cooling thermal behaviour

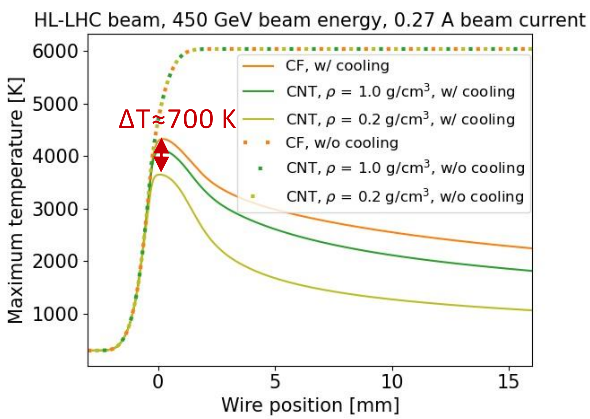
PSI







HL-LHC



The heating is really fast, maximum temperature depends on heat capacity and **not** density: $\left(\frac{\partial T}{\partial t}\right)_{Tot} = \frac{\Phi(x,y,t)}{Cp(T)} \cdot \frac{dE}{dx}$ ← [MeV cm^2 g^{-1}]

… but wires are really small objects → cooling is really fast

Temperature rises are the same for CF and CNT but the cooling is faster for CF because of the smaller amount of material

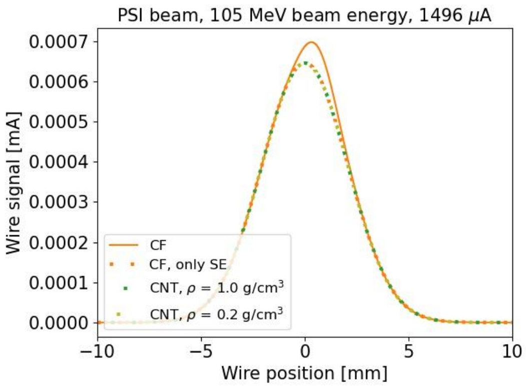
Less materials → cool faster (like when you take a spoonful of hot tea in a cup to cool it down more quickly)

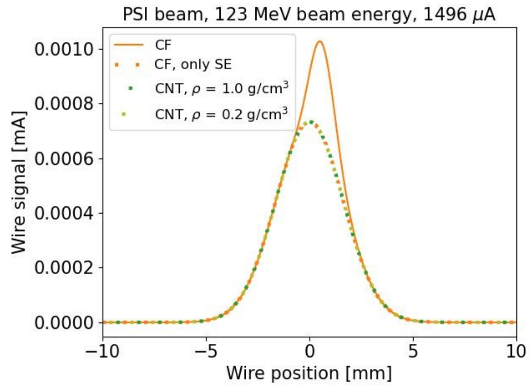
$$-\frac{S \cdot \sigma_{SB} \cdot \epsilon(T) \cdot (T^4 - T_0^4)}{V \cdot Cp(T) \cdot \rho}$$ Radiative cooling

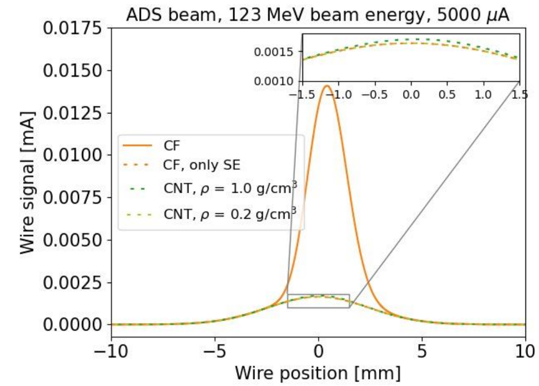
$$- S \cdot (\phi + 2K_B T) \cdot \frac{J_{Th}(T)}{V \cdot Cp(T) \cdot \rho}$$ Thermionic cooling

PSI and HL-LHC wire signal

PSI

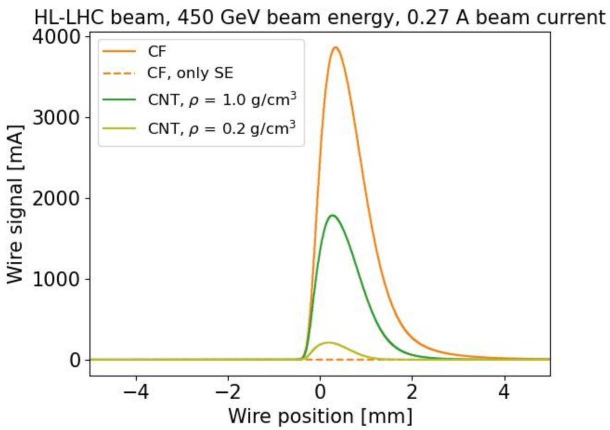






No thermionic emission (or really small) for CNTs with PSI beam parameters.

HL-LHC



Huge thermionic peak for HL-LHC beam → unexploitable measurements → reasons why the SE current is not used for high-energy beams.

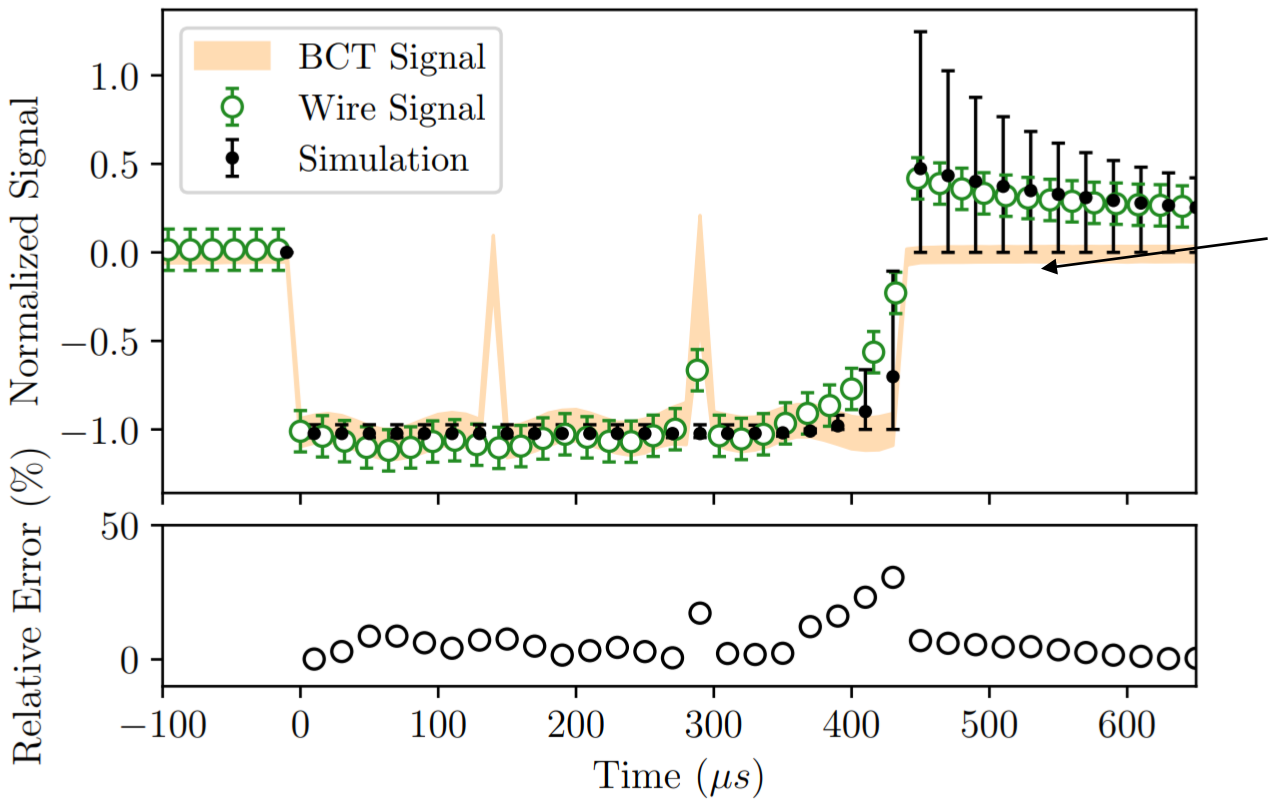
Other phenomena like space charge can occur and are not considered by PyTT.

Conclusion

- PyTT is a tool for estimating the **thermal behavior of thin targets**
- Benchmarking using secondary and thermionic emission is positive
- Discrepancy observed for high thermionic current probably due to space charge from generated electrons
- Simulations show **high sensitivity on materials parameters:**
  - Temperature dependence of work function and emissivity

- Due to low-density materials, the cooling processes are faster → **temperatures reached by CNT wires are lower than those reached by CF wires**
- **Complete suppression** of thermionic emission current for PSI beams

Annexes: Previous benchmarking [1]

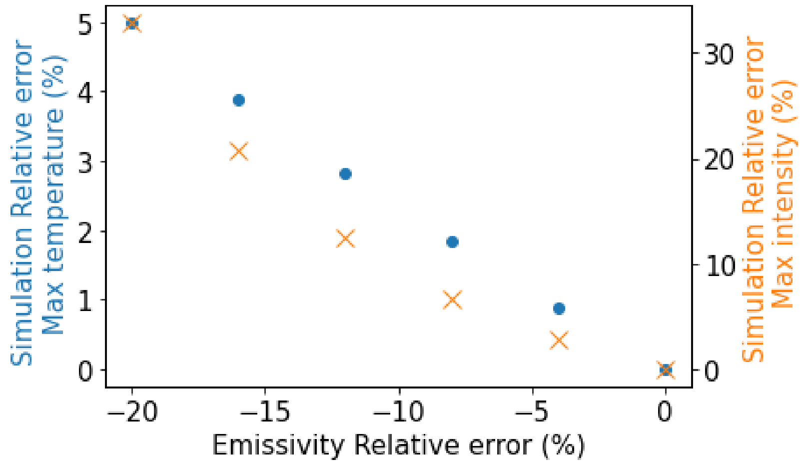


The current measured by the detector at that time does not come from the beam: thermionic current

Simulations and measurements in good agreement

[1] A. Navarro, *Understanding Secondary Emission Processes and Beam Matter interactions for Optimization of Diagnostic Wire Grid System in particle Accelerators*, PhD Thesis, Universitat Politècnica De Catalunya and CERN, 2022

Annexes: Simulation uncertainities

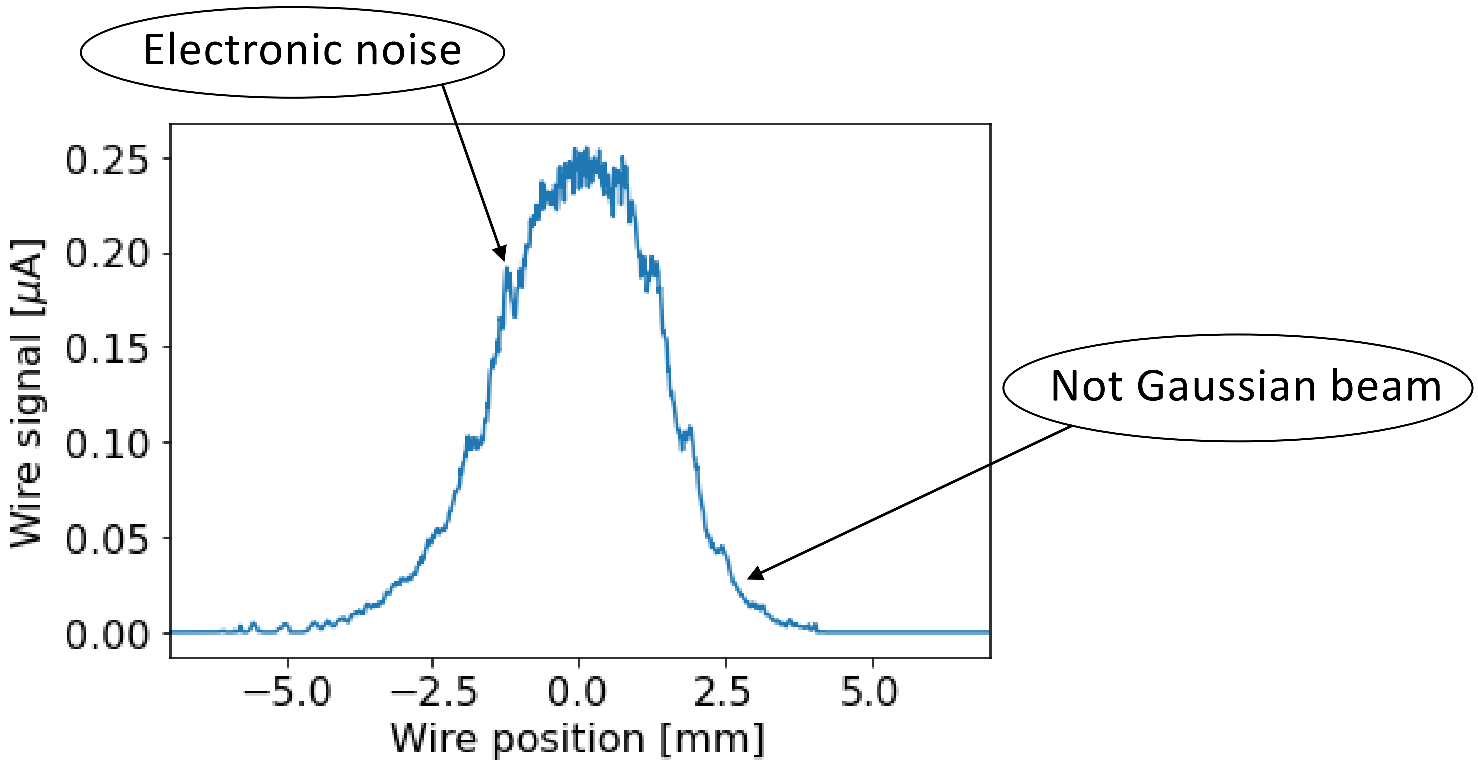


PSI main ring cyclotron beam, 105.6 Mev beam energy, 1496 µA beam current.
Initial work function : 5 eV
Initial emissivity : 1

For emissivity and work function, relative errors are **bigger for intensity than for temperature**

The simulated intensity is high-sensitive to emissivity and work function change, especially for work function for which the relative error **grows exponentially** (due to the exponential term of thermionic current).

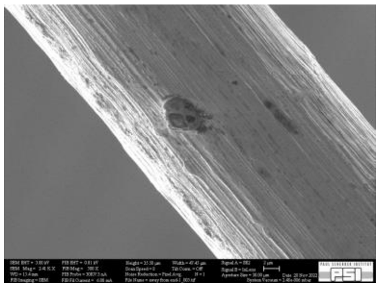
Annexes: RRL measurements uncertainties

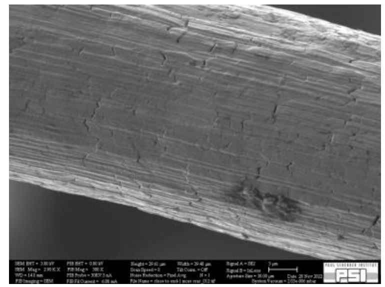


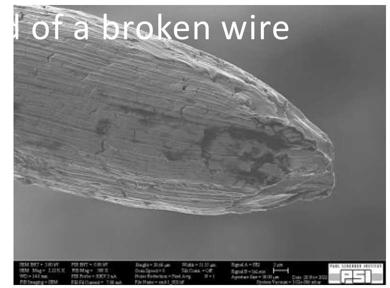
The response function of MESON acquisition card

Annexes: Influence of the material surface on work function

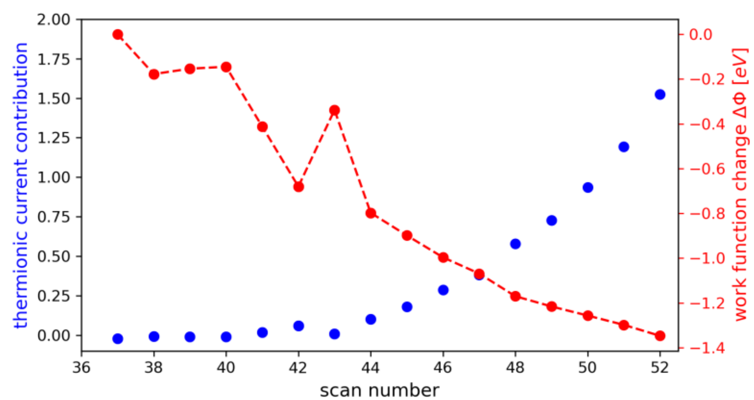
Ductile damage of a Molybdenum wire due to multiple scans [1]







Passages through the beam **damage the wire**, the smoothness of the wire decreases → increase of the **thermionic emission** → explained by a decrease in the **work function**.



[1] M.Sapinski, *About the Damage Mechanisms of Thin Targets Exposed to High-power Particles Beams*, THPL151, in Proc. of International Particle Accelerator Conference (IPAC23), Venice, Italy, May 2023

Annexes: The heat equation

$$\left(\frac{\partial T}{\partial t}\right)_{Tot} = \frac{\Phi(x,y,t)}{Cp(T)} \cdot \frac{dE}{dx} - \frac{S \cdot \sigma_{SB} \cdot \epsilon(T) \cdot \left(T^4 - T_0^4\right)}{V \cdot Cp(T) \cdot \rho} - \frac{k(T)}{Cp(T) \cdot \rho}\left(\frac{\partial^2 T}{\partial^2 x} + \frac{\partial^2 T}{\partial^2 y}\right) - S \cdot (\phi + 2K_B T) \cdot \frac{J_{Th}(T)}{V \cdot Cp(T) \cdot \rho \cdot Q_e}$$

With:

$\Phi(x, y, t)$ [cm^{-2} s^{-1}] the flux of particles

$Cp(T)$ [J K^{-1} g^{-1}] the specific heat

$\frac{dE}{dx}$ [MeV cm^2 g^{-1}] the energy loss

S the radiative surface

σ_{SB} = $5.67*10^{-8}$ W m^{-2} K^{-4} The stefan-Boltzmann constant

$\epsilon(T)$ [-] the emissivity

T_0 [K] the initial temperature

V volume of the wire slice

ρ [g cm^{-3}] the material density

$k(T)$ [W m^{-1} K^{-1}] the conductivity

ϕ [eV] the work function

K_B = $1.380649*10^{-23}$ m^2 kg s^{-2} K^{-1} the Boltzmann constant

$J_{Th}(T)$ [A] the thermionic current

Q_e = $1.602*10^{-19}$ C the elementary charge