EPFL

PAUL SCHERRER INSTITUT

MASTER THESIS
Thin targets in extreme conditions: probing high-brightness hadron beams

Manon Boucard

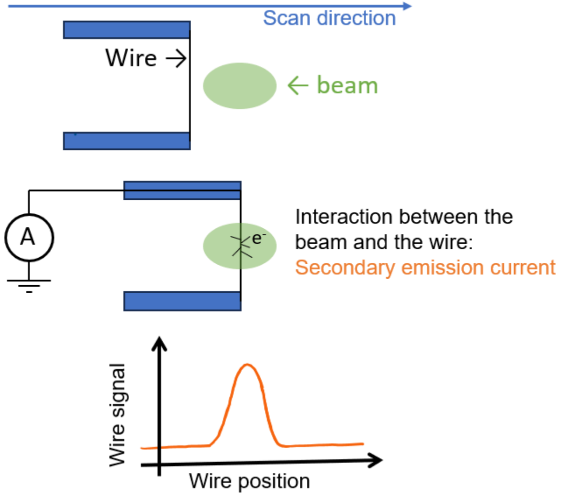
Supervisor: Dr. Mariusz Sapinski

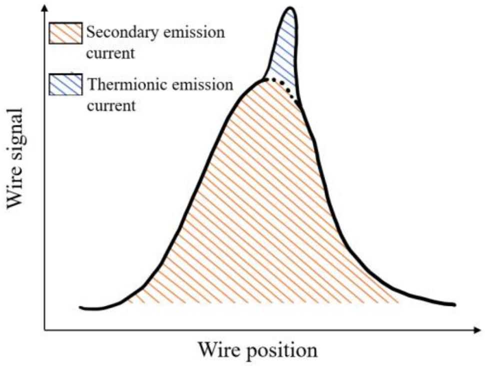
Responsible: Prof. Dr. Mike Seidel

21st September 2023

Motivation - Introduction

- Wire scanners are used to measure beam profile
- A thin target is moved through the particle beam
- The secondary electron emission is **proportional** to the beam profile
- When beam current increases → the temperature of the target increases → thermionic electron emission
- Not proportional to the particle density → **distorts the measured signal**





How to get rid of this thermionic emission? What are the solutions currently applied? How to improve wire scanners targets to avoid this disturbance?

PSI and HIPA

- **PSI**
  - Paul Scherrer Institute
  - Biggest research centre in Switzerland for natural and engineering sciences
  - Multi-disciplinary research institute

- **HIPA**
  - High-Intensity Proton Accelerator
  - Highest-power particle beam in Europe (1.4 MW)

- **HIPA's components:**
  - The proton source
  - Cockcroft-Walton DC acceleration (final energy: 870 keV)
  - Injector 2 cyclotron (final energy: 72 MeV)
  - Main Ring cyclotron (final energy: 590 MeV)

- **Applications:**
  - Muon physics
  - Neutron imaging


Photo: Mariusz Sapinski

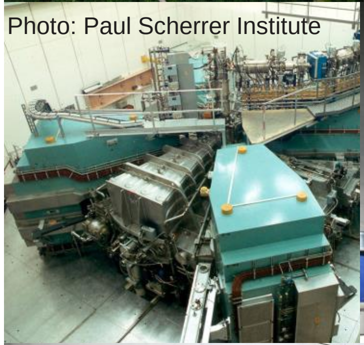


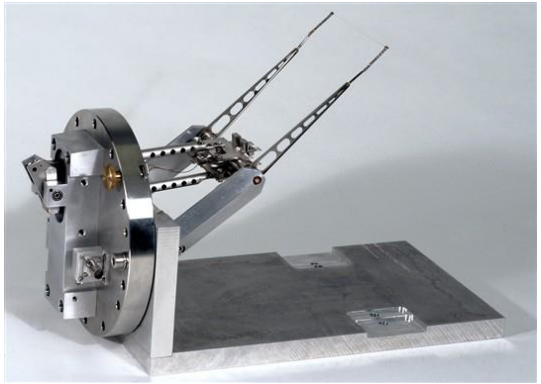
Photo: Paul Scherrer Institute


Photo: Paul Scherrer Institute

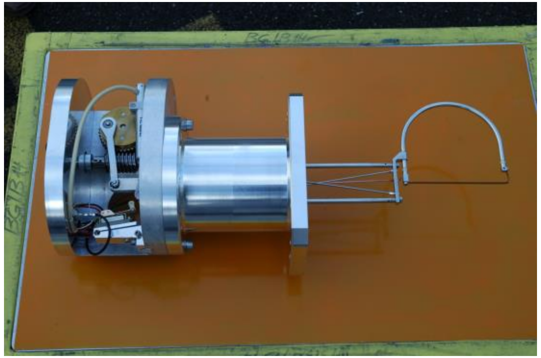

Photo: Paul Scherrer Institute

Wire scanners

- **Beam transverse profile measurements**
- Moving a **thin wire** (a few tens of microns) through the beam and measuring the effects of the interaction
- Two types of measurements:
  - Beam energy relatively small: profile reconstructed by using **the current generated by secondary electron emission (eV)**
  - Beam energy is higher: profile reconstructed by **detecting the high-energy particle shower (keV - MeV)**

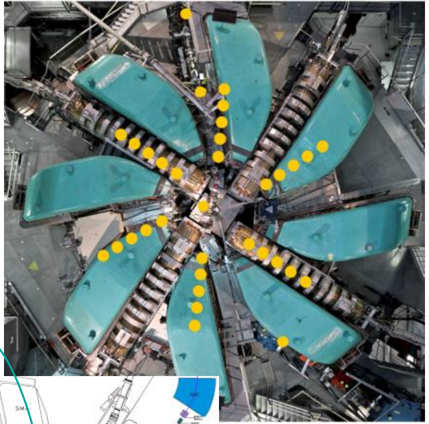


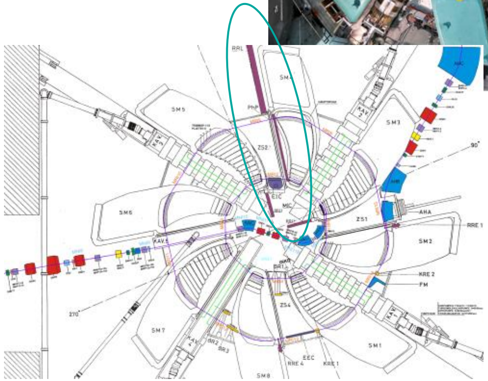
Rotational wire scanner
Photo: Maximillien Brice, CERN



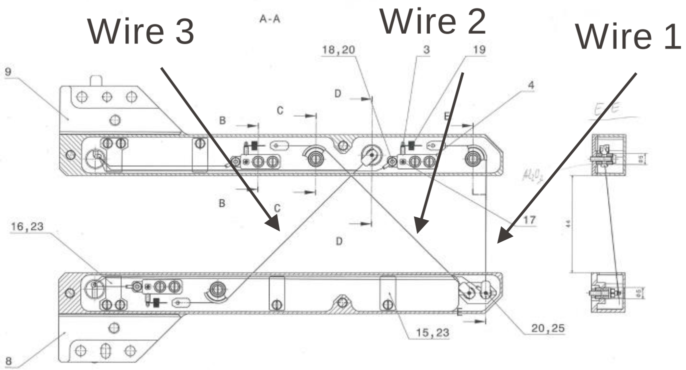
Another type of rotational wire scanner, «swinging» wire scanner
Photo: Paul Scherrer Institute

PSI's Main Ring Long Radial Probe: RRL



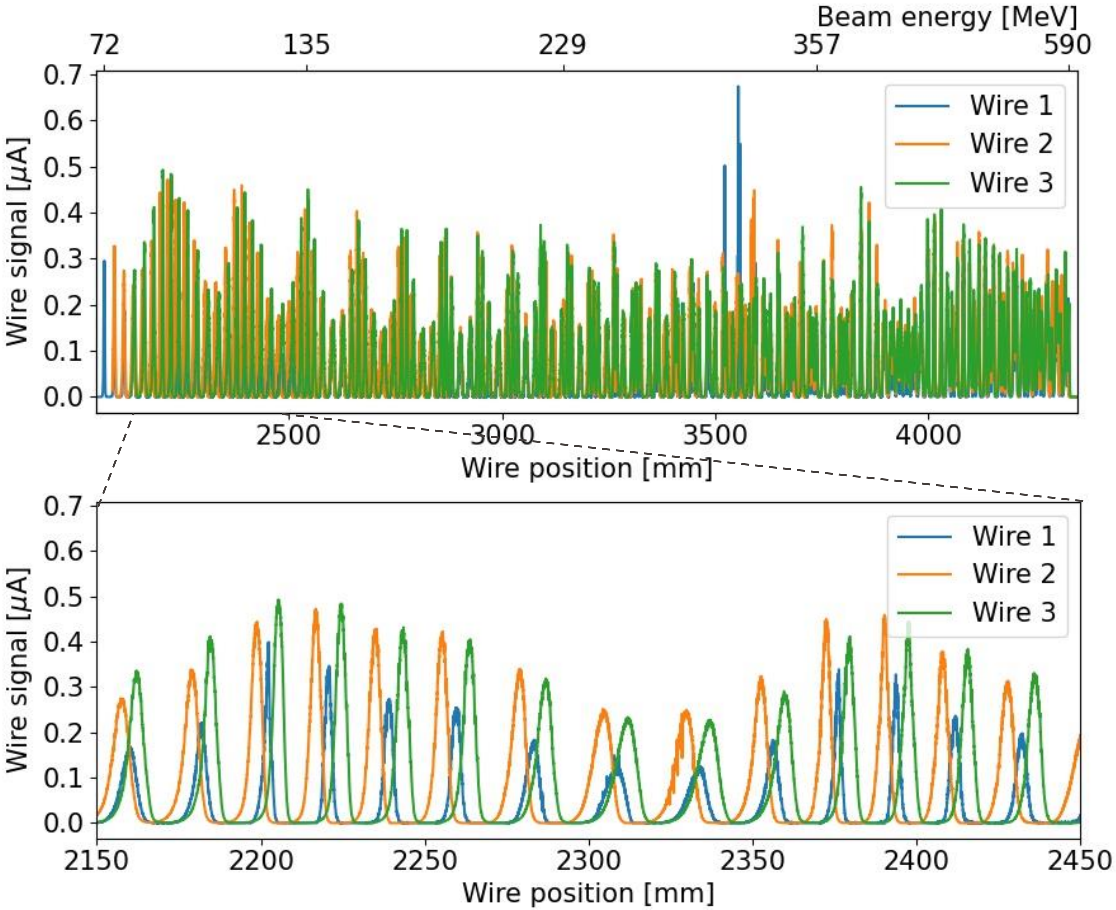


- Linear wire scanner placed in the main ring cyclotron of HIPA
- Special case: scan **all the orbits** along the ring cyclotron radius (2.048 m to 4.480 m)
- Most advanced probe and the newest one
- Profile reconstructed **with the wire current**



Wire in carbon fibre, 34 µm diameter, 3 cm/s speed

RRL's scans



Beam energy [MeV]
72
135
229
357
590
Wire 1
Wire 2
Wire 3
Wire signal [µA]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
2500
3000
3500
4000
Wire position [mm]
2150
2200
2250
2300
2350
2400
2450

The energy deposition

- Particle passing through matter: **losing its energy**
- Depends on the type of particle, the beam energy and the target material
- **Stopping power** → Bethe-Bloch Formula

$$\left\langle -\frac{\mathrm{d}E}{\mathrm{d}X} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- PSTAR database [1] (typically protons with 100 MeV kinetic energy in carbon have a 6.488 MeV cm^2 g^{-1} stopping power)

[1] S. Seltzer, Stopping-Powers and Range Tables for Electrons, Protons, and Helium Ions, NIST Standard Reference Database 124, en, 1993. doi: 10.18434/T4NC7P.

Wire heating model

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

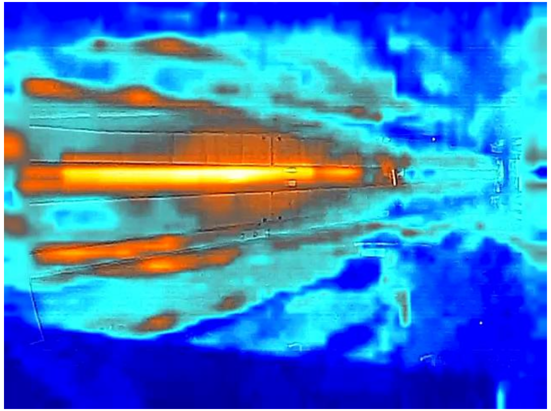
Beam heating: direct beam energy deposition

Radiative cooling: thermal radiation, dominant cooling process up to temperatures of about 2000 K

Conductive cooling: spatial temperature gradient, negligible due to the small diameter of the target

Thermionic cooling: electrons emitted when they reach a sufficient thermal energy to exceed the work function, dominant process for high-temperature

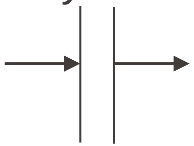
RF heating: coupling between the wire and the RF leakage in the machine, leads to wire temperature in range 530-1130 K. Makes the wire glow.



On the video: no beam, only RF heating

Wire current

- Secondary electron emission
  - Energy transferred by the proton beam to the electrons in the medium may be enough for them to escape
  - **SEY (Secondary Emission Yield):** Strenglass formula, number of electrons emitted by incident proton



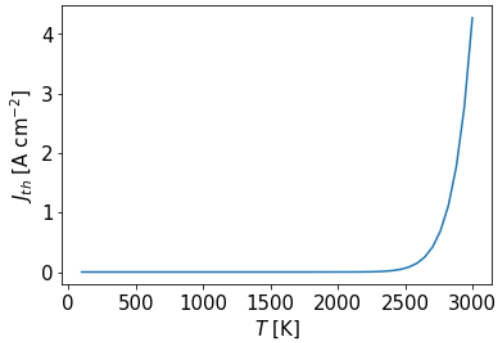
  - **Charge induced by one proton passing through a thin wire**

$$Q_{SE} = 2 \cdot \mathrm{SEY}$$

Proportional to the number of protons passing through the wire

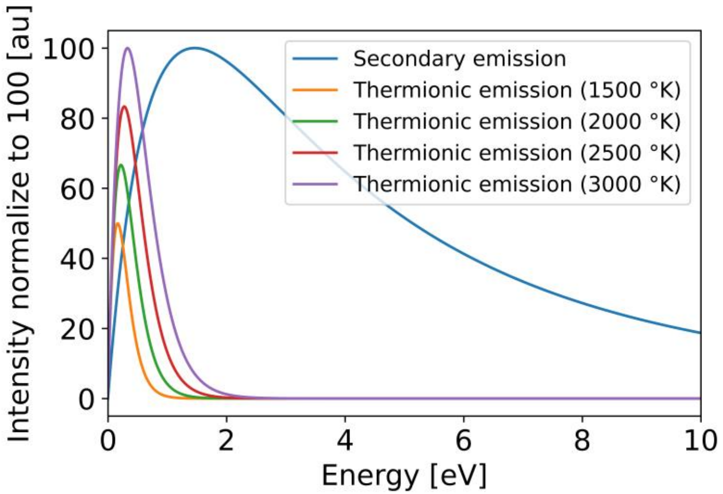
- Thermionic emission
  - Electrons that gain enough thermal energy **to break the work function** and escape
  - Richardson and Dushman formula:

$$J_{th} = A_R \cdot T^2 \cdot \exp\left(-\frac{\phi}{k_B T}\right)$$



Not proportional to the particle density

Energy distribution



Secondary emission: peak aroud 1-2 eV, high energy tail
Thermionic emission: peak lower than 1 eV, the peak position and the amplitude increase with temperature

- **Secondary emission:** not well described by theory, proportional to an approximate formula [1]:

$$f_{SE}(E) = \frac{E - E_F - \phi}{(E - E_F)^4}$$

- **Thermionic emission:** depends on the temperature, proportional to [2]:

$$f_{Th}(E) = \frac{E - \phi}{1 + \exp\left(\frac{E-\phi}{k_B \cdot T}\right)} \cdot H(E - \phi)$$

[1] M. S. Chung and T. E. Everhart, “Simple calculation of energy distribution of low-energy secondary electrons emitted from metals under electron bombardment,” Journal of Applied Physics, vol. 45, no. 2, pp. 707–709, Feb. 1974. doi:10.1063/1.1663306
[2] K. Uppireddi, T. L. Westover, T. S. Fisher, B. R. Weiner, and G. Morell, “Thermionic emission energy distribution from nanocrystalline diamond films for direct thermal-electrical energy conversion applications,” Journal of Applied Physics, vol. 106, no. 4, p. 043 716, Aug. 2009. doi: 10.1063/1.3204667.

PyTT

- PyTT [1]: **Py**thon **T**hin **T**arget, implemented by M. Sapinski and A. Navarro
- Simulates the thermal behaviour and the wire signal for thin targets
- Finite element method in 1D
- **Experimental validation** by comparing RRL measurements and PyTT simulations

[1] A. Navarro. "PyTT GitHub page https://github.com/navarrof/PyTT." (2022), [Online]. Available: https://github.com/navarrof/PyTT (visited on 07/08/2023).

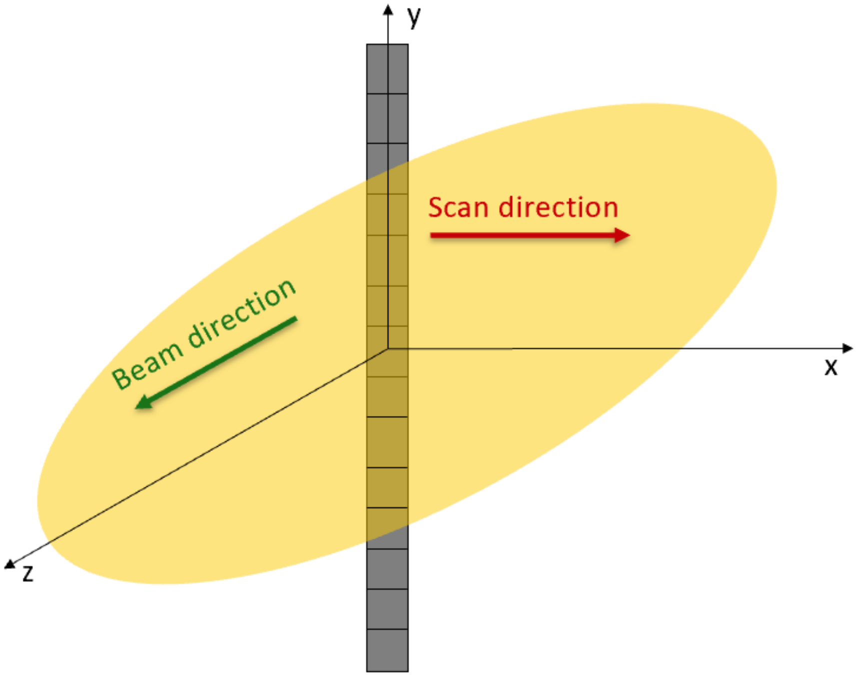
Transverse beam sizes

- Transverse size: vertical beam size derived from horizontal and diagonal beam sizes measured:

$$\sigma_y = \sqrt{\frac{\sigma_x^2 \sigma_d^2}{2\sigma_x^2 - \sigma_d^2}}$$

- When the beam current increases the size of the beam increases too due to the space charge effect → Empirical relation for a cyclotron:

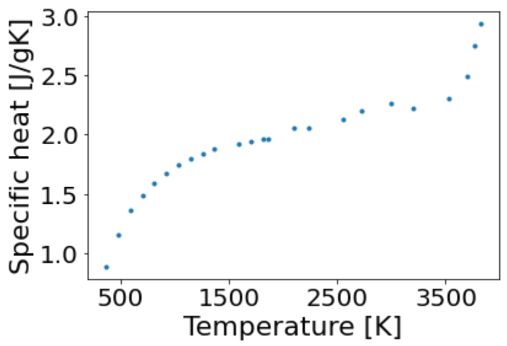
$$\sigma(I) = \sigma(I_0) \cdot \left(\frac{I}{I_0}\right)^{1/3}$$

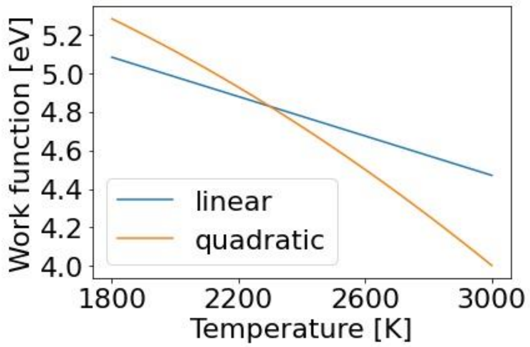


Material parameters

- **Material**: carbon fiber
  - Density: 2.1 g cm^{-3}
  - Emissivity: 0.8 [1], simplified assumption
  - Specific heat: depends on the temperature, taken from the TPRC data series [2]

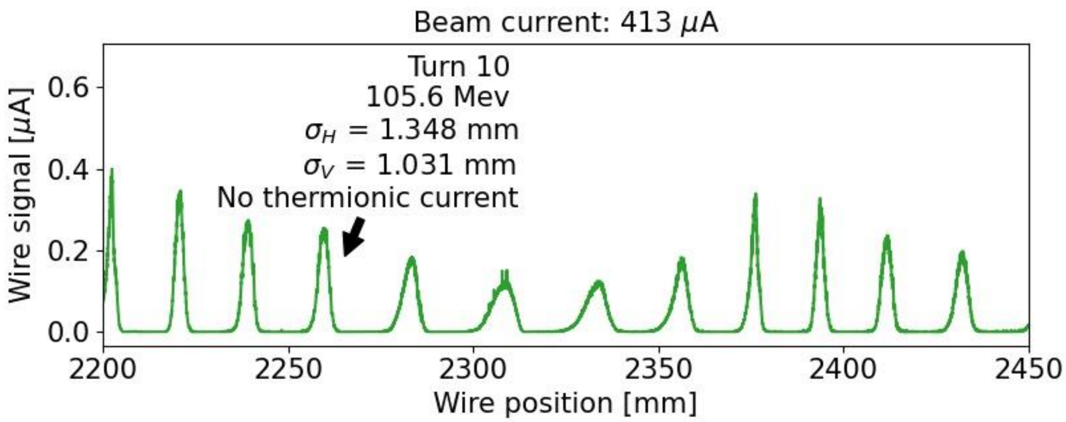
  - Work function: literature suggests that work function decreases with temperature, but no exact behaviour is known, indeed it could be:
    - Linear [3], what is used typically: $\Phi = \Phi_0(1 - \beta T)$
    - Quadratic [4], tested because of the discrepency: $\Phi = \Phi_0 - \gamma \frac{k_B T^2}{\Phi_0}$

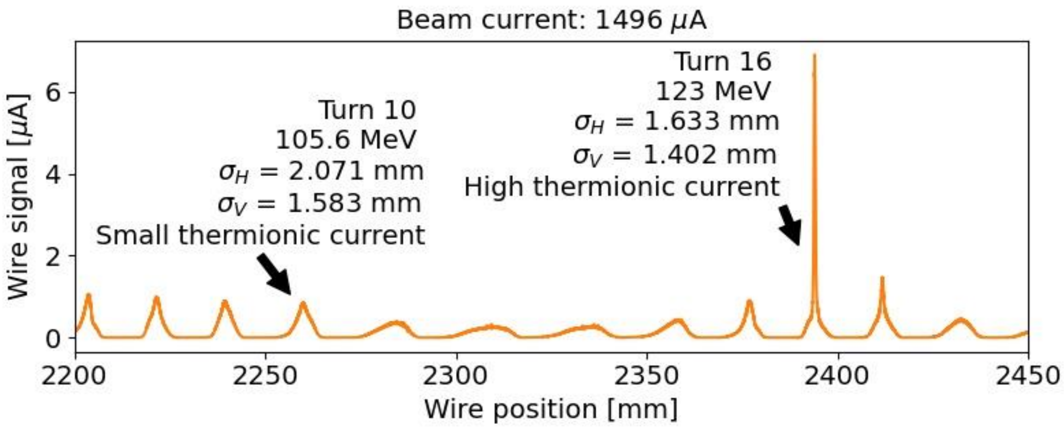




[1] X. Li and W. Strieder, "Emissivity of high-temperature fiber composites," Industrial &amp Engineering Chemistry Research, vol. 48, no. 4, pp. 2236–2244, Jan. 2009. doi: 10.1021/ie8008583.
[2] Y. S. Touloukian and E. H. Buyco, "Thermophysical properties of matter – the TPRC data series. Volume 5. Specific heat - nonmetallic solids. data book," Purdue Univ., Lafayette, IN (United States). Thermophysical and Electronic Properties Information Center, Tech. Rep., 1970. [Online]. Available: https: //www.osti.gov/biblio/5303501 (visited on 07/08/2023).
[3] A. Kiejna, K. F. Wojciechowski, and J. Zebrowksi, "The temperature dependence of metal work functions," Journal of Physics F: Metal Physics, vol. 9, no. 7, pp. 1361–1366, Jul. 1979. doi: 10.1088/0305-4608/9/7/016.
[4] R. Rahemi and D. Li, "Variation in electron work function with temperature and its effect on the Young's modulus of metals," Scripta Materialia, vol. 99, pp. 41–44, Apr. 2015. doi: 10.1016/j.scriptamat.2014.11.022.

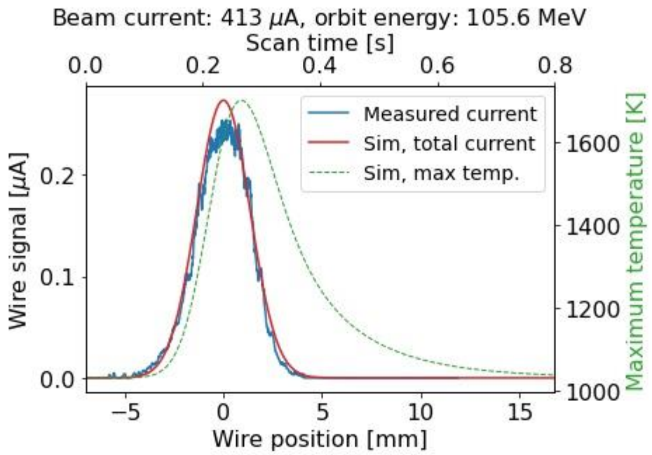
Benchmarking: cases



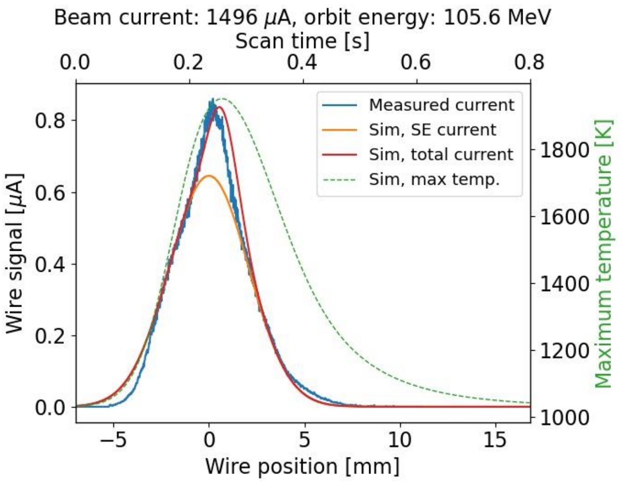


Benchmarking: results (1/2)

- Case 1: **no thermionic peak**
  - Shape of the wire signal well reproduced
  - Simulated current slightly higher than the measured one

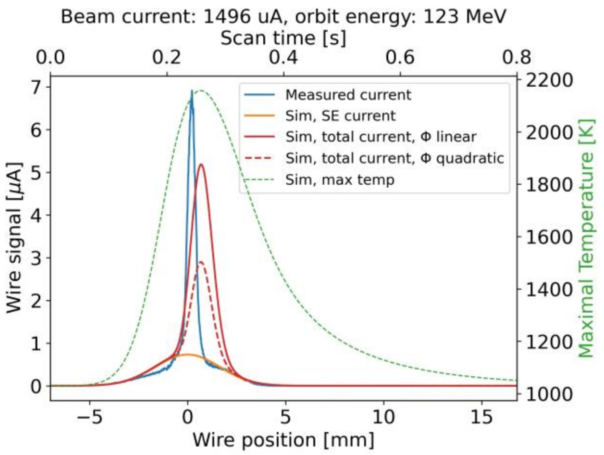


- Case 2: **small thermionic peak**
  - Total current and only secondary emission current seperated
  - Accurately reproduced



Benchmarking: results (2/2)

- Case 3: **high thermionic current**
  - Not accurately reproduced
  - Simulated secondary emission current higher than measured one
  - Thermionic current is wider for both work functions and amplitudes do not correspond

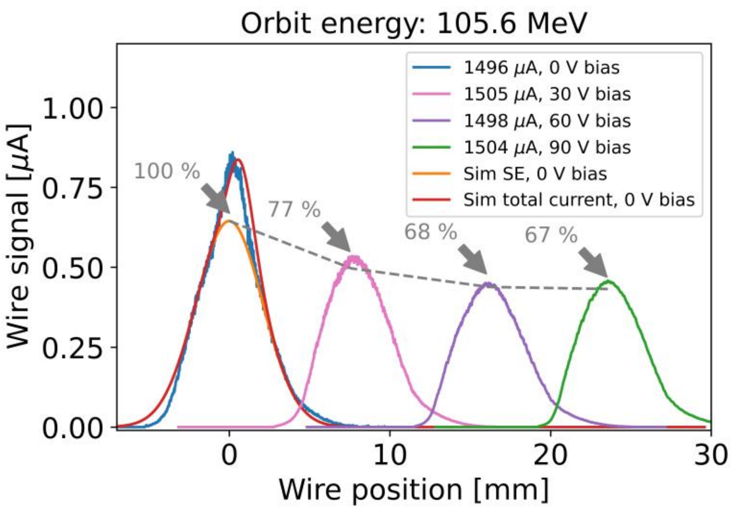


- The discrepancy could come from:
  - High sensitivity to work function and emissivity for which the temperature dependency is not well-known
  - Phenomena that are not simulated by PyTT like the build-up of electron space charge

Manon Boucard

Bias voltage: small thermionic current

- The solution currently applied to remove thermionic emission: **application of a bias voltage:** 30V, 60V, 90V
- Observation of the influence of the bias voltage on the wire signal for a small thermionic peak (orbit 10, 105 MeV beam energy, with 1496 µA beam current)



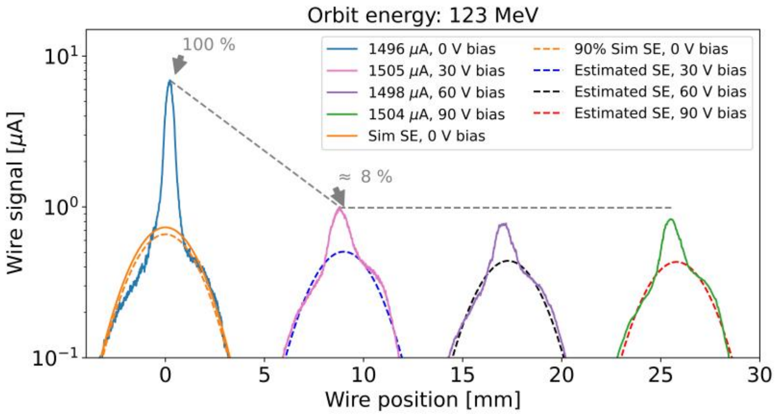
Peaks are shifted for visibility

Thermionic emission seems to be **already suppressed by 30 V bias voltage**

Secondary emission is also affected by bias voltage

Bias voltage: high thermionic current

- The solution currently applied to remove thermionic emission: **application of a bias voltage:** 30V, 60V, 90V
- Observation of the influence of the bias voltage on the wire signal for a high thermionic peak (orbit 16, 123 MeV beam energy, with 1496 µA beam current)



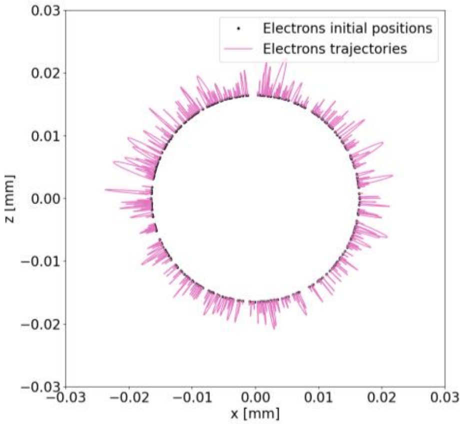
Peaks are shifted for visibility
Logarithmic scale

Estimation of the secondary emission current with percentage found in the previous slide

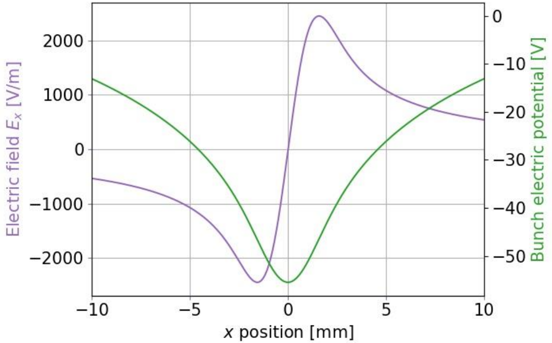
Thermionic peak is not completely eliminated → remaining part of about 8 %

Bias voltage: discussion

- Hypothesis for the remaining thermionic emission: **presence** or **absence** of the bunch. Inspired by R. Dölling in [1].
- Bunch length is about 8% of the bunch spacing (20 ns)
- **Absence of the bunch**:
  - Secondary electrons are not emitted
  - Thermionic electrons are emitted because the wire is still hot.
  - If a bias voltage is applied, the thermionic electrons are coming back to the wire: no thermionic emission
- **Presence of the bunch**:
  - Secondary and thermionic electrons are emitted
  - Presence of an additional transient electric field, which gives the electrons a kick and removes them from the wire.



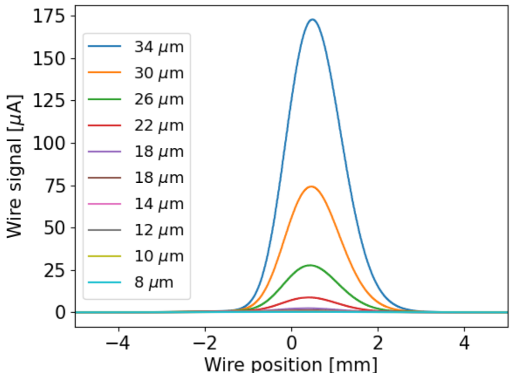
Thermionic electrons trajectories in the absence of a bunch (Virtual-IPM [2] simulations) with 30 V bias voltage. Electrons are coming back to the wire thanks to the bias voltage. Trajectories are closed.

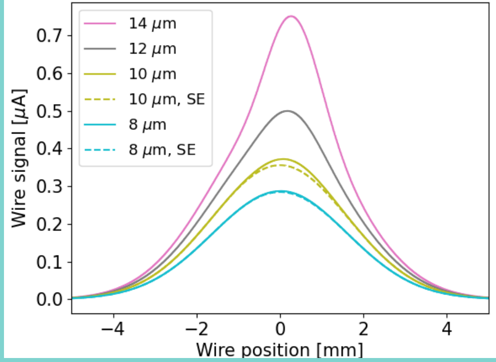


[1] R. Dölling, “Bunch-shape Measurements at PSI’s High-power Cyclotrons and Proton Beam-line,” in Proceedings of Cyclotrons 2013, Vancouver, Canada, ser. Cyclotron subsystem, Diagnostics, 2013, pp. 257–261. [Online]. Available http://accelconf.web.cern.ch/CYCLOTRONS2013/papers/tu3pb01.pdf (visited on 08/07/2023).
[2] D. Vilsmeier. “Virtual-IPM Python Package Index .”, [Online]. Available: https://pypi.org/project/virtual- ipm/ (visited on 06/30/2023).

Thermionic peak VS wire diameter

- 123 MeV beam energy, 2.4 mA beam current





With an **8 μm** diameter wire, there is **no thermionic emission**, even for a 2.4 mA beam current, the bigger current obtained in the Main Ring.

Problem:

- really difficult to mount 8 μm diameter wire on the trolleys (the technician at PSI tried)
- Wires become less strong

Low-density materials

- Solution: Change the material that constitutes the wire → Low-density materials
- Carbon nanotube (CNT): can have a lower density than CF, and potentially be stronger.

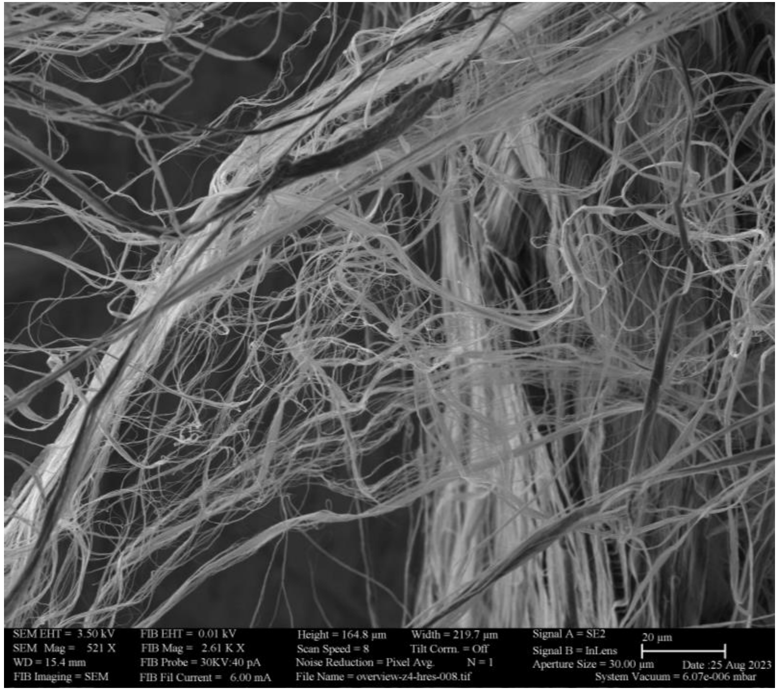
- Comparing the **thermal behaviour of CF with CNT** as wire scanners targets.
- **PyTT simulations** to study how the low-density materials can improve wire scanners measurements.

- Results presented at the Low-density Materials for Beam Instrumentation workshop at CERN on 20 and 21 June 2023 [1].

[1] "Low-density materials for beam instrumentation, indico webpage." (2023), [Online]. Available: https://indico.cern.ch/event/1275649/.

Density of the materials

- CF: 2.1 g cm^{-3}
- CNT:
    - Used for an experiment at CERN [1], from Madrid group (IMDEA Material institute): 1.0 g cm^{-3}
    - Anticipated, investigated at CERN and PSI, not yet available on the market [2]: 0.2 g cm^{-3}



SEM image of the 0.2 g cm^{-3} density CNT material

[1] A. 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 “, Ph.D. dissertation, Université de Franche-Comté, 2023. [Online]. Available: http://cds.cern.ch/record/2860710.
[2] H. Sugime, T. Sato, R. Nakagawa, T. Hayashi, Y. Inoue, and S. Noda, “Ultra-long carbon nanotube forest via in situ supplements of iron and aluminum vapor sources,” Carbon, vol. 172, pp. 772–780, Feb. 2021. doi: 10.1016/j.carbon.2020.10.066.

Beams and wires parameters

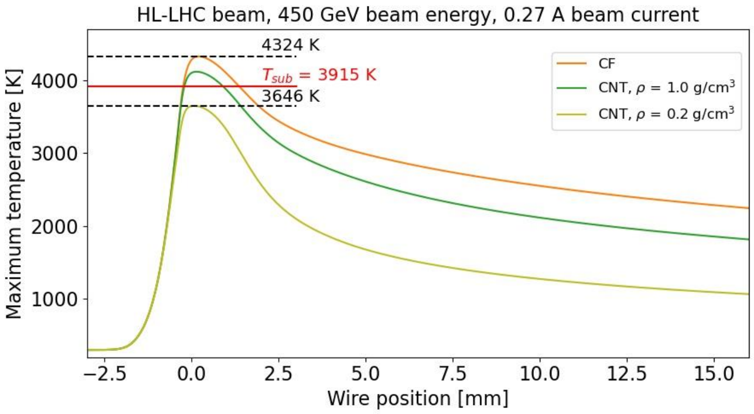
	PSI orbit 10	PSI orbit 16	ADS orbit 16	HL-LHC
Beam energy	105.6 MeV	123 MeV	123 MeV	450 GeV
Stopping power	6.231 MeV cm^2 g^{-1}	5.575 MeV cm^2 g^{-1}	5.575 MeV cm^2 g^{-1}	1.27 MeV cm^2 g^{-1}
Beam current	1.496 mA	1.496 mA	5 mA	270 mA (25 % of the nominal current)
σ_H	2.071 mm	1.633 mm	2.44 mm	0.625 mm
σ_V	1.583 mm	1.402 mm	2.09 mm	0.625 mm

Wires

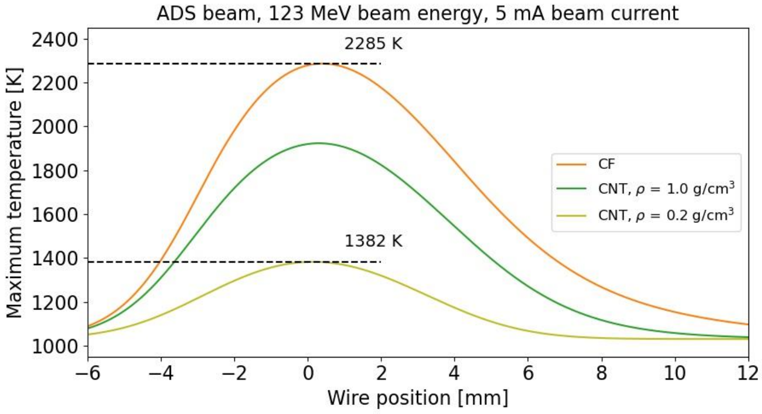
- PSI and ADS: speed of 3 cm/s and 34 µm diameter
- HL-LHC: speed of 1 m/s and 34 µm diameter

[1] "Accelerator-driven Nuclear Energy, Updated August 2018." (), [Online]. Available: https://world-nuclear.org/informationlibrary/current-and-future-generation/accelerator-driven-nuclear-energy.aspx (visited on 07/08/2023)

Thermal evolution

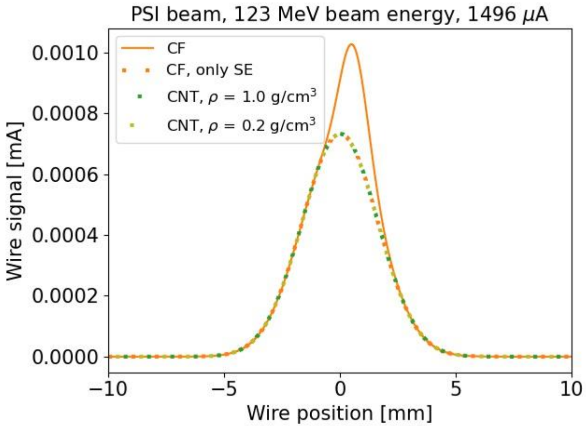


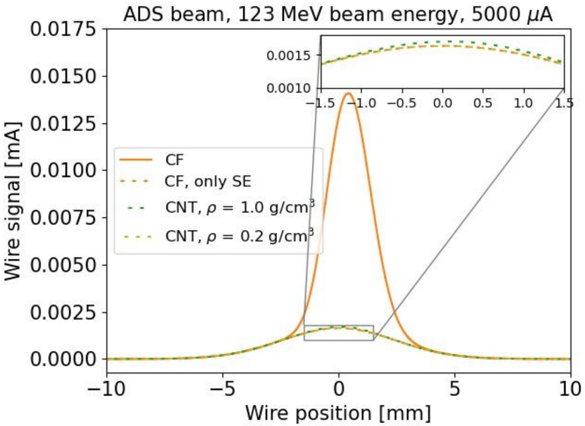
- **HL-LHC:** significant advantages for HL-LHC due to the smaller amount of material, CNT wire should not suffer from sublimation, unlike CF wire.



- **PSI and ADS** scans are much longer, and cooling processes have more time to react so there is no sublimation, even with CF wires. However, the wire reached temperatures high enough to emit thermionic electrons

Wire signal





- **PSI cases:** thermionic peak **totally disappears** when the wire is in CNT.
- **ADS case:** thermionic current disappears with 0.2 g cm^{-3} CNT and a very weak current remains for the 1 g cm^{-3} CNT

- Temperature is much lower for CNT than for CF → thermionic current is therefore much lower too, or even non-existent.

Great advantages for PSI measurements!

Conclusion

- Problem: The emission of thermionic electrons when the temperature of the wire increases leads to deformation of the measured signal.
- The solution currently applied: bias voltage to bring back the thermionic electron to the wire
  - Seems to be inefficient when the bunches cross the wire due to the bunch field trapping the electrons
  - Problem for cyclotrons that operate with long bunches, the presence of the beam has a large time fraction.
- Possible solutions:
  - Ultra-thin wire: could work but really hard to handle
  - Low-density materials: wires could survive from sublimation at HL-LHC, complete suppression of thermionic emission for PSI case without bias voltage or ultra-thin wire
- Benchmarking of the numerical method PyTT
- Participation in a workshop [1] and writing of a paper for IPAC 2023 [2]
- Open questions:
  - Trajectories of electrons with the presence of the bunch
  - Temperature dependency of work function and emissivity

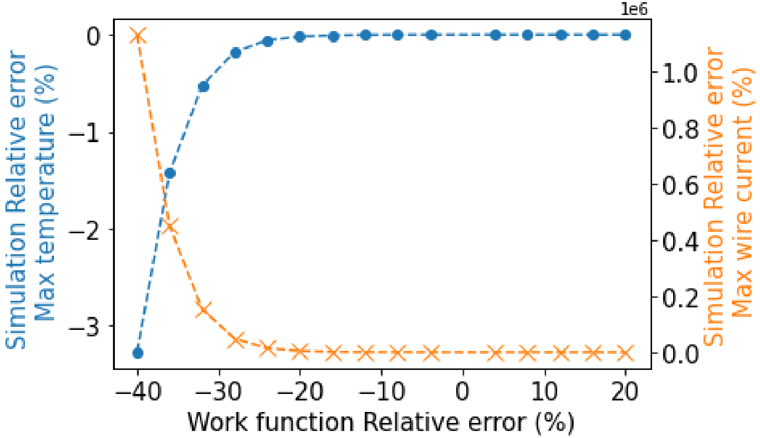
[1] "Low-density materials for beam instrumentation, indico webpage." (2023), [Online]. Available: https://indico.cern.ch/event/1275649/.
[2] M. Sapinski and M. Boucard, "Dealing with Thermionic Emission in Wire Scanners based on Secondary Electron Emission," in Proc. IPAC'23, (Venezia), ser. IPAC'23 - 14th International Particle Accelerator Conference - Venezia, JACoW Publishing, Geneva, Switzerland, May 2023, pp. 4769–4772, isbn: 978-3-95450-231-8. doi: doi:10.18429/jacow-ipac2023-thpl150.

Perspectives – Future work

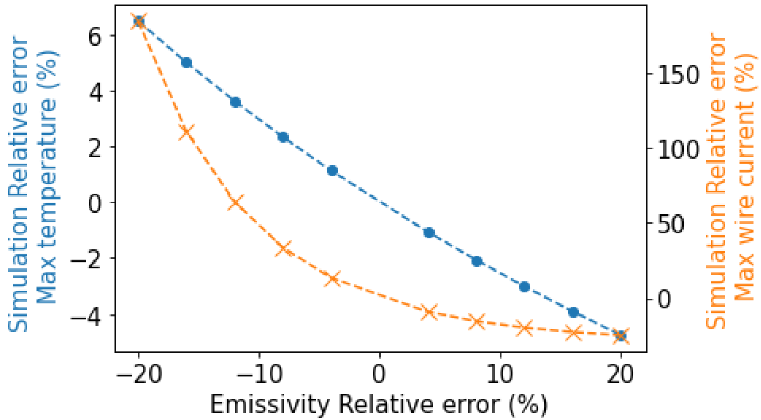
- Simulation of the energy deposition and secondary emission energy distribution with Geant4
- Simulation of the electric field around the wire and tracking of electrons in the presence of bunch field
- Taking data at low biases (2-5 eV)
- Taking data with new materials like carbon nanotubes wires
- Study the space charge influence on the thermionic emission
- Laboratory determination of the work function

Wire signal's high sensitivity

Orbit 16: 123 MeV beam energy, 1496 µA beam current
Initial work function: 5 eV
Initial emissivity: 0.8



Effect on the temperature is smaller than the effect on the wire signal

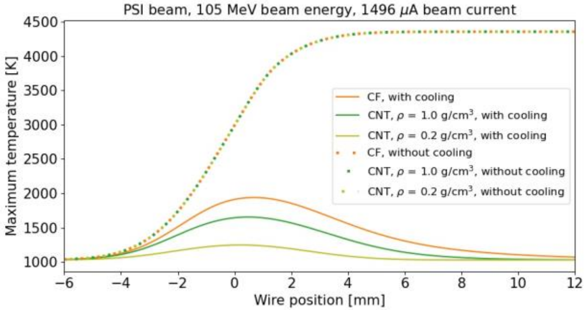


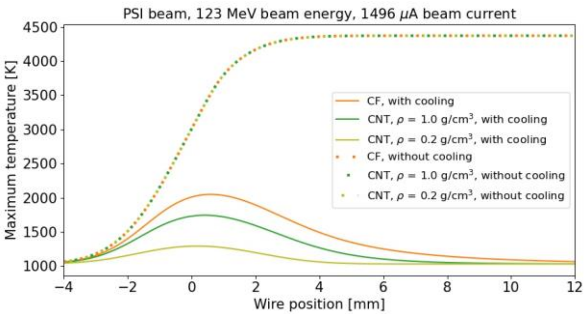
The simulated wire current is high-sensitive to emissivity and work function change, especially for work function for which the relative error **grows exponentially** (due to the exponential term of thermionic current).

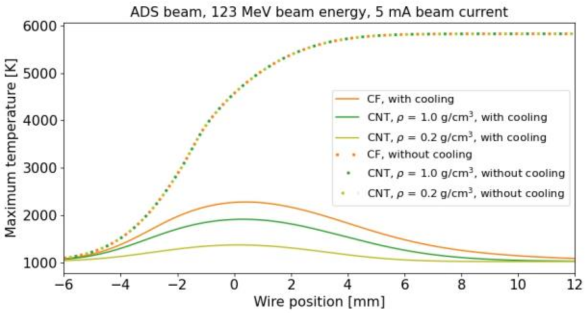
EPFL

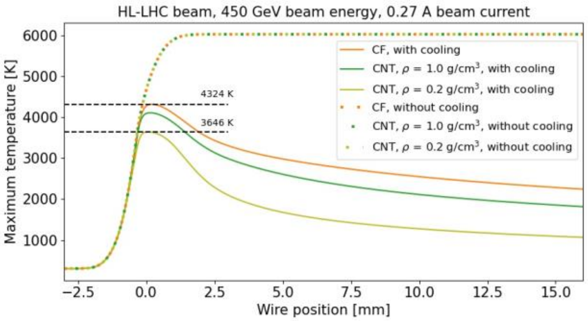
PAUL SCHERRER INSTITUT PSI

Thermal behaviour









- **Without cooling:** the heating is really fast, the maximum temperature depends only on the heat capacity of the materials and **not** on the density

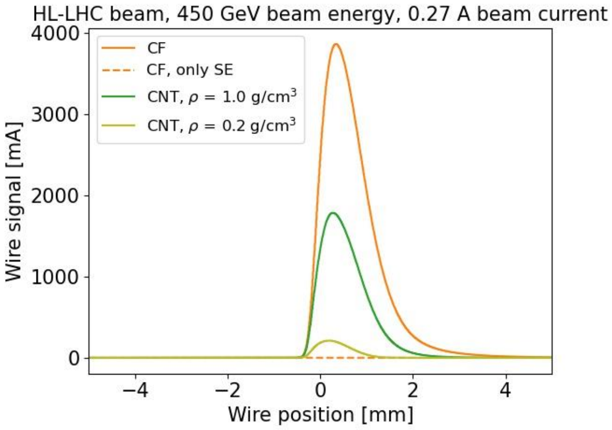
$$\left(\frac{\partial T}{\partial t}\right)_{BH} = \frac{\Phi(x,y,t)\ S_{CS}}{V\cdot Cp(T)\cdot\rho}\cdot d\cdot\rho\cdot\frac{\pi}{4}\frac{dE}{dx} = \frac{\Phi(x,y,t)}{Cp(T)}\cdot\frac{dE}{dx}$$

- **With cooling:** wires are really small objects, so the cooling is also really fast

$$-\frac{S\cdot\sigma_{SB}\cdot\epsilon(T)\cdot\left(T^4-T_0^4\right)}{V\cdot Cp(T)\cdot\rho} \quad -S\cdot(\phi+2K_BT)\cdot\frac{J_{Th}(T)}{V\cdot Cp(T)\cdot\rho}$$

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

HL-LHC wire signal



Material parameters

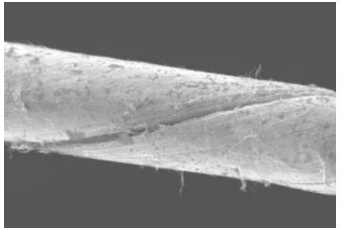


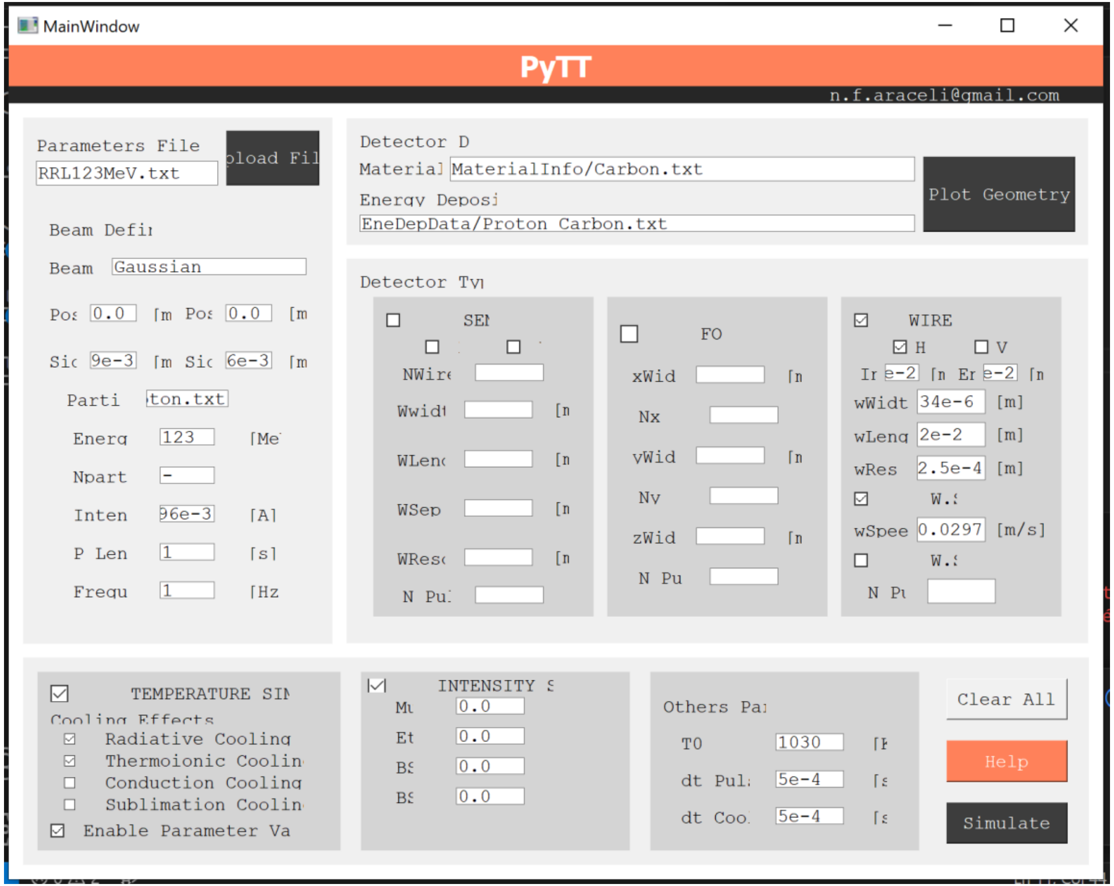
Photo: A. Mariet
PhD thesis [1]

- **Density:**
  - CF: 2.1 g cm^{-3}
  - CNT:
    - Used for an experiment at CERN [1], from Madrid group (IMDEA Material institute): 1.0 g cm^{-3}
    - Anticipated, investigated at CERN and PSI, not yet available on the market [2]: 0.2 g cm^{-3}
- **Specific heat:** due to the lack of data, assumed to be the same for both materials (TPRC data series [3])
- **Emissivity:**
  - Same for both materials, assumed to be 1 (wires are black),
  - Depends on the wire surface → emissivity can drop if there are irregularities. Emissivity could be lower for CNT
- **Work function:**
  - Defined as a constant (5 eV) for CF and CNT
  - Irregularities on the surface can decrease the work function
  - As discussed before, work function should decrease with the temperature

[1] A. 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 “, Ph.D. dissertation, Université de Franche-Comté, 2023. [Online]. Available: http://cds.cern.ch/record/2860710.
[2] H. Sugime, T. Sato, R. Nakagawa, T. Hayashi, Y. Inoue, and S. Noda, “Ultra-long carbon nanotube forest via in situ supplements of iron and aluminum vapor sources,” Carbon, vol. 172, pp. 772–780, Feb. 2021. doi: 10.1016/j.carbon.2020.10.066.
[3] Y. S. Touloukian and E. H. Buyco, “Thermophysical properties of matter – the TPRC data series. Volume 5. Specific heat - nonmetallic solids. data book,” Purdue Univ., Lafayette, IN (United States). Thermophysical and Electronic Properties Information Center, Tech. Rep., 1970. [Online]. Available: https://www.osti.gov/biblio/5303501 (visited on 07/08/2023).

Speaker

PyTT GUI


MainWindow
PyTT
n.f.araceli@gmail.com
Parameters File
RRL123MeV.txt
pload Fil
Beam Defi
Beam
Gaussian
Pos 0.0 [m Pos 0.0 [m
Sic 9e-3 [m Sic 6e-3 [m
Parti
ton.txt
Energ 123 [Me
Npart -
Inten 96e-3 [A]
P Len 1 [s]
Frequ 1 [Hz
Detector D
Material MaterialInfo/Carbon.txt
Energy Deposi
EneDepData/Proton_Carbon.txt
Plot Geometry
Detector Ty
SEI
NWire
Wwid [n
WLen [n
WSep [n
WRes [n
N Pu
FO
xWid [n
Nx
yWid [n
Ny
zWid [n
N Pu
WIRE
H
V
Ir e-2 [n Er e-2 [n
wWidt 34e-6 [m]
wLeng 2e-2 [m]
wRes 2.5e-4 [m]
W.
wSpee 0.0297 [m/s]
W.
N Pu
TEMPERATURE SIM
Cooling Effects
Radiative Cooling
Thermoionic Coolin
Conduction Cooling
Sublimation Coolin
Enable Parameter Va
INTENSITY S
Mu 0.0
Et 0.0
BS 0.0
BS 0.0
Others Pa
T0 1030 [K
dt Pul 5e-4 [s
dt Coo 5e-4 [s
Clear All
Help
Simulate

$$\mathrm{SEY} = 0.01 \cdot L_S \cdot \frac{\mathrm{d}E}{\mathrm{d}x} \cdot \rho \cdot \left(1 + \frac{1}{1 + 5.4 \cdot 10^{-6} \cdot \frac{E}{M}}\right)$$

$$Q_{SE} = N_p \cdot \mathrm{SEY}_p + N_p(1-\eta)\mathrm{SEY}_p + N_p \cdot BS_p \cdot \mathrm{SEY}_p + \\ N_e \cdot \mathrm{SEY}_e + N_e(1-\mu)\mathrm{SEY}_e + N_e \cdot BS_e \cdot \mathrm{SEY}_e$$