Manon Boucard :: Master thesis :: EPFL-LPAP

Thin targets in extreme conditions: probing high-brightness hadron beam

17/08/2023

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Responsible: Prof. Dr. Mike Seidel

Outlook

- Wire scanners, the interactions between the beam and the wire, what are thermionic emissions
- Presentation of PyTT code and experimental benchmarking
- Influence of the bias voltage on the measured signal
- Wire diameter effect on thermionic emission
- Study of low-density materials as wire scanners targets

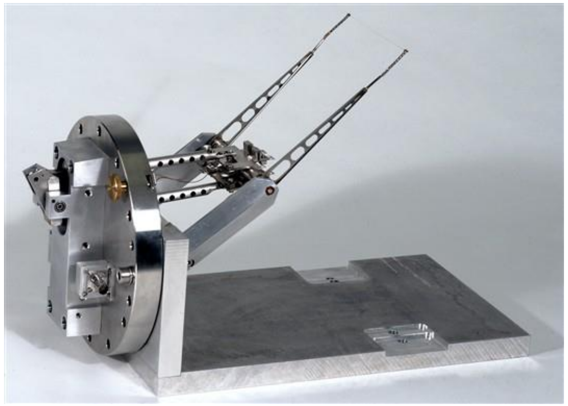
Introduction

- Wire scanners targets are subject to extreme conditions when probing high-brightness hadron beams
- Reach very high temperatures due to the passage of the beam
- High temperature → thermionic emission that will distort the measured signal
- Wire scanners are typically made of Carbon fiber (CF), Molybdenum, or Tungsten.
- Chosen for their mechanical, electrical, and thermal properties but can reach their limits (e.g. thermionic electron emission).

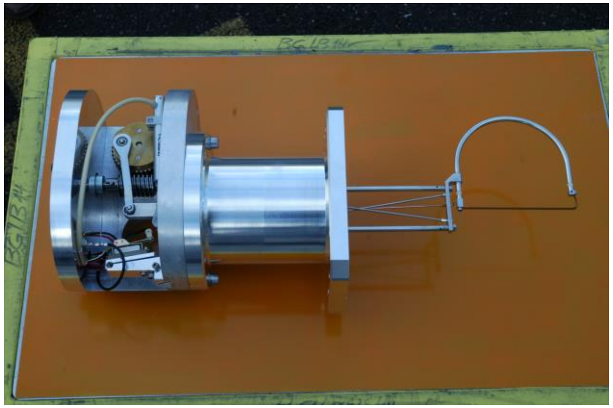
How to get rid off this thermionic emission ? What are the solution currently apply? How to improve wire scanners targets to avoid this disturbance?

Wire scanners

- **Beam transverse profile measurements**
- Moving a **thin wire** through the beam and measuring the effects of the interaction
- Rotational (high speeds) or linear (more precise)
- Two types of measurements:
  - Beam energy relatively small: profile reconstructed by using **the current generated by secondary electron emission**
  - Beam energy is higher: profile reconstructed by **detecting the secondary electron emitted**



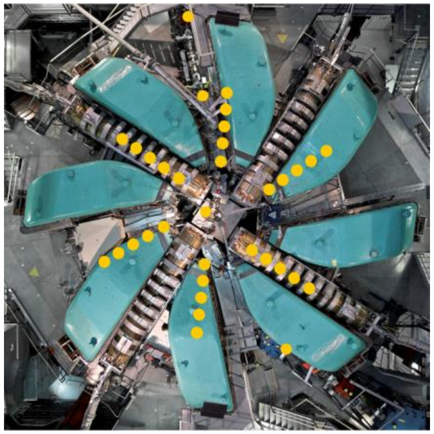
Rotational wire scanner
Photo: Maximillien Brice, CERN

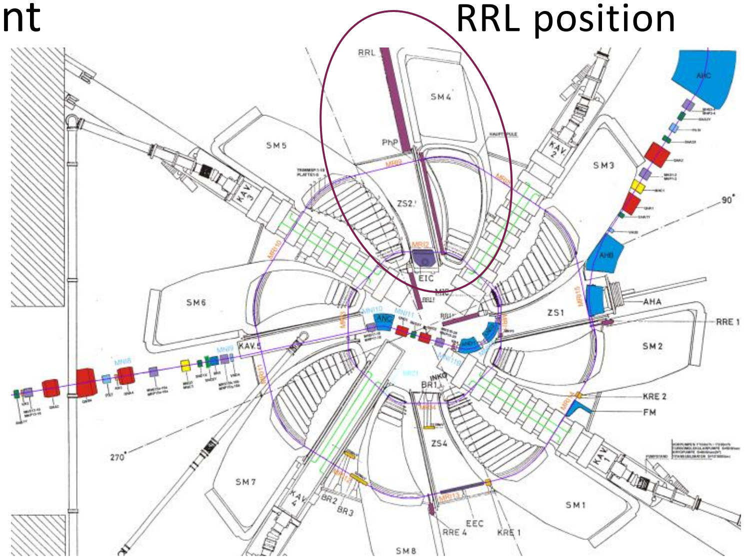


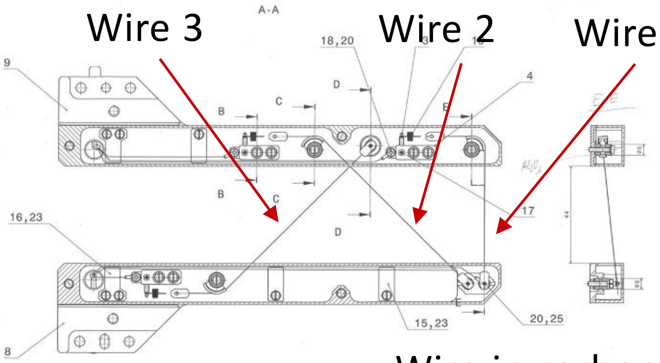
Another type of rotational wire scanner, «swinging» wire scanner
Photo: Paul Scherrer Institute

PSI's Main Ring Long Radial Probe: RRL

- Linear wire scanner placed in the main ring cyclotron of HIPA
- Scan **all the orbits** along the ring cyclotron radius (2.048 m to 4.480 m)
- Profile reconstructed with the wire current




RRL position

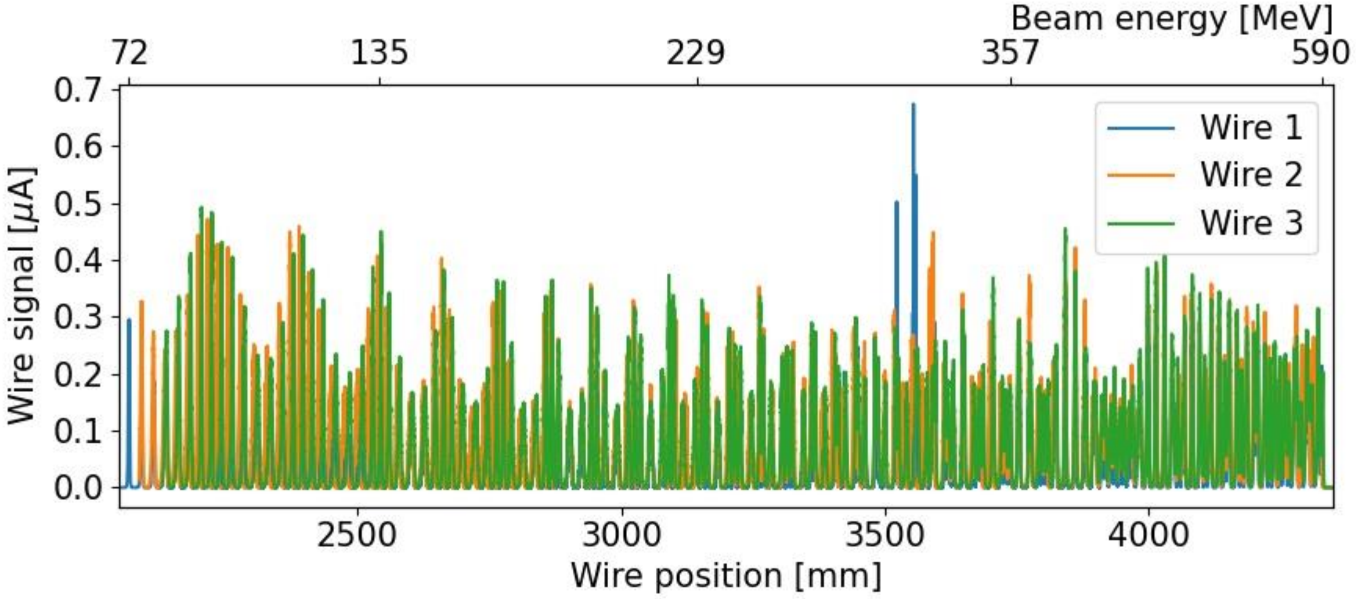

Wire 3

Wire 2

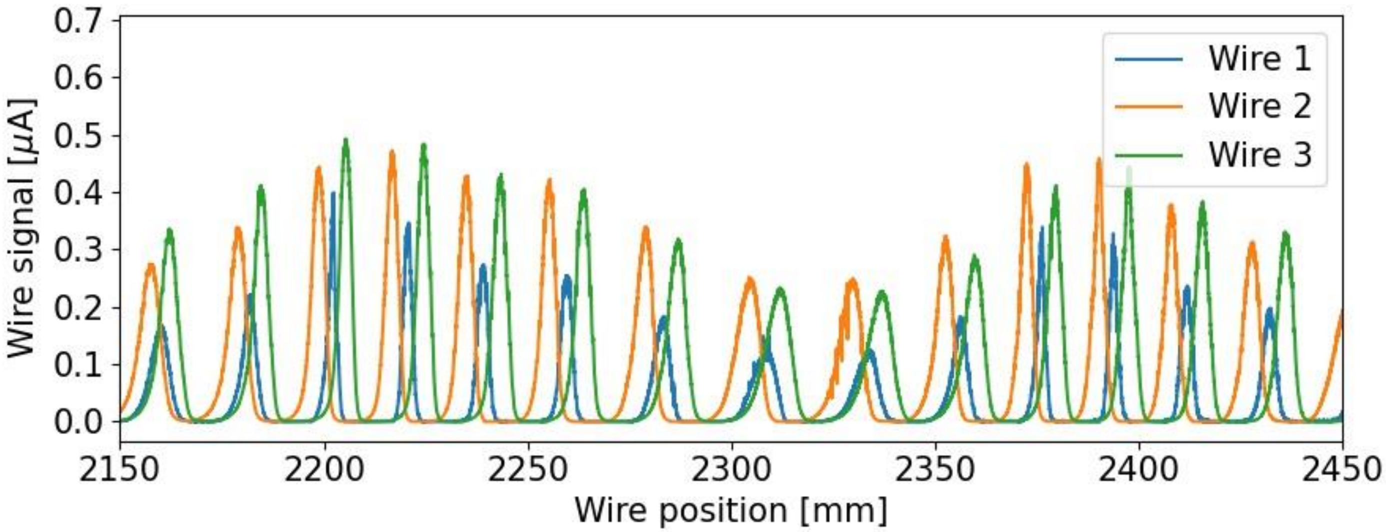
Wire 1

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

RRL’s scans



Scan IN



Diagonal wires signal $\sqrt{2}$ times bigger than vertical wire signal

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

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

- Units : [MeV cm^2 g^{-1}]
- δ-electrons: some of the electrons which gain high energy by interacting with the beam particles escape carrying out a part of the energy foreseen by Bethe-Bloch equation. Not taken into account in this work.

Wire heating model

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

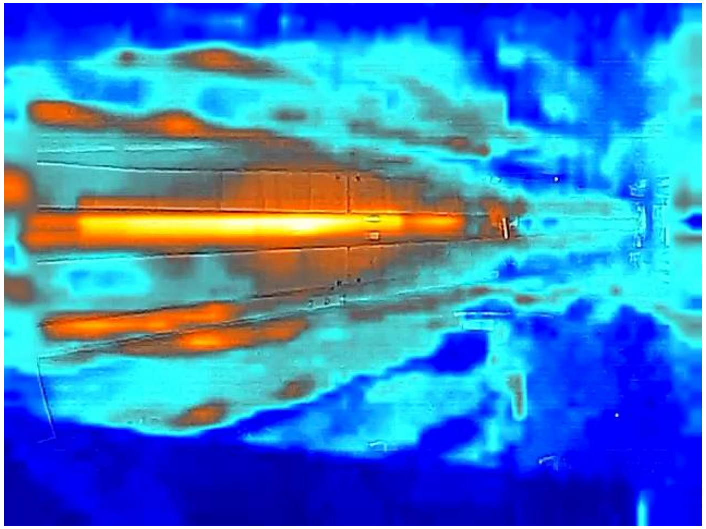
Beam heating: direct beam energy deposition

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

Secondary electron and thermionic electron current

Secondary electron emission

- Energy transferred by the proton beam to the electrons in the medium may be enough for them to escape
- **Secondary Emission Yield (SEY)** Sternglass formula**:**

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

- Charge induced by secondary electron emission when a projectile hits a target:

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

- **Charge induced by one proton passing through a thin wire** ($N_p = 1,\ N_e = 0,\ \eta = 0,\ \mu = 0,\ BS_p = BS_e = 0$):

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

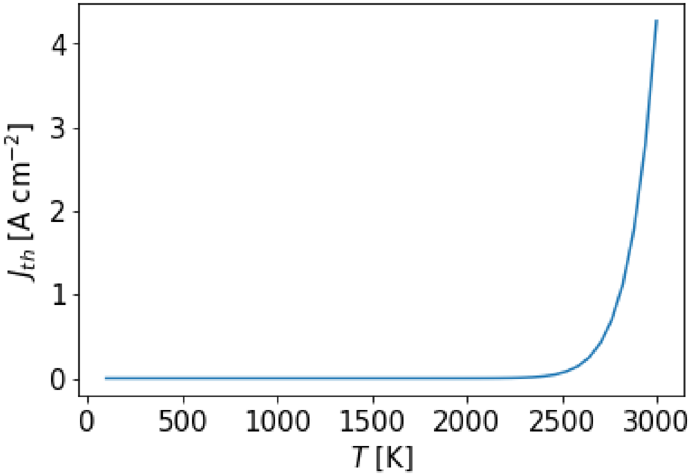
Proportional to the number of protons passing through the wire

Thermionic emission

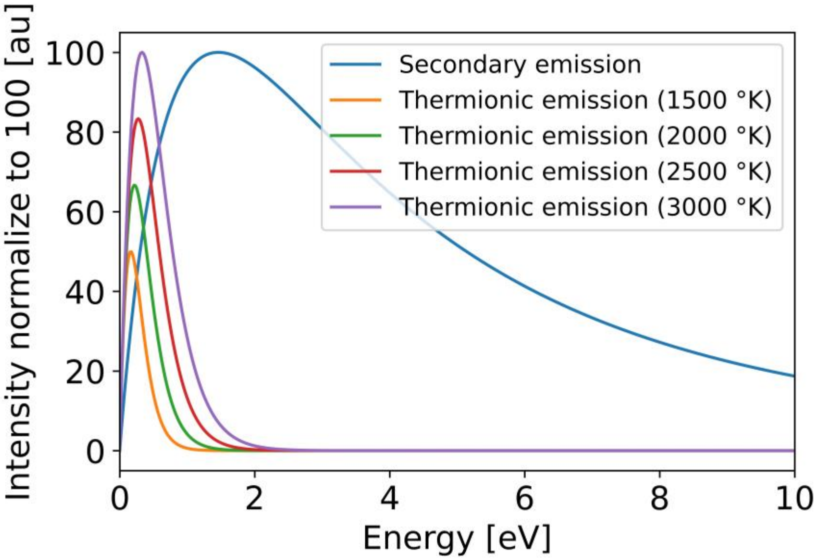
- Electrons that gain enough thermal energy **to break the work function** and escape
- Richardson and Dushman formula:

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

Not proportional to the particle density



Energy distribution



Secondary emission: 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]:

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

Secondary emission: peak aroud 1-2 eV, high energy tail

Thermionic emission: peak lower than 1 eV, increases with temperature

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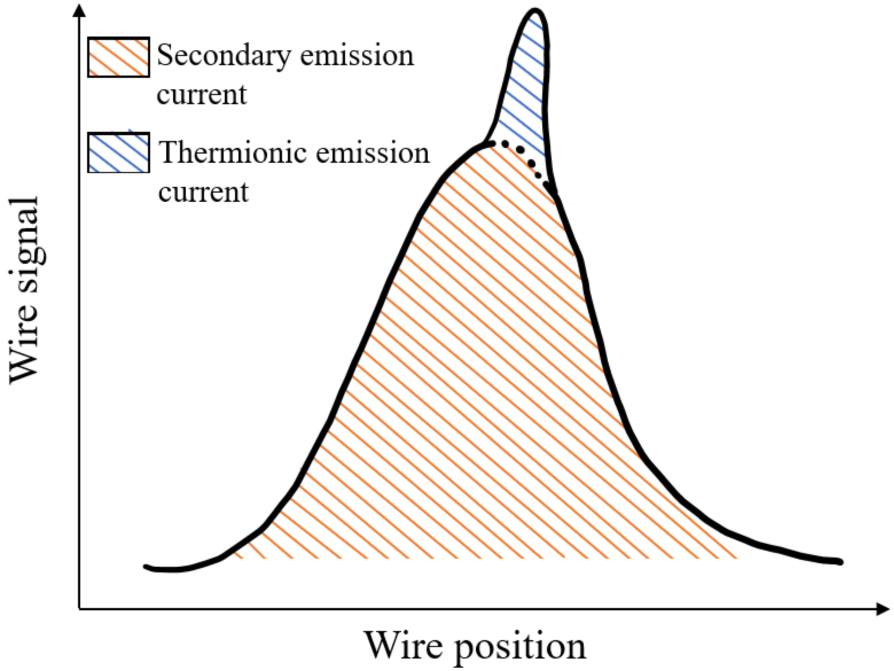
[1] M. S. Chung and T. E. Everhart, “Simple calculation of energy distribution of low-energy secondary electrons emitted from metals under electron bombardment,” Journal of Applied Physics, vol. 45, no. 2, pp. 707–709, Feb. 1974. doi:`10.1063/1.1663306`

[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`.

Thermionic peak

- When beam current increase → temperature of the wire increases → thermionic electron emission
- **Not proportional to the particle density** → **distort** the measured signal



PyTT

- PyTT [1]: **Py**thon **T**hin **T**arget, implemented by M. Sapinski and A. Navarro

- Simulates the thermal behavior and the wire signal for thin targets

- Finite element method
- Wire temperature and signal computed per «bin» thanks to equations discussed before

- **Experimental validation** with comparisons between RRL measurements and PyTT simulations
- **Wire signal benchmarking**, more complicated with wire temperature

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

Beam parameters

- **Transverse bunch shape**: assumed to be a multivariate 2D Gaussian distribution
- **Beam size:**
  - Transverse size: vertical beam size derived from horizontal and diagonal beam sizes measured:

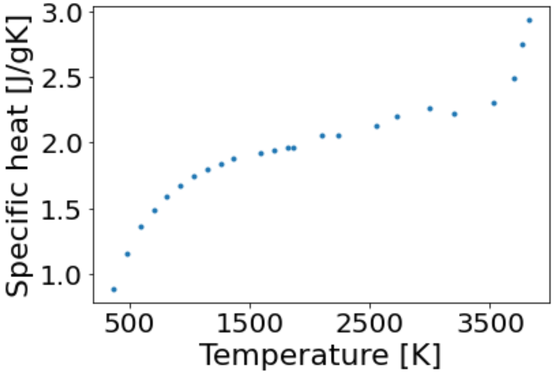
$$\sigma_y = \sqrt{\frac{\sigma_x^2 \sigma_d^2}{2\sigma_x^2 - \sigma_d^2}}$$

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

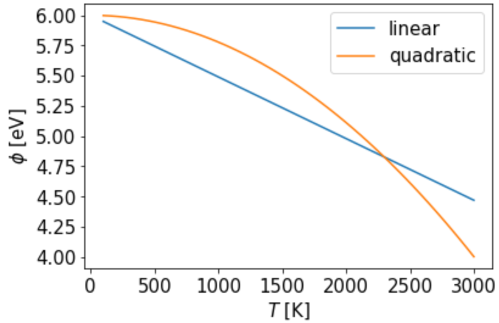
$$\sigma(I) = \sigma(I_0) \cdot \left(\frac{I}{I_0}\right)^{1/3}$$

- **Type of particle**: proton with a mass of $1.27 \cdot 10^{-27}$ kg
- **Beam energy**: to compute the correct stopping power $\frac{dE}{dx}$
- **Beam current**

Wire parameters / Material parameters



- **Length**: 2 cm for simulation (8.8 cm for real)
- **Diameter**: 34 µm
- **Speed**: 3 cm/s
- **Material**: carbon fiber
  - Density: 2.1 g cm^{-3}
  - Emissivity: 0.8 [1], simplified assumption
  - Specific heat: depends on the temperature, taken from TPRC data series [2]
  - Work function: literature suggests that work function decreases with temperature, but no exact behavior is known, indeed it could be linear [3] or even quadratic [4]. Two behaviors are tested:
    - Linear: $\Phi = \Phi_0(1-\beta T)$
    - Quadratic: $\Phi = \Phi_0 - \gamma \frac{k_B T^2}{\Phi_0}$



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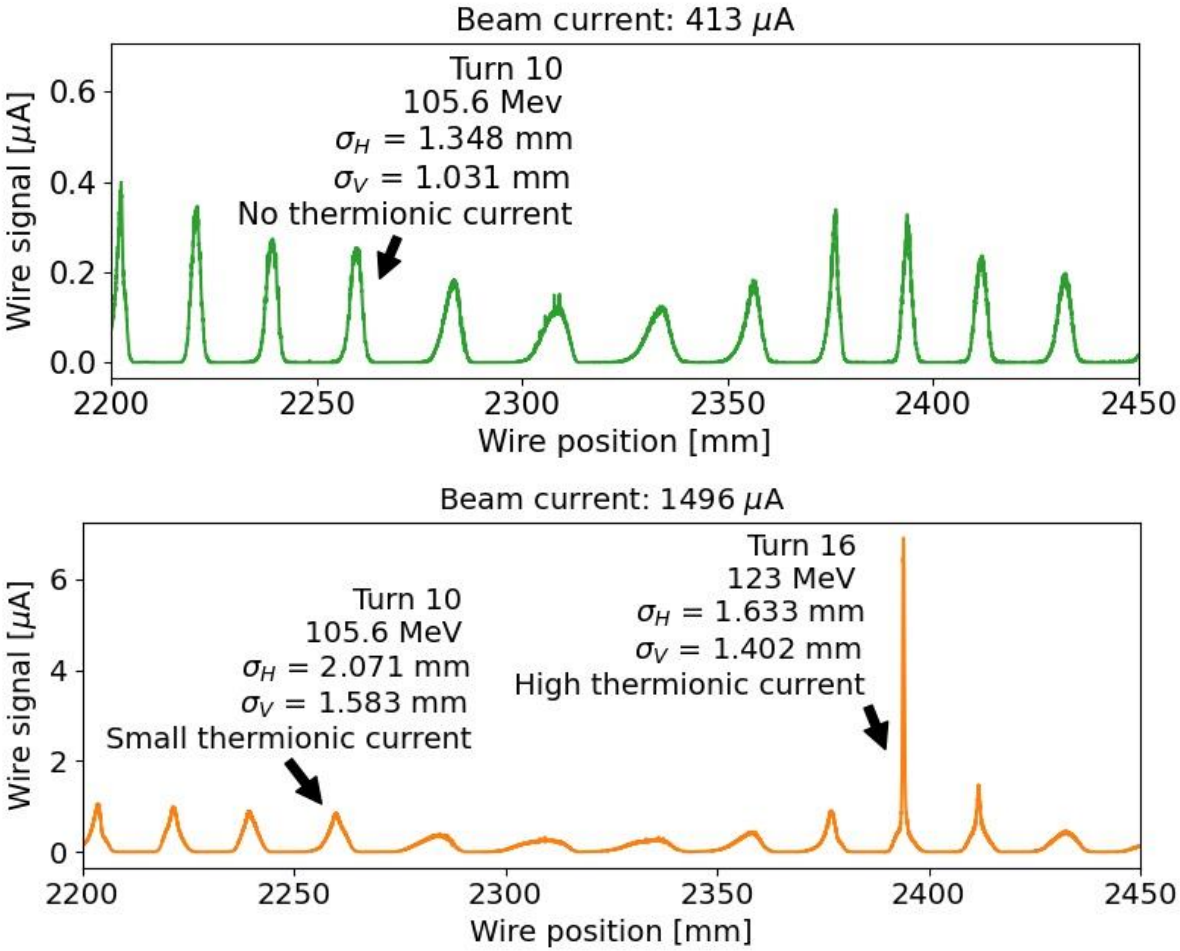
[1] X. Li and W. Strieder, “Emissivity of high-temperature fiber composites,” Industrial &amp Engineering Chemistry Research, vol. 48, no. 4, pp. 2236–2244, Jan. 2009. doi: `10.1021/ie8008583`.

[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).

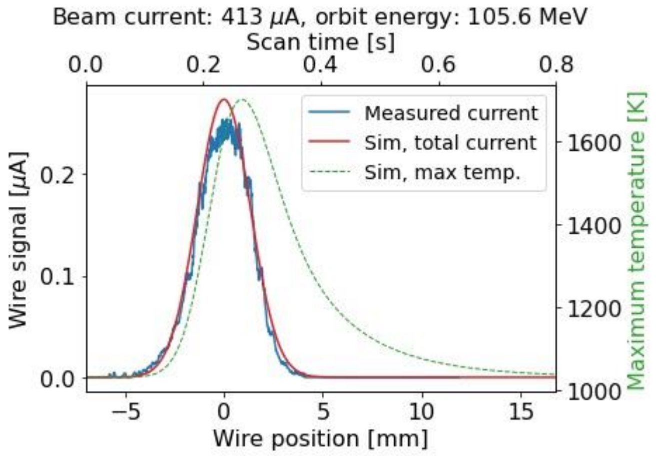
[3] A. Kiejna, K. F. Wojciechowski, and J. Zebrowksi, “The temperature dependence of metal work functions,” Journal of Physics F: Metal Physics, vol. 9, no. 7, pp. 1361–1366, Jul. 1979. doi: `10.1088/0305-4608/9/7/016`.

[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

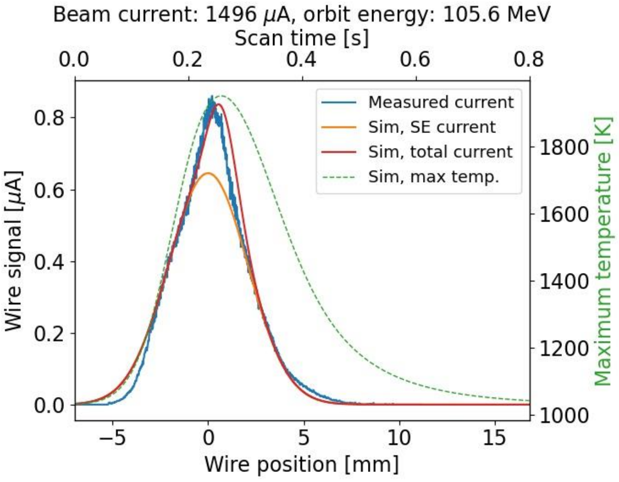


Case 1: **no thermionic peak**

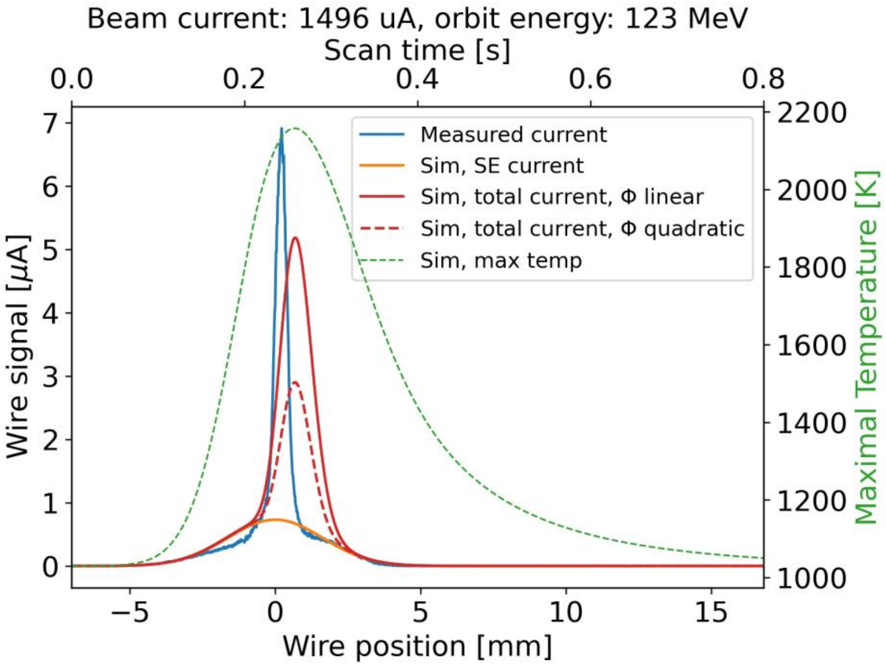
- Shape of the wire signal well reproduced
- Simulated current slightly higher than the measured one

Case 2: **small thermionic peak**

- Total current and only secondary emission current seperated
- Accurately reproduced



Benchmarking: results



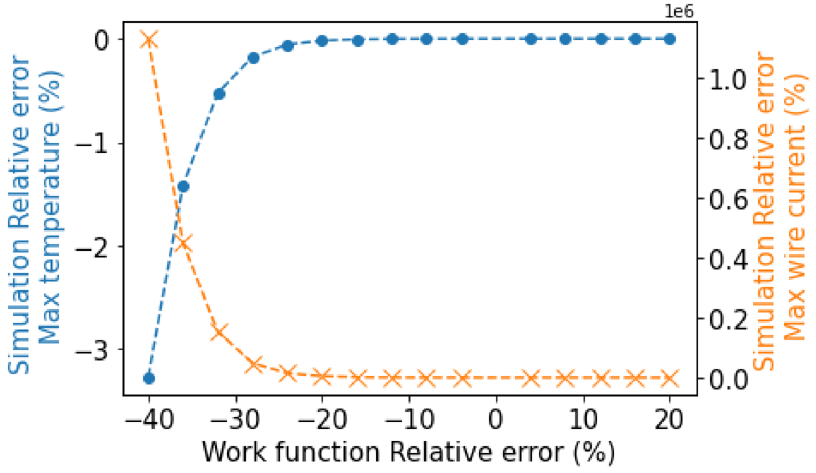
Case 3: **high thermionic current**

- Not accurately reproduced
- Simulated secondary emission current higher than measured one
- Thermionic current is wider for both work function 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 build-up of electron space charge

Wire signal’s high sensitivity

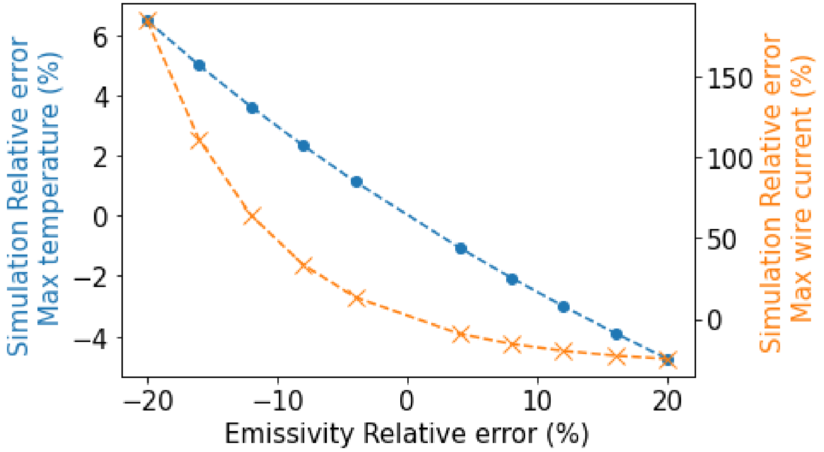


Orbit 16: 123 MeV beam energy, 1496 μA beam current

Initial work function: 5 eV
Initial emissivity: 0.8

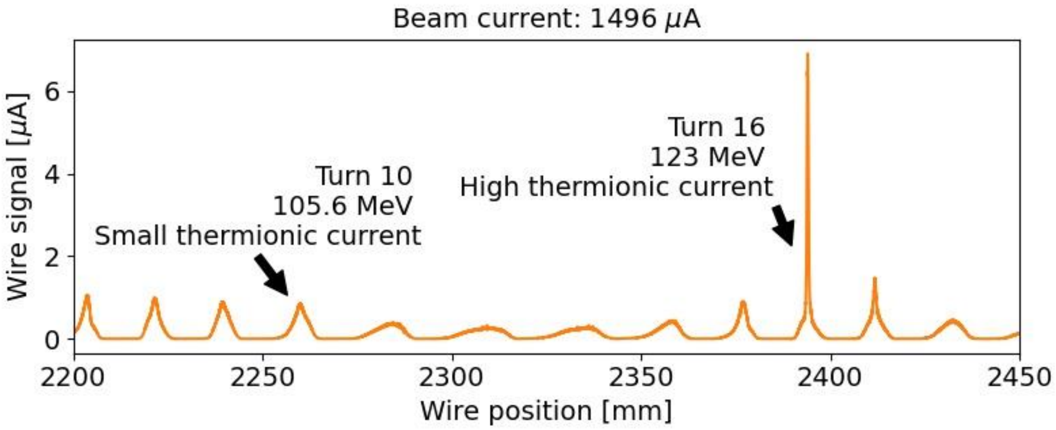
Effect on the temperature is smaller than the effect on the wire signal

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).



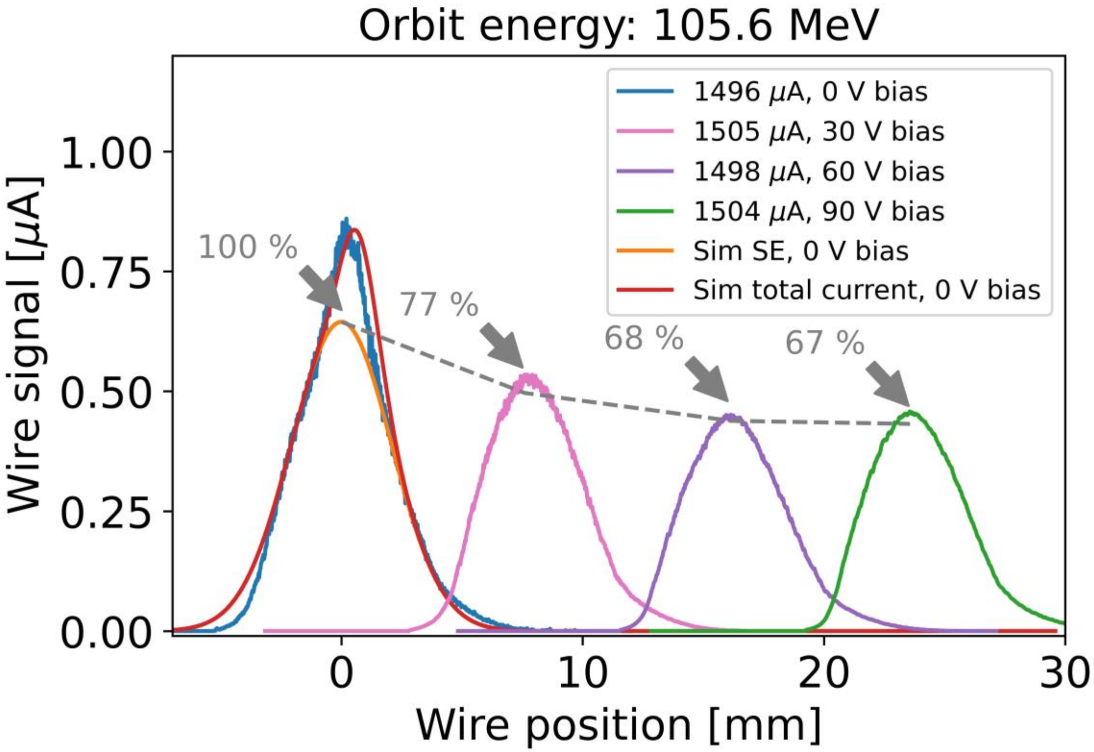
Application of the bias voltage

- To get rid of the thermionic current → **apply of a positive bias voltage to the wire**
- RRL scans from 2022 commissioning are analyzed
- RRL can perform scan with several bias voltage applied with a battery (30 V, 60 V and 90 V are taken into account)
- Two orbits are selected in a scan with ≈1500 µA beam current to observe the influence of the bias voltage on the wire signal obtained with the probe:
  – An orbit with **a small thermionic peak** (orbit 10 → 105 MeV beam energy)
  – An orbit with **a high thermionic peak** (orbit 16 → 123 MeV beam energy)



Bias voltage: small thermionic current

Peaks are shifted for visibility



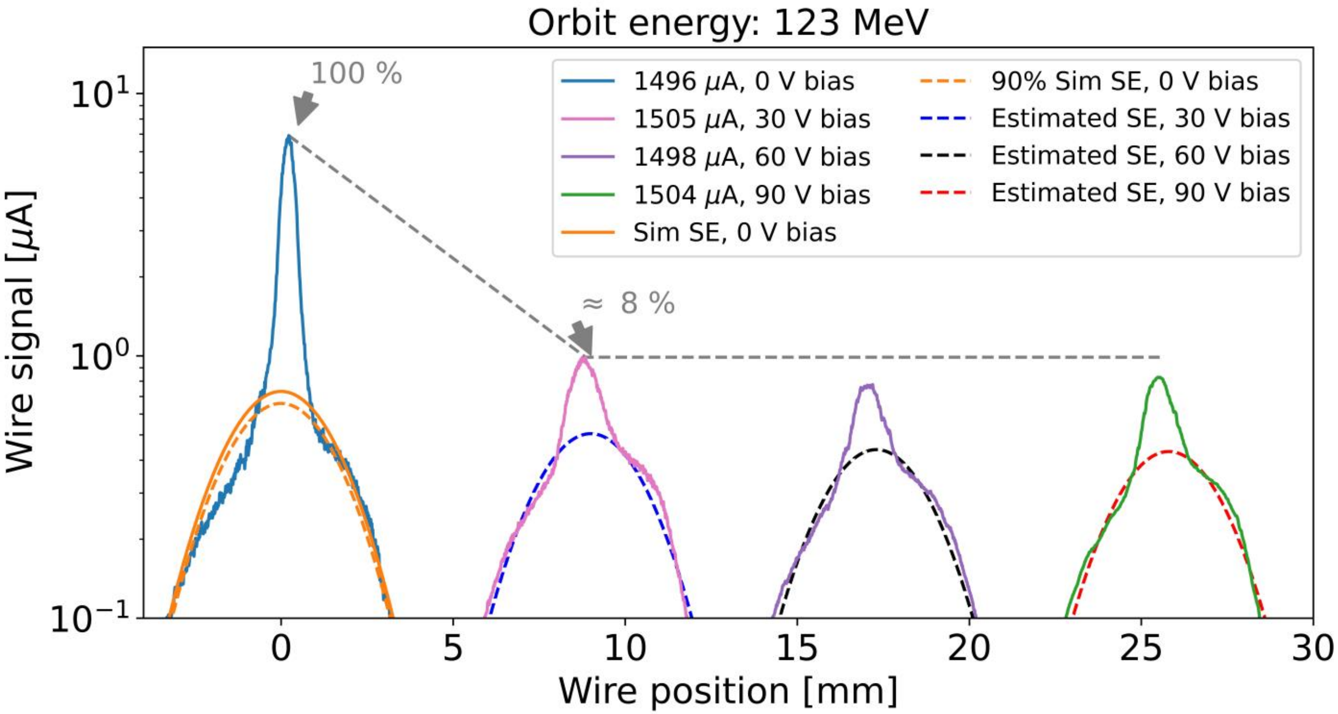
Thermionic emission seems to be **already suppressed by 30 V bias voltage**

Red curve: simulation of the total current emitted by the wire (PyTT simulations)

Orange curve: simulation of the secondary emission current

Secondary emission is also affected by the bias voltage

Bias voltage: high thermionic current



Logarithmic scale

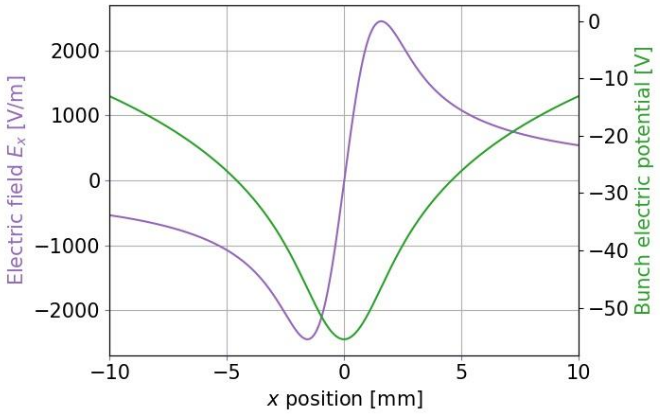
Peaks are shifted for visibility

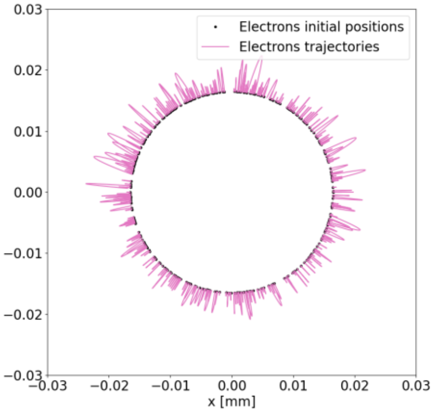
Orange solid line: simulated secondary emission current with PyTT with no bias, overestimated
Orange dashed line: 90 % of the simulated secondary emission current
Others dashed lines: estimation of the secondary emission current with percentage found in the previous slide

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

Discussion

- Hypothesis for the remaining thermionic emission: **presence** or **absence** of the bunch
- Bunch length is about 8% of the bunch spacing (20 ns) [1]
- **Absence of the bunch**:
  - Secondary electrons are not emitted
  - Thermionic electrons can be emitted because it depends only on the wire temperature.
  - 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
  - Additional transient electric field present
  - Bunch potential could facilitate the escape of the electrons from the wire





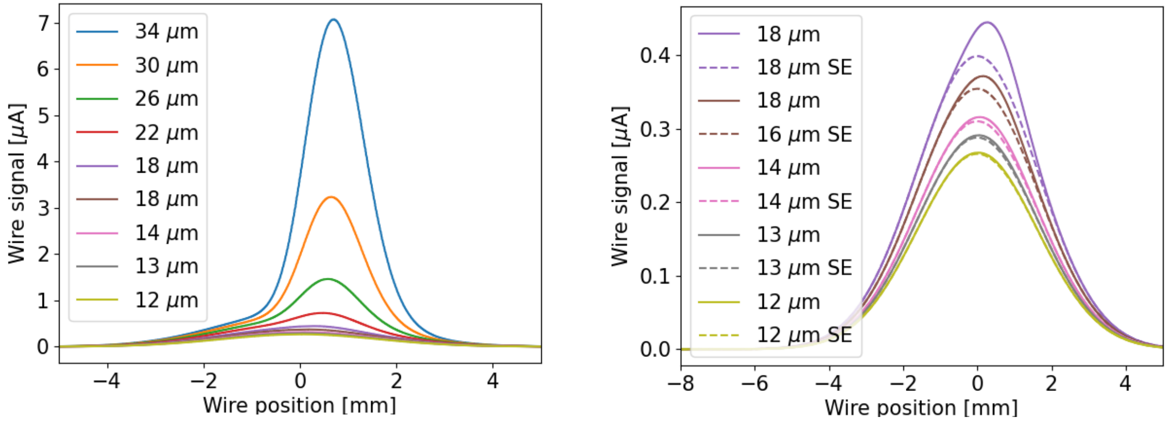
Thermionic electrons trajectories in the absence of a bunch (Virtual-IPM [2] simulations).
Electrons are coming back to the wire thanks to the bias voltage

[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).

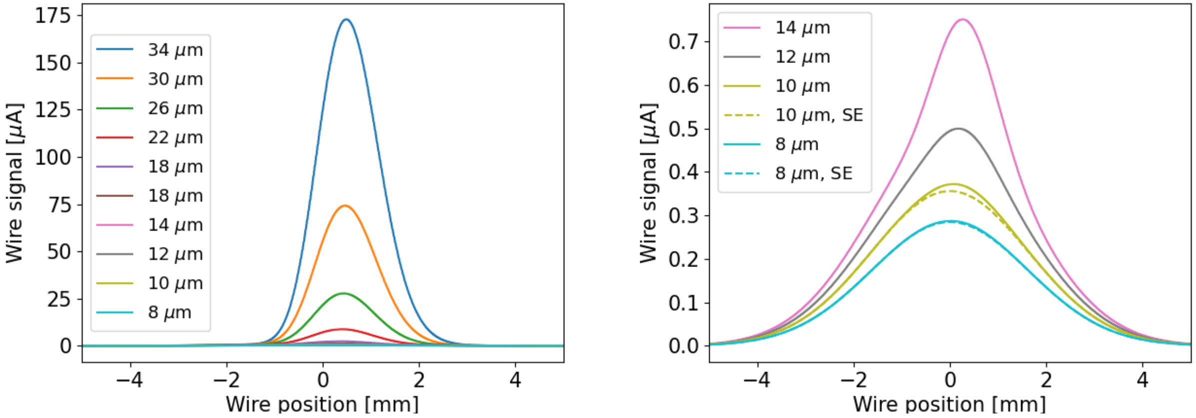
[2] D. Vilsmeier. “Virtual-IPM Python Package Index https://pypi.org/project/virtual-ipm/.” (), [Online]. Available: `https://pypi.org/project/virtual-ipm/` (visited on 06/30/2023).

Thermionic peak VS wire diameter

123 MeV beam energy, 1.496 mA beam current



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
- Wires become weak (less mechanical strength)

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 behavior 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].

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

Material parameters

- **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

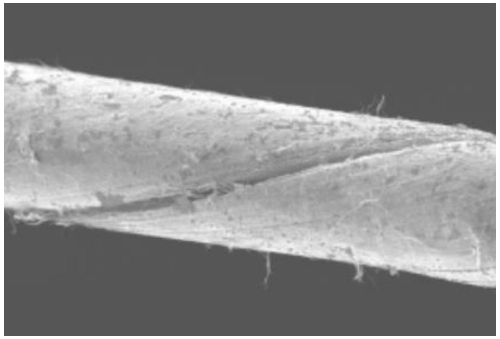

Photo: A. Mariet PhD thesis [1]

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[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).

Beams and wires parameters

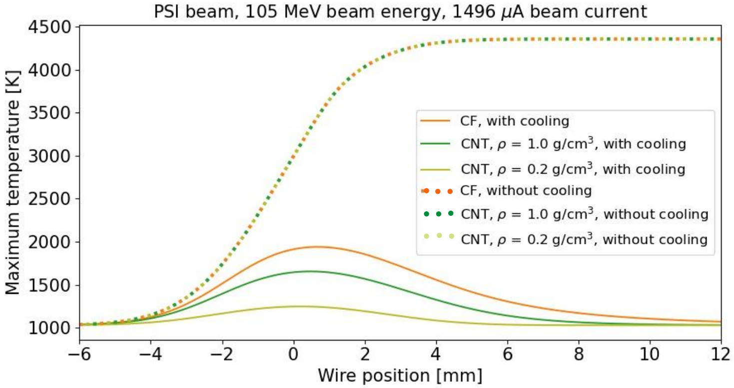
	PSI orbit 10	**PSI orbit 16**	**ADS orbit 16**	**HL-LHC**
Beam energy	105.6 MeV	123 MeV	123 MeV	450 GeV
Stopping power	6.231 MeV $\mathrm{cm}^2\,\mathrm{g}^{-1}$	5.575 MeV $\mathrm{cm}^2\,\mathrm{g}^{-1}$	5.575 MeV $\mathrm{cm}^2\,\mathrm{g}^{-1}$	1.27 MeV $\mathrm{cm}^2\,\mathrm{g}^{-1}$
Beam current	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

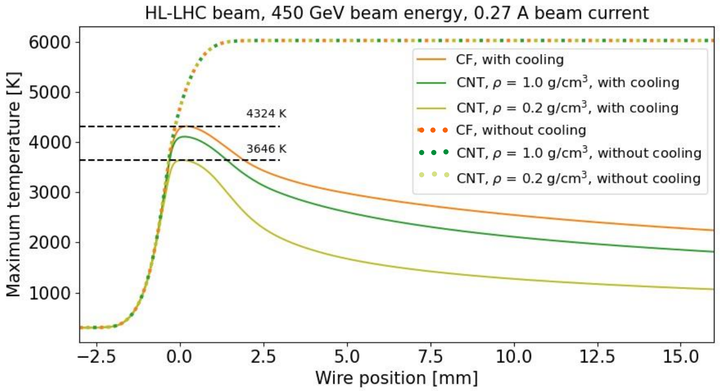
Wires

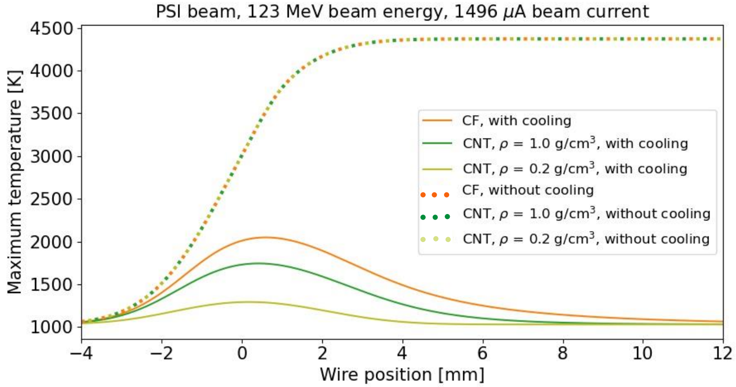
- PSI and ADS: speed of 3 cm/s and 34 µm diameter
- HL-LHC: speed of 1 m/s and 34 µm diameter

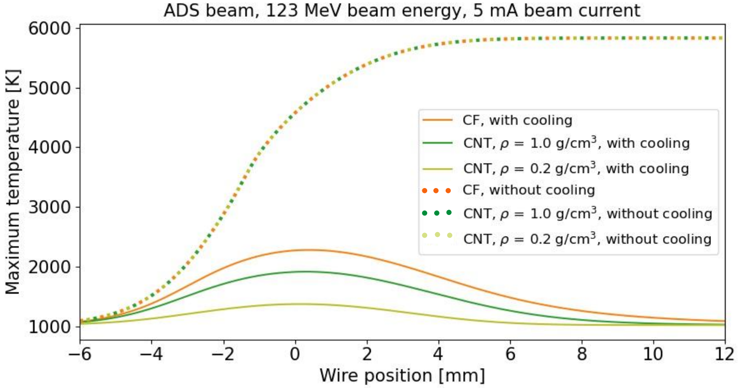
[1] "Accelerator-driven Nuclear Energy, Updated August 2018." (), [Online]. Available: `https://world-nuclear.org/informationlibrary/current-and-future-generation/accelerator-driven-nuclear-energy.aspx` (visited on 07/08/2023)

Results: thermal behaviour


PSI beam, 105 MeV beam energy, 1496 μA beam current


HL-LHC beam, 450 GeV beam energy, 0.27 A beam current


PSI beam, 123 MeV beam energy, 1496 μA beam current


ADS beam, 123 MeV beam energy, 5 mA beam current

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

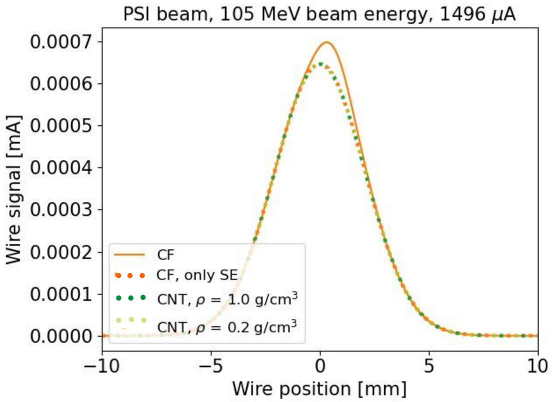
$$\left(\frac{\partial T}{\partial t}\right)_{BH} = \frac{\Phi(x,y,t)\ \cancel{S}_{CS}}{\cancel{V}\cdot Cp(T)\cdot\cancel{\rho}}\cdot\cancel{d}\cdot\cancel{\rho}\cdot\frac{\cancel{\pi}}{\cancel{4}}\frac{dE}{dx} = \frac{\Phi(x,y,t)}{Cp(T)}\cdot\frac{dE}{dx}$$

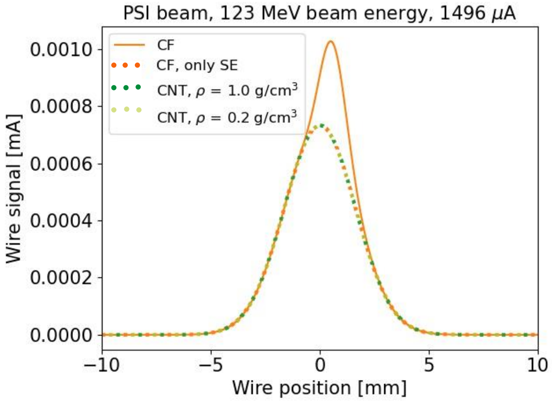
With cooling: wires are really small objects, so the cooling is also really fast

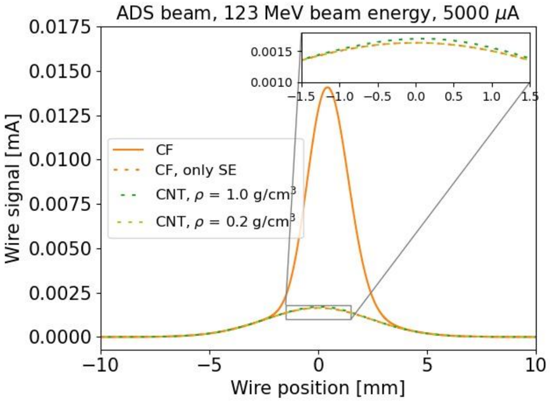
$$\underbrace{-\frac{S\cdot\sigma_{SB}\cdot\epsilon(T)\cdot\left(T^4-T_0^4\right)}{V\cdot Cp(T)\cdot\rho}}_{\text{Radiative cooling}}\quad\underbrace{-S\cdot(\phi+2K_BT)\cdot\frac{J_{Th}(T)}{V\cdot Cp(T)\cdot\rho}}_{\text{Thermionic cooling}}$$

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

Results: wire signal





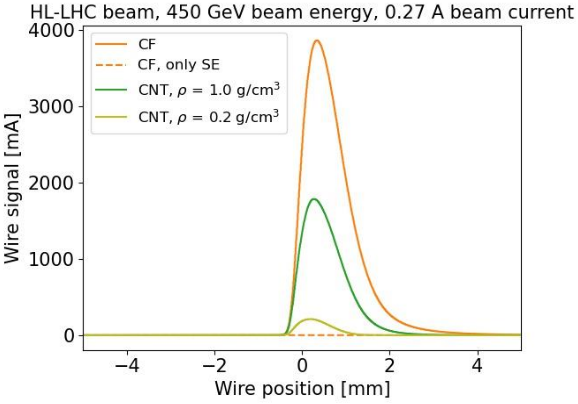


PSI cases: thermionic peak **totally disappears** when the wire is in CNT.

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!



HL-LHC case: Huge thermionic peak → unexploitable measurements.

High energy beam: wire scanners based on detection of SE not on generated current

Other phenomena, like space charge, can occur and are not taken into account by PyTT

Summary and conclusions

- Benchmarking of PyTT code:
  - Seems consistent for moderate thermionic current
  - High sensitivity to work function and emissivity
  - **Discrepency at high thermionic current**, may be due to the space charge effect

- **Biasing the wire is not solving the problem completely**:
  - likely due to the presence of the bunch
  - Problem for cyclotrons that operate in CW with long bunches

- Low-density material could solve the thermionic current problem:
  - CNT wires reached lower temperatures than CF wires
  - **Complete suppression of thermionic emission** in PSI beam profile measurements: **no need of a bias voltage or ultra-thin wire**

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

- Thank you for your attention
- Questions?