Beam wire scanner at CERN
Simulation of behavior of carbon nanotube wires with protons at high energies

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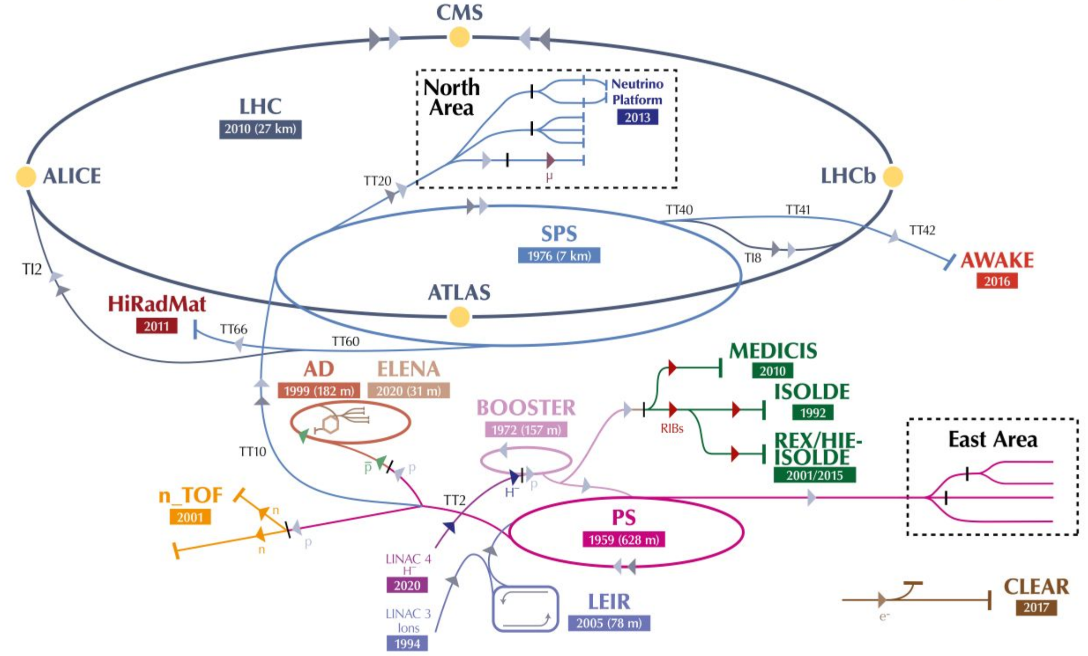
The CERN accelerator complex
Complexe des accélérateurs du CERN



▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ $\bar{p}$ (antiprotons) ▶ e^- (electrons) ▶ μ (muons)

LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE-ISOLDE - Radioactive EXperiment/High Intensity and Energy ISOLDE // MEDICIS // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials // Neutrino Platform

Wire Scanner

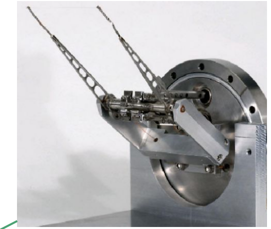
- Wire Scanner (WS) is a device used to measure the transverse beam profile.

- Wire Scanner is of ones or tens of μm in diameter and tens of cm in length

- WS is getting heated up while scanning the beam and undergoes cooling process.

- With certain parameters the current Carbon fiber WS might sublimate and get damaged.

- Carbon nanotubes are considered to be a replacement of the current WS



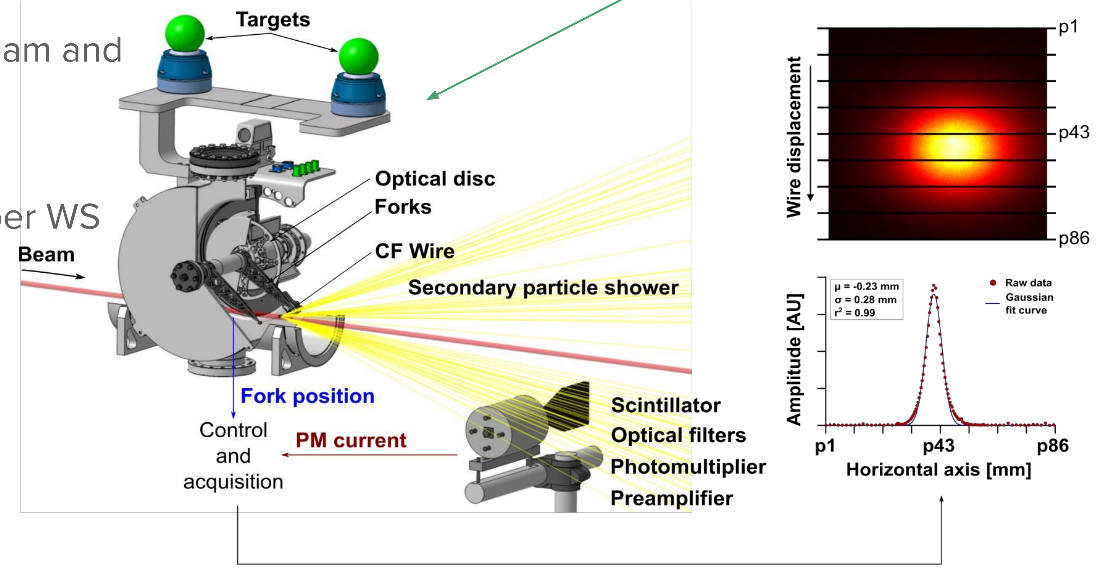


Photo from Alexandre MARIET 's Ph.D Defense

Scan speed [m.s^{-1}]	Momentum [GeV.c^{-1}]	Intensity [N_p]	$\sigma_{l/t}$ [mm]
0.5	400	2.41 x 10^{13}	0.57 / 0.73

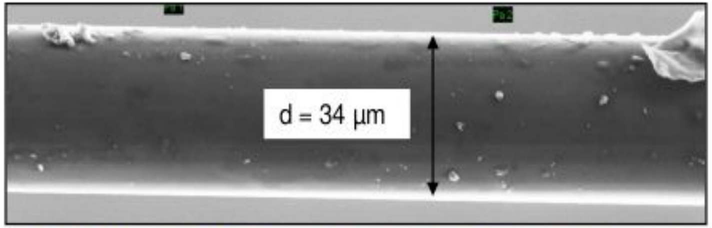


Fig.1: Pristine 34 µm Carbon Fiber (CF) before irradiation

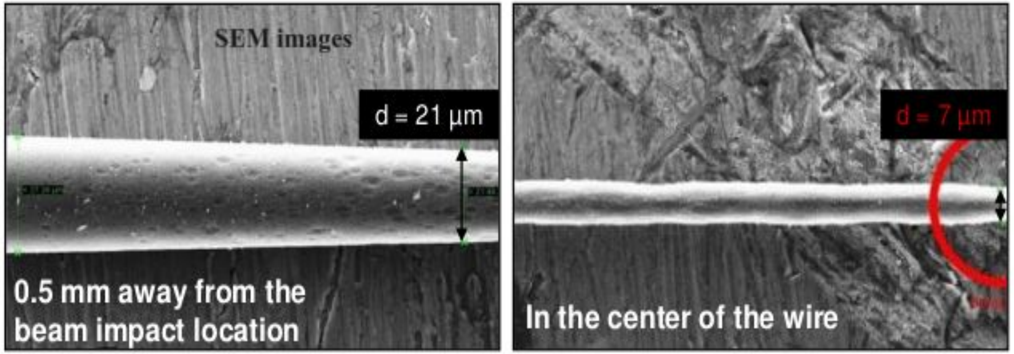


Fig.2: Aging Carbon Fiber (CF) after irradiation

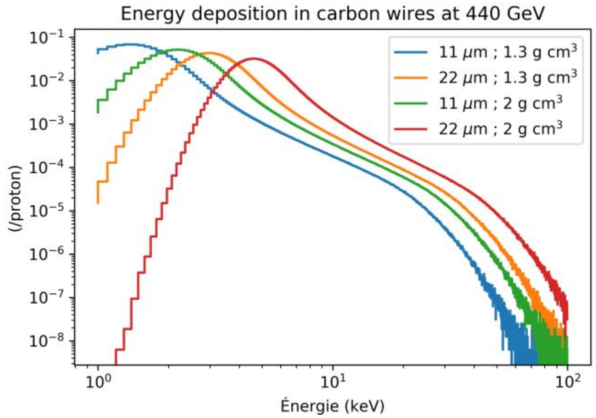
M. Sapinski, B. Dehning, A. Guerrero, J. Koopman, E. Metral, Carbon fiber breakage experiment on SPS, 2010
Photo from Alexandre MARIET ‘s Ph.D Defense

Energy Deposition

WS is being heated by the energy deposited by the protons on the wire

The Energy deposited per proton is described by Bethe- Bloch formula

$$-\frac{1}{\rho}\left\langle \frac{dE}{dx} \right\rangle = \frac{KZ}{A}\frac{q_p^2}{\beta^2}\left(\frac{1}{2}\ln\left[\frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2}\right] - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right)$$



	ρ (g cm-3)	d (μm)	< E_D > (eV)
CNT	1.3	11.4	2063
		22.3	4151
Graphite	2	11.4	3154
		22.3	6365

Heating Model

Heating of the wire by hitting protons

Main Cooling processes:

- Conductive cooling
- Radiative cooling
- Thermionic emission

$$E_{\text{dep}} \frac{\Delta N_{\text{hits}}}{\Delta t} = \rho V c_p(T) \frac{\Delta T}{\Delta t}$$
$$\boxed{- A_{rad} \epsilon \sigma (T^4 - T_{amb}^4)} \boxed{- k(T) A_d \frac{\Delta T}{\Delta y}}$$
$$\boxed{- A_{rad}(\phi + \frac{2k_B T}{q_e}) J_{th}(y)} + C(y) \Delta R J_{th-tot}^2$$
$$- H_{sub} \frac{\Delta n}{\Delta t}$$

M. Sapinski, Model of Carbon Wire Heating in Accelerator Beam, CERN internal report CERN-AB-2008-030, 2008, https://cds.cern. ch/record/1123363/.

Brief about COMSOL

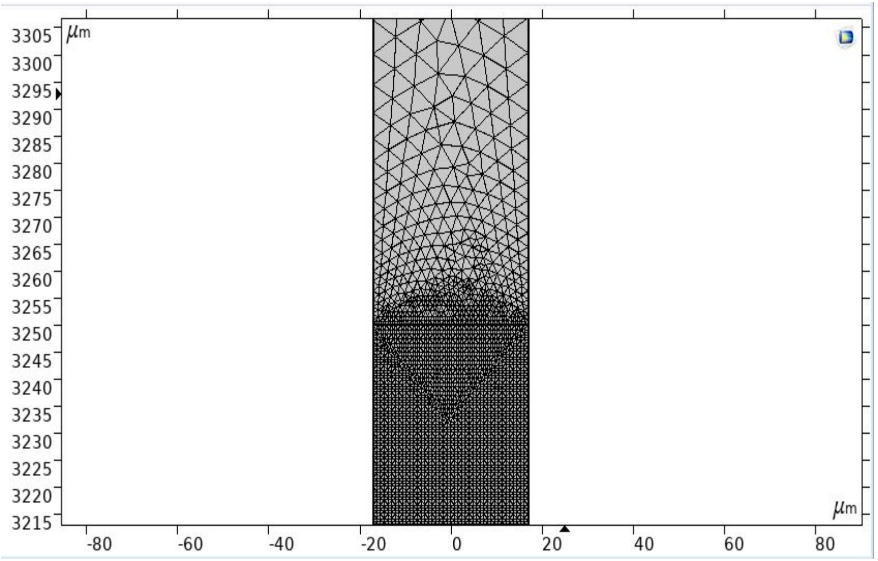
- Comsol is a software package solve physical problems using finite element method.
- FEM discrete the geometry into finite elements
- Each element has its own equations.
- All of the equations are assembled and

  being solved

- Advantages and disadvantages of FEM
- In this model, takes the reference frame

  of the wire

2D-Model



Comparisons between models

- Model implemented with COMSOL will be compared to results obtained by M. Sapinski in 2008.
- Three scans will be performed with the shown parameters., but with 3 different velocities.

Parameter	Value
Beam energy	450 GeV
Energy deposited by a proton E_{dep}	7640 eV
Wire's density ρ	2 g cm^{-3}
Wire diameter d	30 μm
beam σ_x	0.163 cm
beam σ_y	0.065 cm
Wire velocity	10 cm/s
Revolution time	2.3×10^{-5} s
No of protons in beam	2×10^{13}

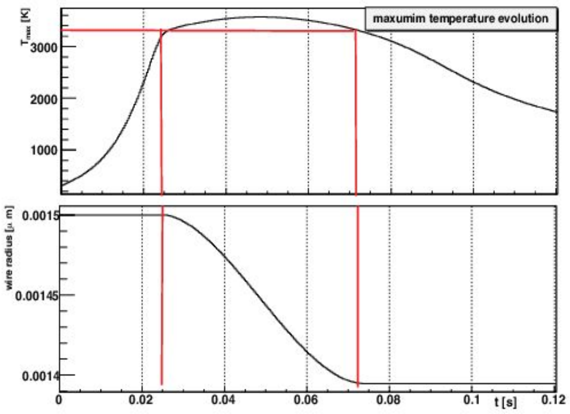
- Mean goal of the comparison

  is to check the COMSOL model

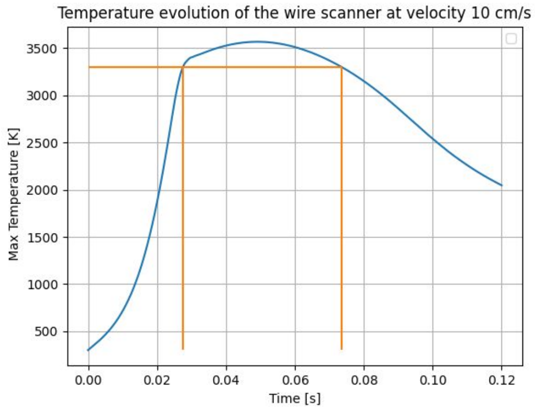
Velocity 10 cm/s

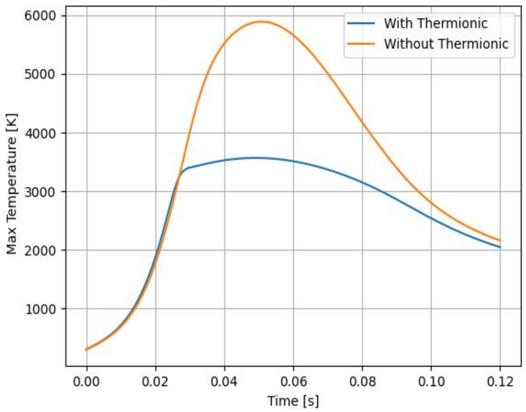
- The duration of the scan is 0.1 sec with max temperature reached at 49ms at the beginning of the scan.
- The sublimation rate increases drastically above 3300 K.
- The differences between the two results.

Result from M. Sapiniski



COMSOL model

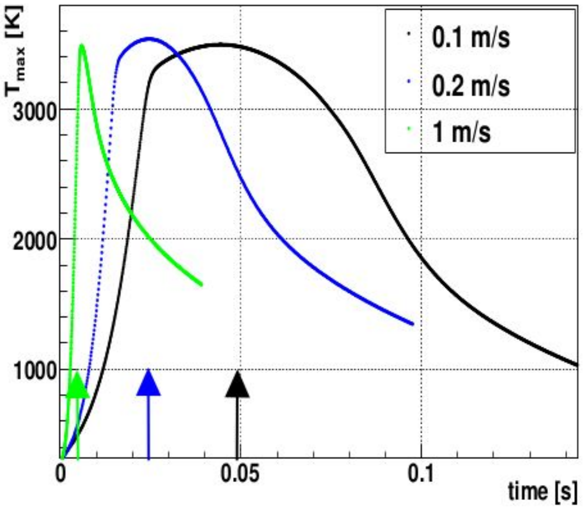




M. Sapinski, Model of Carbon Wire Heating in Accelerator Beam, CERN internal report CERN-AB-2008-030, 2008, https://cds.cern. ch/record/1123363/.

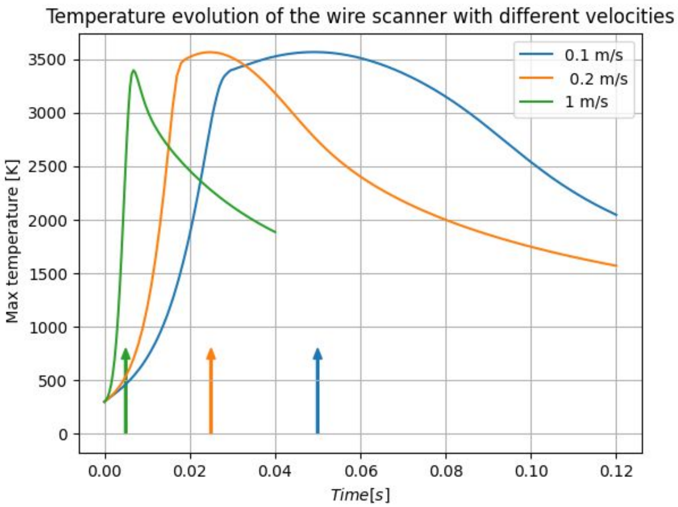
Different velocities

- Figures show the influence of the wire velocity on the temperature
- Scan with velocity of 1 m/s shows different temperature behaviour from slower velocities.
- Difference in the behaviour with scan 1m/s between the two models.



COMSOL model

M. Sapinski



CNT wires

- Assumption regarding the change some wire properties with changing the material of the wire CNT with iron impurities.
- Assumptions are made due to the lack of knowledge about the exact properties value.

$$c_p(T)_{CNT} = w_C \times c_p(T)_C + w_{Fe} \times c_p(T)_{Fe}$$

$$k(T)_{CNT} = w_C \times k(T)_C + w_{Fe} \times k(T)_{Fe}$$

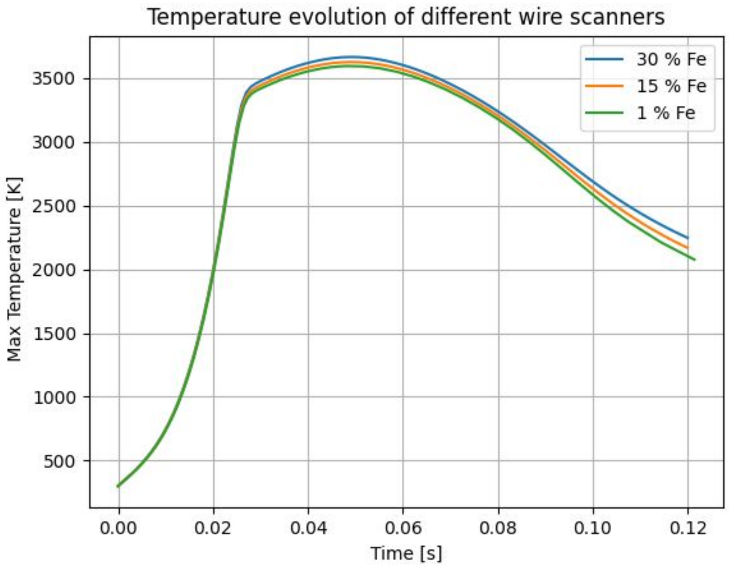
$$\frac{1}{\rho_{CNT}} = \frac{w_C}{\rho_C} + \frac{w_{Fe}}{\rho_{Fe}}$$

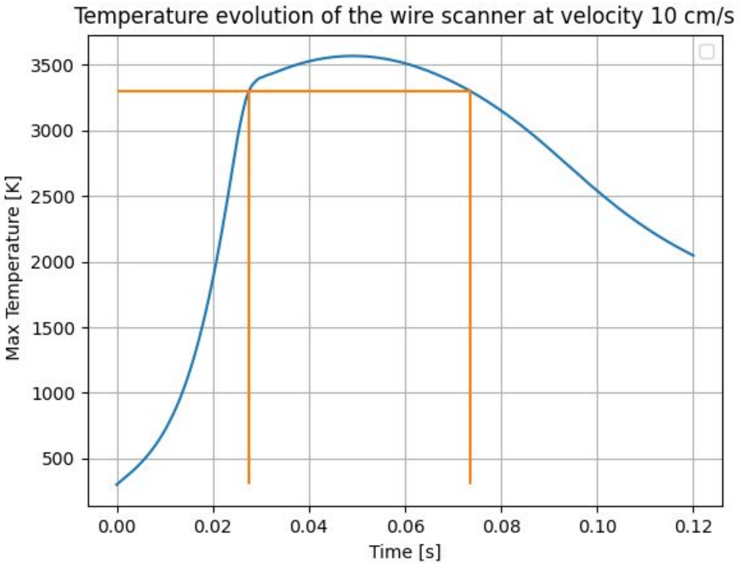
w_C and w_{Fe} are the weight fractions of carbon and iron

Alexandre MARIET’s Ph.D Thesis "Study of the effects of copper-coating and proton irradiation at 440 GeV on the mechanical properties of carbon nanotube wires for particle beam "

Behaviour of different CNT wires

- The change in the properties don’t show much temperature difference
- Example of the effect of thermal conductivity’s decreasing on temperature of portion near the wire center but not hit by the beam.
- Difference between maximum temperatures of wires with highest and lowest temperatures are about 100 K





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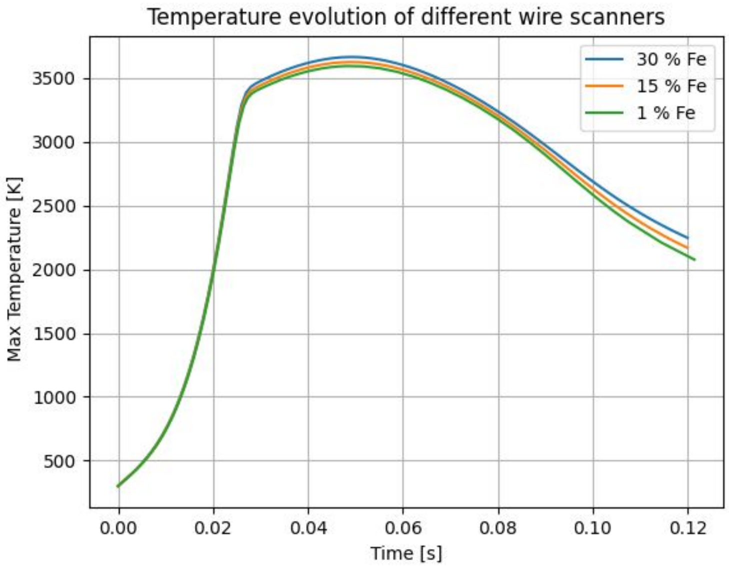

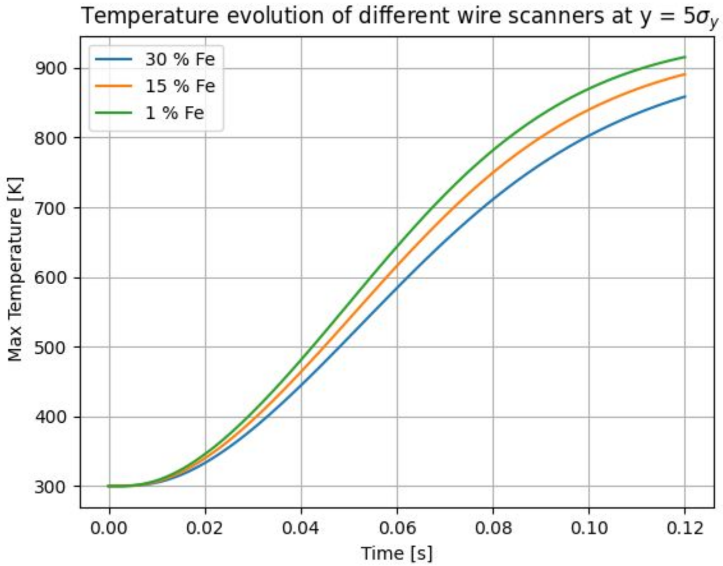

Conclusion

- WS are getting overheated during the scan and suffer from sublimation.
- Heating model is used to simulate the temperature evolution of WS taking into several cooling processes
- COMSOL model is compared with results obtained by M. Sapinski
- Three samples of CNT wires are investigated
- Model still needs improvements (E.g. 3D Model) and testings with various beam parameters
- There is interest in comparing the COMSOL model to PPYT code which is currently used (CERN & PSI beams)

Acknowledgements

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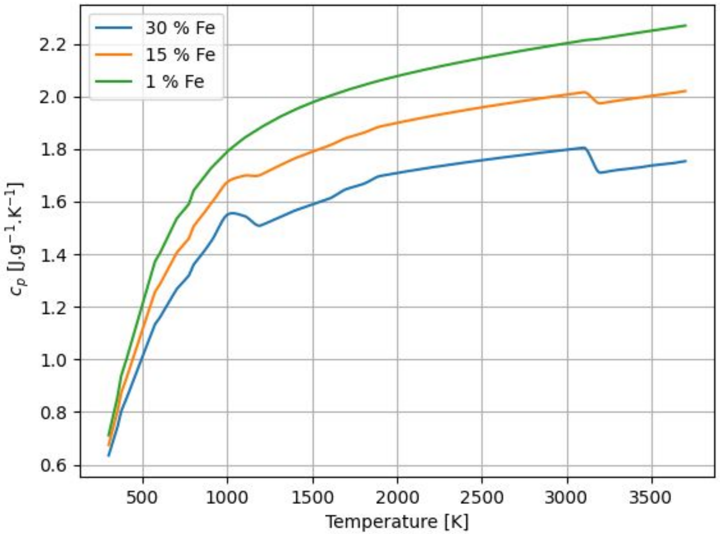
- Raymond Veness **(CERN)**

CNT wires

- With increase in iron percentage there is a decrease in the heat capacity and thermal conductivity and increase in the density.



Iron percentage	CNT density	E_{dep}
1%	1.713 g.cm^{-3}	8466 eV
15%	1.927 g.cm^{-3}	9457 eV
30%	2.223 g.cm^{-3}	10812 eV

Moving beam

- The COMSOL model is taking the reference of the wire.
- In this case the beam appears to move

Nb of protons' surface density [Protons / m^2]