LAB PROJECT MASTER 1 COMPUPHYS

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

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Contents

1 Abstract

In order to guarantee the stability of the beam shape during acceleration, wire scanners are tools used in accelerators to measure the transverse beam density profile. However, certain beam conditions can cause damage and sublimation to the carbon fiber wires currently in use. A heating model is used to simulate the wire's temperature evolution. Carbon nano tubes material is also introduced as replacement of carbon fiber because of excellent mechanical and thermal properties, to limit this problem and to extent this kind of material to higher luminosity in future projects at CERN (HL-LHC, FCC). The energy deposition of protons in the wire is analyzed, taking into account factors such as wire density and diameter. FLUKA simulation code is employed to calculate the energy deposition, considering the interactions between protons and the wire material.

The study focuses on estimating the temperature evolution of the wire scanner using a heating model that considers the beam-induced heating and cooling processes, including conduction, radiation, and thermionic emission. The author used COMSOL Multiphysics software for simulating the heating power balance equation.

This report will give a brief about the stopping power concept which quantize the energy deposition by protons in the beam on the wire, then introduce a heating model of the wire introduced by Mariusz Sapinski in 2008 and discussing the three main cooling processes in the model, namely the conductive cooling, the radiative cooling and the thermionic emission.

Results of model implemented in COMSOL will be compared with the results obtained by M. Sapinski and some comments will be given about the COMSOL model. Following this, the COMSOL model will simulate the temperature behaviour of three different CNT wires with various amount in iron impurities, which could be responsible in changing the thermal properties of the wires.

2 Introduction

CERN, the European Council for Nuclear Research, founded in 1954, is located on the Franco-Swiss border near Geneva. It is home to the largest particle accelerator complex in the world. The complex includes a series of linear and circular accelerators interconnected by transfer lines, leading up to the accelerator, the Large Hadron Collider (LHC). Within the LHC, beam collisions currently reach energies of 14 TeV, and future projects such as the Future Circular Collider (FCC) aim to increase this to 100 TeV.

The initial step of the accelerator chain involves generating protons from an hydrogen source, where the electrons are stripped away. These resulting protons are then directed towards LINAC4, the first accelerator in the sequence. LINAC4 raises the proton energy to 160 MeV.

Subsequently, the protons are transferred to the Proton Synchrotron Booster (PSB) for a further acceleration step, reaching up to 2 GeV. From there, they are transported to the Proton Synchrotron (PS), a circular accelerator. In the PS, the protons are attaining an energy level of 26 GeV.

Upon reaching 26 GeV in the PS, the protons are injected into the Super Proton Synchrotron (SPS), which is the second largest accelerator after the LHC with a circumference of 7 km. The protons undergo acceleration to 450 GeV.

Finally, they are transferred to the two rings of the Large Hadron Collider (LHC) of circumference 27 km and energy of 7 TeV per ring and 14 TeV upon collision. The particles within one ring circulate in a clockwise direction, while those in the other ring move counterclockwise. The counter-rotating rings intersect at the four detector cabins (ALICE, ATLAS, CMS, LHCb), where particle collisions occur and are observed and analyzed.

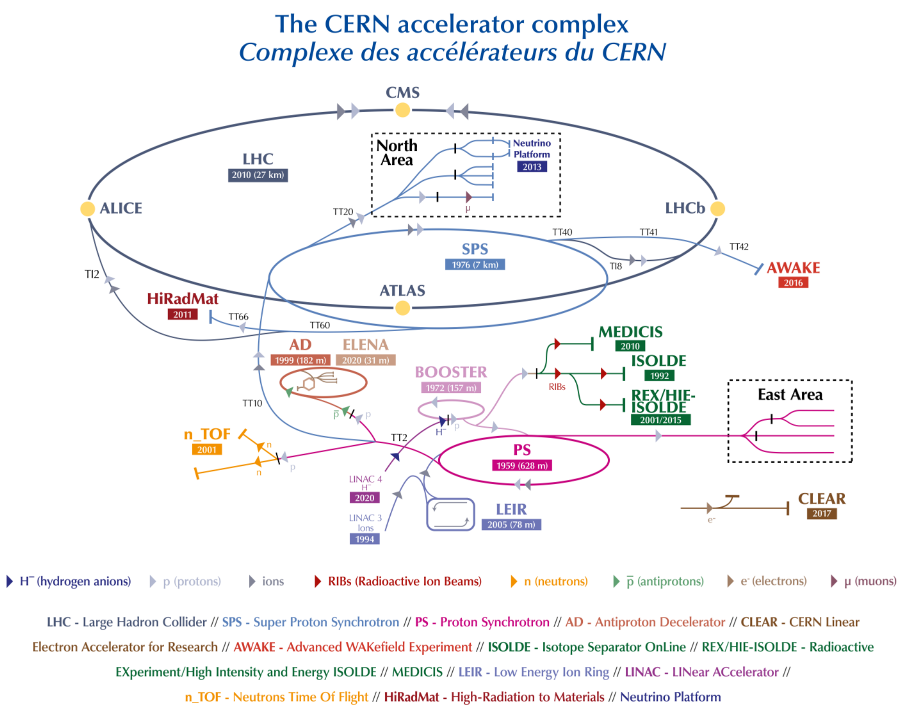


Figure 1: Scheme of Cern accelerators complex from Cern website

Wire scanners are devices that are being used since the 80's to measure the transverse beam density profile in accelerators to ensure the stability of the beam shape under acceleration. During the scan, the wire is moving across the beam with constant velocity. The shower of particles produced from the wire-beam interaction are being measured by a scintillator outside the vacuum pipe and the beam profile can be reconstructed [1].

After entering the beam and being radiated, it gets heated up and undergoes cooling processes by conduction, radiation, and thermionic emission. Depending on the beam parameters, it might melt or sublimate. The currently used wire which is composed of carbon fiber can be sublimated and damaged under some beam conditions. To overcome this problem, some solutions are proposed as reduce the interaction time between the wire and the beam, but this could lead to much reduction in the particle shower being measured by the detector, and decrease in the data needed to reconstruct the beam profile. Therefore the idea in searching for new materials that can be used with slower wire velocity, minimizing damages.

The material being for must have better mechanical and thermal properties, and low density to reduce the number of proton interactions with the wire and minimize the risk of over heating. Carbon nanotubes shows good combination of mechanical and thermal properties among several materials. A heating model depends on estimation of the beam inductive heating and the mentioned cooling process will be used to estimate the temperature evolution of the wire during the scan.[2]

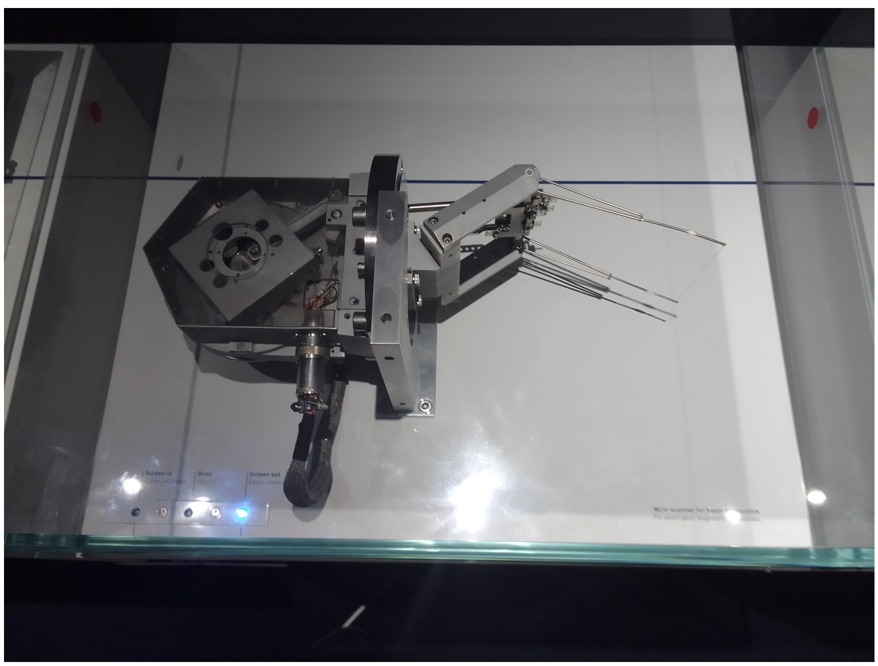


Figure 2: A dummy model of wire scanner at Cern. The wire is held by the forks at the right

3 Methodology

There are many parameters that must be taken into the account as the beam size, the beam position and its revolution time, the wire size and its scan velocity, the number of particles in the beam. Those parameters shape the temperature evolution in the wire [3]. When the beam is scanned by the wire scanner, the reconstruction of the beam profile gives a quasi-Gaussian shape. The beam is assumed to have Gaussian distribution in vertical and horizontal transverse plans. The transverse beam profile ρ_{part} surface density described in two-dimensional Gaussian distribution as :

$$\rho_{part} = N_0 \exp\left\{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right\} \tag{3.1}$$

with σ_x are σ_y are the beam sizes, while the normalization factor N_0 is described as :

$$N_0 = \frac{N_{tot}}{2\pi\sigma_x\sigma_y} \tag{3.2}$$

which is obtained from

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho_{part}\ dxdy = 2\pi\sigma_x\sigma_y N_0 = N_{tot} \tag{3.3}$$

The beam makes many revolutions during the scan, which make the same protons can be seen multiple times by the wire. The number of turns that are made by the beam is expressed by the diameter of the wire d, it's velocity v and the revolution time τ.

$$n_{turns} = \frac{d}{v\tau} \tag{3.4}$$

Which makes equation (3.2) become

$$N_0 = \frac{N_{tot} d}{2\pi\sigma_x\sigma_y v\tau} \tag{3.5}$$

We can accurately describe the surface density of number of protons passing through the wire and take into account the multiple revolutions the beam makes during the scanning process via these parameters and equations. By multiplying (3.1) by the energy deposition by a proton to the wire, we can obtain the energy density distribution of the beam.

3.1 Energy deposition

When a particle passes through a material, it has a certain probability of interacting with the nuclei or electrons present in that medium. For charged particles, such as protons, their primary interactions occur with the electrons of the medium, either through Coulomb force interactions or collisions. At lower energies, the contribution from nuclei interactions becomes more significant [4] .

The specific processes involved in the energy loss depend on both the irradiated material and the characteristics of the incident particle. In this discussion, we will specifically focus on protons, which are considered heavy particles. Protons primarily lose their energy by ionizing or exciting the atoms within the material.

To quantify the stopping power and the rate of energy loss for a specific particle traveling through a medium, the Bethe equation is employed. The stopping power represents the average rate at which the particle loses energy during its traversal through the medium [5] .

$$-\frac{1}{\rho}\left\langle\frac{dE}{dx}\right\rangle = \frac{KZ}{A}\frac{q_p^2}{\beta^2}\left(\frac{1}{2}\ln\left[\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2}\right] - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right) \tag{3.6}$$

with ρ, Z, A and I are the density, the atomic and mass number and the characteristic mean excitation potential of the material respectively, K is a factor depending on the classical electron radius r_e, the electron mass m_e and the Avogadro number and $\delta(\beta\gamma)$ is a correction function. $T_{\max}$ is the maximum energy transfer possible in a single collision[1]. The energy deposited can be calculated using FLUKA simulation code, which is a Monte-Carlo code used to simulate the interaction and transport of particles as hadrons, heavy ions in materials. The energy deposited on the wire depends on the density and the size of the wire as shown below (Fig. 3). The deposited energy increases with the wire diameter and the density, leading to increase in the number of beam - wire interactions More results can in found in [5] & [6].

	ρ (g cm^{-3})	d (μm)	$< E_{\mathrm{D}} >$ (eV)
CNT	1.3	11.4	2063
		22.3	4151
Graphite	2	11.4	3154
		22.3	6365

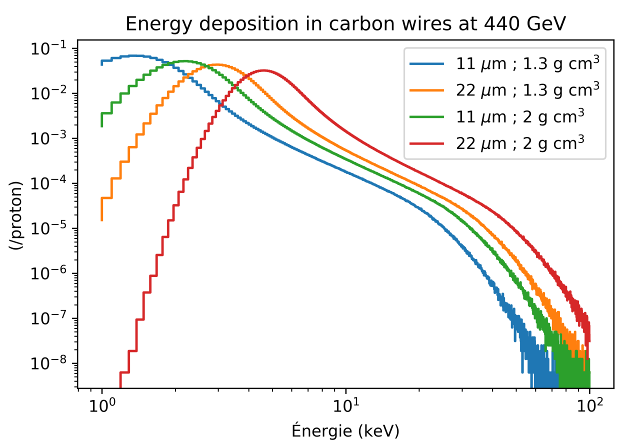


Figure 3: Previous simulations of energy deposition per proton for four carbon wires with different densities ρ and diameters d. The simulations were performed by Jean-Emmanuel Groetz

3.2 Heating model

The main work of this lab project is to try to simulate M. Sapinski 2008 heating power balance equation[6], using the COMSOl Multiphysics software. COMSOL Multiphysics is a simulation software program, based on the finite element method, and used for modeling and simulating various physical phenomena across multiple disciplines. It is designed to solve complex multiphysics problems by combining different physics domains, such as electromagnetics, structural mechanics, fluid dynamics, heat transfer and more.

The heating power balance equation represents heating of the wire by the beam and the right side represents the wire heat capacity and four cooling processes: radiation cooling, heat conduction along the wire, the thermionic cooling (together with re-heating by the current compensating thermionic current which gives negligible effect on the temperature evolution) and cooling due to sublimation[6].

$$\begin{aligned} E_{\text{dep}}\frac{\Delta N_{\text{hits}}}{\Delta t} &= \rho V c_p(T)\frac{\Delta T}{\Delta t} \\ &- A_{rad}\epsilon\sigma(T^4 - T_{amb}^4) - k(T)A_d\frac{\Delta T}{\Delta y} \\ &- A_{rad}(\phi + \frac{2k_BT}{q_e})J_{th}(y) + C(y)\Delta R J_{th-tot}^2 \\ &- H_{sub}\frac{\Delta n}{\Delta t} \end{aligned} \tag{3.7}$$

Variable	**Description**
E_{dep}	Energy deposited by a proton
ρ	Wire's density
$C_p(T)$	Specific heat in function of temperature
V	Volume of a wire bin where energy balance is calculated
A_{rad}	Surface of the wire which radiates heat
ε	Thermal emissivity
σ	Stefan-Boltzmann constant (5.67×10^{-12} s cm J2 K4)
T_{amb}	Temperature of environment
$k(T)$	Graphite thermal conductivity as a function of temperature
A_d	Wire cross-section $\pi d^2/4$
$\frac{\Delta T}{\Delta y}$	Local temperature gradient along the wire
k_B	Boltzmann constant (1.38×10^{-23} K·J)
ϕ	Work function per electron
J_{th}	Thermionic current surface density
q_e	Elementary charge (1.602×10^{-19} C)
$C(y)$	A fraction (between 0 and 1) of current compensating for thermionic emission
ΔR	Electric resistance of a bin of the wire
$J_{\text{th-tot}}$	Total thermionic current emitted from the wire
H_{sub}	Enthalpy of sublimation
Δn	Amount of material sublimated

Table 1: Description of the variables in the heating power balance equation.

One of the benefits of the model is that it takes into account the variation of thermal properties with temperature, such as heat capacity and thermal conductivity (although the emissivity shows only a weak dependence on temperature). This is particularly important because the high temperatures achieved cannot neglect these effects[5]. The model implemented in this lab project disregards the the last two processes (re-heating by the current compensating thermionic current and cooling due to sublimation) for simplicity since it's stated that they have negligible effects on the temperature behaviour. Heat conduction, radiation and thermionic emission are the cooling processes considered in the model

3.2.1 Heat conduction

Heat conduction refers to the transfer of thermal energy through direct contact between particles or objects. It occurs when there is a temperature difference between two adjacent regions in the wire, causing the higher temperature region to transfer heat to the lower temperature region. This transfer of heat occurs due to the random motion of wire atoms, where higher energy atoms collide with lower energy particles, transferring their energy and increasing the temperature of the cooler region. The heat conduction along the wire is governed by Fourier's law. Heat will be transferred from the region that is hit by the beam to along the wire. Its expression is given by:

$$-k(T)A_d\frac{\Delta T}{\Delta t} \tag{3.8}$$

The conductive cooling is expected to be low because of the small cross section of the wire, also because it is found that the thermal conductivity decreases with temperature. So it should have a low impact on the wire temperature compared to the other cooling processes, but it plays an important role at low temperature at which the radiation cooling and thermionic emission are inefficient. It's the dominant process to evacuate heat up to 1300 K. Using of a material of better thermal conductivity will not improve the cooling performance due to the decrease of thermal conductivity with heating.

3.2.2 Radiative cooling

Radiative cooling is a process by which an object or surface releases thermal energy in the form of electromagnetic radiation. It occurs when the temperature of the object is higher than its surroundings, causing it to emit radiation. The rate at which radiative cooling occurs depends on the temperature difference between the object and its surroundings, the emissivity of the object's surface and the surface area of the object. Higher temperature differences and higher emissivity values generally lead to more significant radiative cooling. It's driven by the Stefan-Boltzmann law and it is related to the fourth power of the temperature:

$$-A_{rad}\epsilon\sigma(T^4 - T_{amb}^4) \tag{3.9}$$

The radiative cooling is the dominant processes between 1300 Kto 3200 K with nearly 100% at 2400.

3.2.3 Thermionic emission

Thermionic emission refers to the process of electrons being emitted from the surface of a material when it is heated. When the material is heated to high temperatures, electrons near the surface gain enough energy to overcome the work function barrier and escape into the surrounding space. This cooling process becomes dominant at high temperature and is expressed as:

$$-A_{rad}(\phi + \frac{2k_BT}{q_e})J_{th}(y) \tag{3.10}$$

where the current density emitted from the wire $J_{th}(y)$ is:

$$J_{th}(y) = A_R \cdot T^2 \cdot \exp(-\frac{\phi}{k_BT}) \tag{3.11}$$

with $A_R = 4\pi mk^2e/h^3 = 120.173$ [A cm^{-2} K^{-2}]

Due to the exponential in its mathematical expression, the thermionic becomes dominant at high temperatures, above 3200 K and it is the process that is responsible to stabilize the temperature of the wire at 3500 - 3600 K.

4 Results

In this section, some results will be shown from the starting for comparing the model implemented in COMSOL with some results from [6]. Then, the investigation on some virtual CNT wires with some characteristics will be shown.

4.1 Comparison with previous results

The model provided by M. Sapinski in [6] is tested on some results of 1988 experiment on SPS beam with wire composed carbon material. During this experiment, some scans are performed with three different velocities. The wire was broken at speed of 10 cm/s. When the wire was at speed 20 cm/s, it was still not broken, although there was a possibility that it was weakened. The following discussion will be about the temperature evolution at wire's velocity 10 cm/s. Below is a table of parameters used in the simulation.

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}

Table 2: Parameters of beam and wire's characteristics used in the simulations below.

During the scan at 10 cm/s. the beam has made about 4250 revolution in about 0.1 s with peak power deposited when the beam center is reached at t=50 ms after the scan starts. Figures below show the temperature behaviour presented in M. Sapinski work and temperature evolution done with COMSOL. The wire reaches a temperature at 3200 K, the thermionic cooling processes becomes the dominant and starts to slows in a noticeable way till it reaches the maximum at around $t = 50$ ms, but the change when the thermionic emission takes place till 50 ms is small. It is stated in [6] that the wire sublimation is sharply noticed above 3300 K, but after that the sublimation rate weakly depends on the temperature which leads to importance of the scan duration and how long the wire temperature stays above 3300 K. The two behaviours show decent similarity, nevertheless with a small difference in the increasing temperature time to reach 3200 K. Another difference takes place at 0.12, where the reached temperature is less than 2000 K in the left plot, while it is above 2000 K in the right plot.

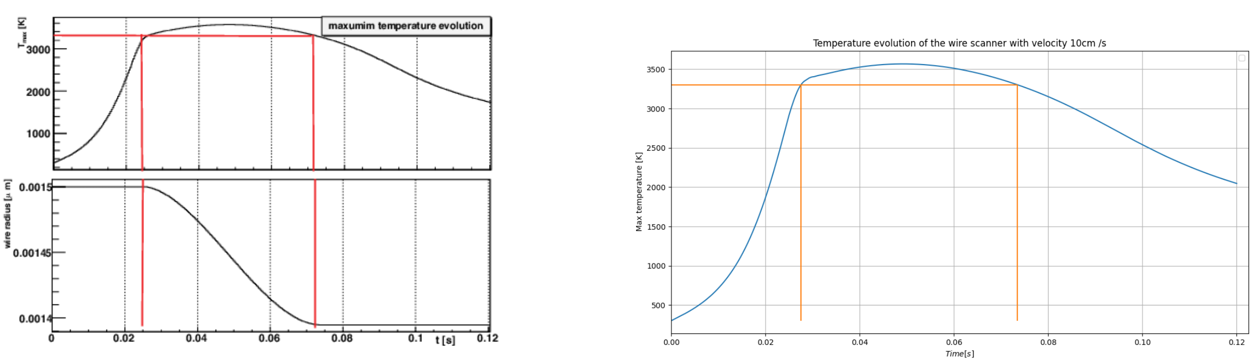


Figure 4: Temperature behaviour of a carbon wire scanner at 10 cm/s. Left plot: behaviour obtained from [6] associated with wire sublimation. Right plot: behaviour obtained from the model implemented in COMSOL.

In the plots below, we show the temperature evolution of the wire center during the scan, with the parameters from table 2 and for different wire velocities at 10 cm/s, 20 cm/s and 1 m/s. The arrows show the time when the wire reaches the beam center. It stated that the maximum temperatures for all velocities are between 3500 K and 3600 K, but for the wire velocity at 1 m /s, we can notice that the maximum temperature is slightly lower, i.e. 3400 K in the COMSOL model.

The fastest scan with velocity at 1 m/s reaches the beam center at approximately 5 ms after the beginning of the scan. We see that the wire continuous to absorb energy without noticeable influence of the cooling processes until the wire reaches the maximum temperature at about (6.2 ms in the left plot and 6.8 ms in the right plot), then the thermionic emission and radiative cooling cools down the wire rapidly.

This is different situation from the other wire speeds where the heating process happens fast that the cooling processes don't catch up. For slower speeds, the time is long enough to switch on the cooling processes [6].With faster velocities, the wire temperature stays above the sublimation temperature for shorter time which decreases the sublimation of the wire, but it also reduces the number of proton interactions with the wire, which might lead to not produce enough data to reconstruct the beam profile.

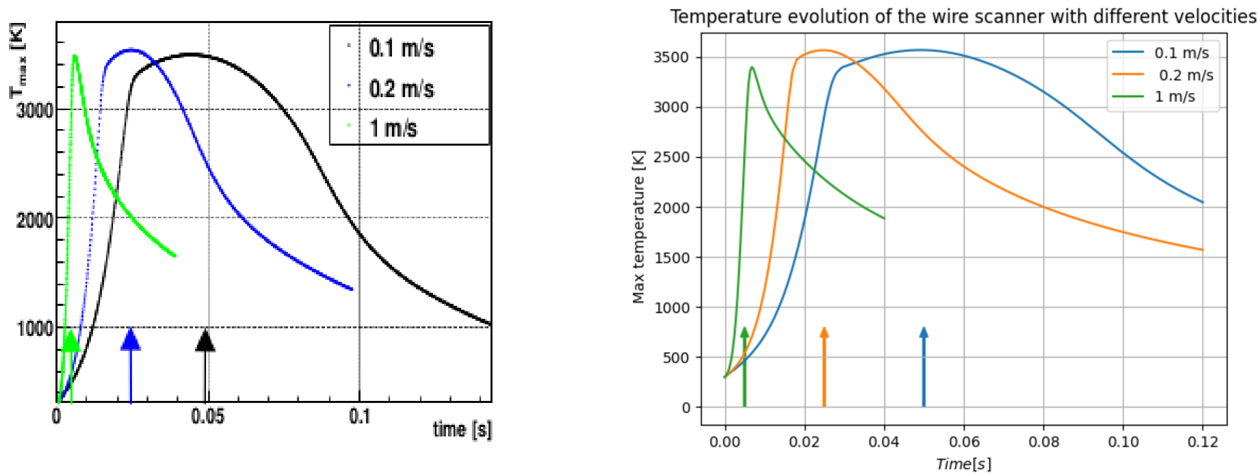


Figure 5: Temperature of the center of the wire with different velocity(10 cm/s, 20 cm/s, 1 m/s). the results obtained by M.Sapanski [6] are on the left , the results obtained by Model implemented in COMSOL are on the right.

4.2 Investigating some CNT wires

The discussion in this section will be about the temperature behaviour of some CNT wires with different ratios of carbon and iron impurities. The iron impurities are residuals from iron catalytic particles used in the manufacturing process of the wire and lacking of purification post-treatment [5]. The iron impurities could affect the properties of the CNT wire as the heat capacity and the thermal conductivity.

Since there are no data for the thermal properties of CNT wires, it is assumed that they are similar to the carbon fibers. By including the thermal properties of iron, the function of the heat capacity and the thermal conductivity of the CNT as a function of temperature are assumed to be a linear combination of each individual element as follows

$$c_p(T)_{CNT} = w_C \times c_p(T)_C + w_{Fe} \times c_p(T)_{Fe} \tag{4.1}$$

and

$$k(T)_{CNT} = w_C \times k(T)_C + w_{Fe} \times k(T)_{Fe} \tag{4.2}$$

where w_C and w_{Fe} are the weight fractions of the carbon and iron in the CNT wires. Some graphs of the heat capacities and thermal conductivities of the CNT wires can be found in [5] according to both equations above. They are showing decrease in the both heat capacity and thermal conductivity because those of the iron are lower than the carbon's ones, leading to a decrease in both thermal properties with the rise of the iron weight fraction in the CNT wires.

On the other hand, the density of the CNT in this lab project is treated as follows:

$$\frac{1}{\rho_{CNT}} = \frac{w_C}{\rho_C} + \frac{w_{Fe}}{\rho_{Fe}} \tag{4.3}$$

Since the density of iron is larger than that of carbon, a greater fraction of iron increases the wire density, which in turn increases the energy deposition in the wire, contributing in the rise of the wire temperature during the scan.

The accompanying figures below come from simulations performed for three CNT wires with iron fraction of 1%, 15% and 30%, still with the parameters from table 2, except for the wire diameter (34 μ m), density of carbon (ρ_C = 1.7 g.cm^{-3}) and iron density (ρ_{Fe} = 7.85 g.cm^{-3}). The table hereunder shows the density and the energy deposited in the different wires, from the FLUKA code simulation.

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

Table 3: Densities and energies deposited in different three CNT wires with different fractions of iron.

The results show that the increase in the density and the energy deposited in the wire, with the increase of the iron fraction, does not affect so much the maximum temperature, since the lowest iron percentage and the highest percentage give only a difference of about 100 K. On the other side, the decrease in the heat conduction cooling process is not affected much as in the right plot below shows the biggest difference in the temperature at length 5 times σ_y is less than 100 K. This results show an optimistic view of decreasing the maximum temperature with less dense wire.

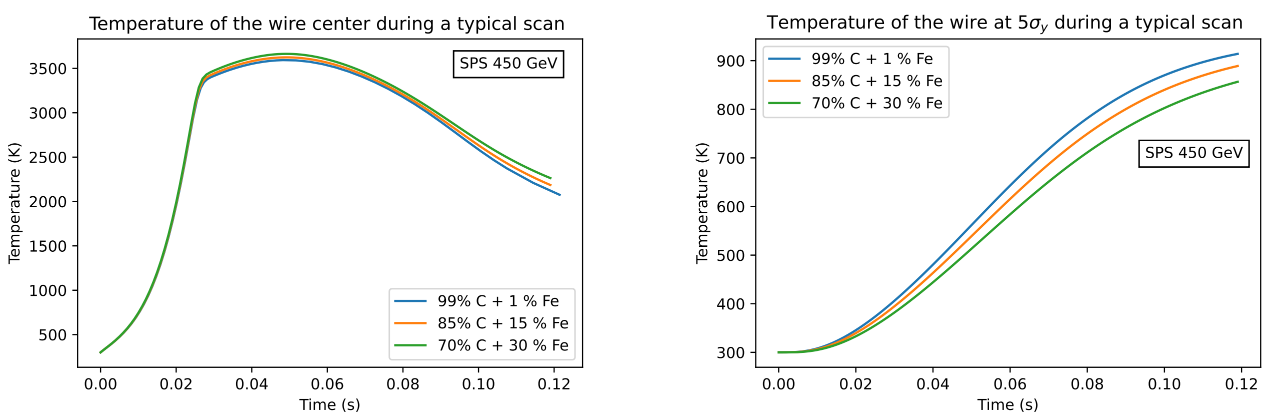


Figure 6: Temperature evolution of different CNT wires with different amount of iron impurities (1%, 15%, 30%) showing increase in the max temperature but showing lowering in the conduction process with rise of iron amount.

5 Conclusion

Wire scanners are essential devices used in accelerators to measure the transverse beam density profile. By moving a wire across the beam and detecting the particles emitted during the interaction, the beam profile can be reconstructed. However, the current wire materials, such as carbon fiber, suffer from damage and sublimation under certain beam conditions. The search for alternative materials with improved mechanical and thermal properties is underway. Carbon nanotubes, known for their exceptional mechanical and thermal characteristics, are being explored as potential candidates for wire scanners. The temperature evolution of the wire scanner is crucial in understanding the effects of beam-induced heating and the subsequent cooling processes.

During beam scanning, the temperature evolution in the wire scanner is being investigated. We carefully considered a number of factors that have an important impact on the temperature profile, like beam size, position, wire size, and particle count. We made the assumption that the transverse beam profile follows a Gaussian distribution. In addition, we took into account the beam's numerous rotations during scanning, which affect the wire's overall temperature evolution. The Bethe equation was highlighted as a way to quantify the rate of energy loss and the stopping power for protons in the wire material as we talked about the energy deposition process, while.the heating model used in this lab project was based on M. Sapinski's heating power balance equation. It considers the energy deposition by protons and the cooling processes of heat conduction, radiative cooling, and thermionic emission. The model takes into account the variation of thermal properties with temperature, by simulating the temperature behavior of the wire under these influences.

The COMSOL model for carbon wire scanners and the results from M. Sapinski's research can be compared in terms of temperature evolution . The simulations in COMSOL display behaviors similar to those described in [6]. Around 3200 K, the wire's maximum temperature at which point thermionic cooling takes over. In the COMSOL model, the rise in temperature that leads to the maximum temperature is slightly slower. When comparing different wire speeds, slower speeds allow cooling processes to catch up while faster speeds cause a fast rise in temperature and a corresponding fast fall in temperature. The findings indicate that the wire's sublimation and data collection for beam integrity depend on how long it is exposed above the sublimation temperature.

The heat capacity and thermal conductivity of the wires are impacted by iron impurities that are present because of the manufacturing process. It is believed that the linear combination of carbon and iron properties determines the heat capacity and thermal conductivity of CNT wires. Results indicate that as the iron fraction increases, heat capacity and thermal conductivity decrease. As the iron fraction rises, the wire's density also rises, increasing the energy deposited and wire temperature during scanning. However, there is little impact on the maximum temperature reached. For those simulation parameters, a decrease in thermal conductivity has only a small impact on the conduction cooling process.

All these suggest that the model may undergo some improvements, such as a 3D model. Also the results encourage to simulate the temperature of less dense CNT wires that might result in notable decrease in the max temperature.

6 Appendix : Technical report

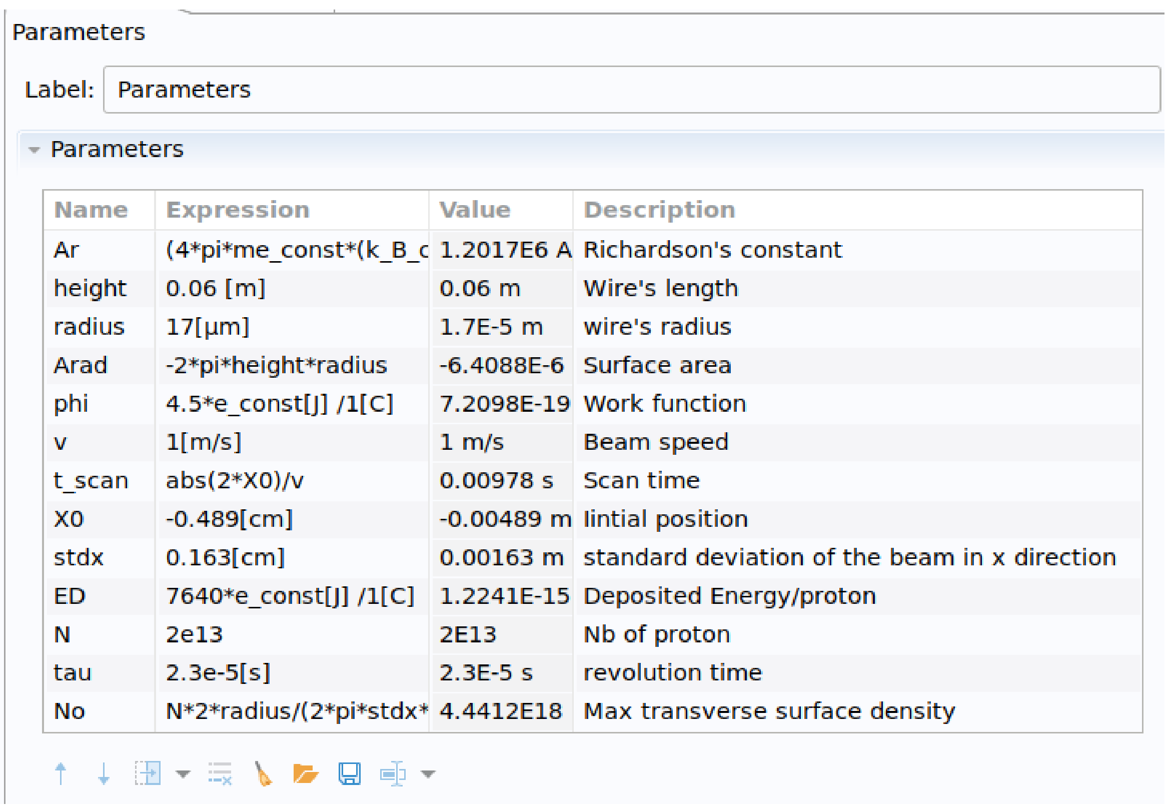
This lab project uses COMSOL which is a software package used to modeling simulating various phenomenon using the Finite Element Method (FEM). FEM is a powerful numerical technique used to solve scientific problems governed by partial differential equations (PDE).

Due to its ability to deliver precise solutions by increasing the number of elements, the finite element method has several advantages. Additionally, it is adaptable, enabling the analysis of various physics issues within the same framework. However, it faces obstacles like implementation complexity, the requirement for appropriate mesh generation, and challenges in achieving solution convergence for specific issues. The finite element method is widely used in engineering and science to address a range of issues despite these difficulties. It is now considered to be a standard tool for predicting behavior and understanding physical phenomena.

The COMSOL model is simulating equation (3.7) to predict the temperature evolution of the wire scanner during the beam scanning. To perform the simulation the model a number of input that in general are the wire and beam parameters. The parameters are put in the parameters subtab which is in global definition tab.

6.1 Global definition tab

The main thing in COMSOL user interface is the model builder. It contains all the information about the system and the computation and it consists of different tabs. In the global definition tab the tables of thermal conductivity o both carbon and iron obtained from JANAF and EFUNDA and a function are created in the tab to calculate the thermal properties in the CNT by summing the tables of the each material theraml properties using equations (4.1) and (4.2).


Parameters

Label: Parameters

Parameters

Name	Expression	Value	Description
Ar	(4*pi*me_const*(k_B_c	1.2017E6 A	Richardson's constant
height	0.06 [m]	0.06 m	Wire's length
radius	17[μm]	1.7E-5 m	wire's radius
Arad	-2*pi*height*radius	-6.4088E-6	Surface area
phi	4.5*e_const[J] /1[C]	7.2098E-19	Work function
v	1[m/s]	1 m/s	Beam speed
t_scan	abs(2*X0)/v	0.00978 s	Scan time
X0	-0.489[cm]	-0.00489 m	Iintial position
stdx	0.163[cm]	0.00163 m	standard deviation of the beam in x direction
ED	7640*e_const[J] /1[C]	1.2241E-15	Deposited Energy/proton
N	2e13	2E13	Nb of proton
tau	2.3e-5[s]	2.3E-5 s	revolution time
No	N*2*radius/(2*pi*stdx*	4.4412E18	Max transverse surface density

Figure 7: parameters section in global definition tab

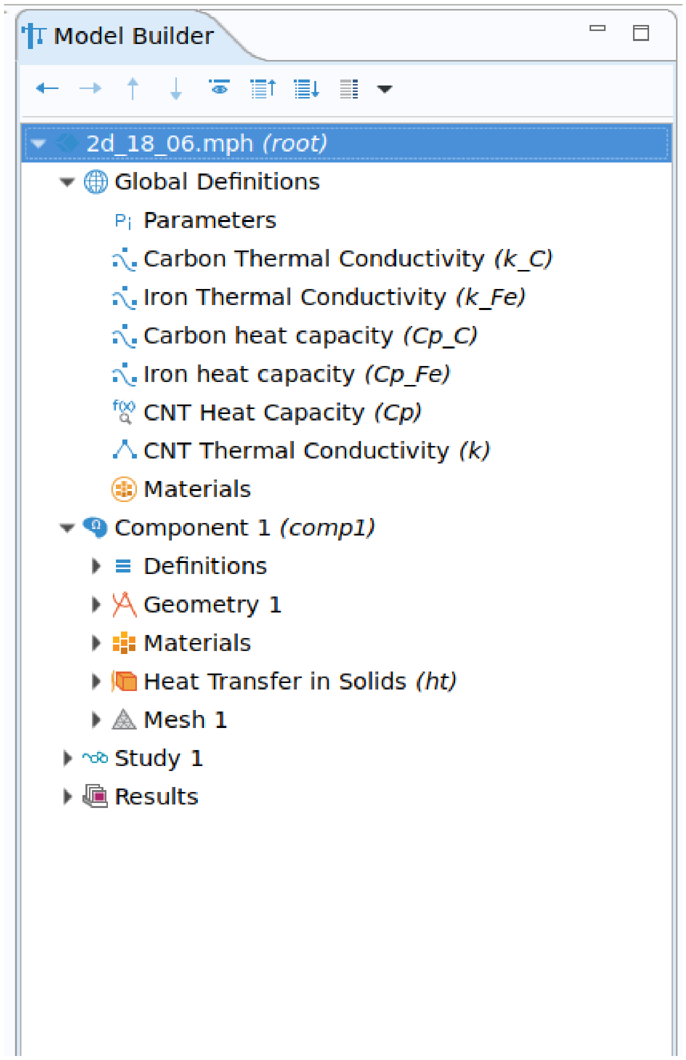


Figure 8: Model builder which contains all the information in the model

6.2 Component tab

The Second tab is the component tab which contains all the system, their geometry, their materials and maybe the physical equations that govern the system.

6.2.1 Geometry subtab

The Geometry of the system is simple. It is just a 2D shape (Rectangle because there is no cylinder in 2D model in COMSOL) with height of wire's length and width of the diameter of the wire and points where you want to measure the temperature evolution and combine the shape and points using the constructive sold geometry 's union operation.

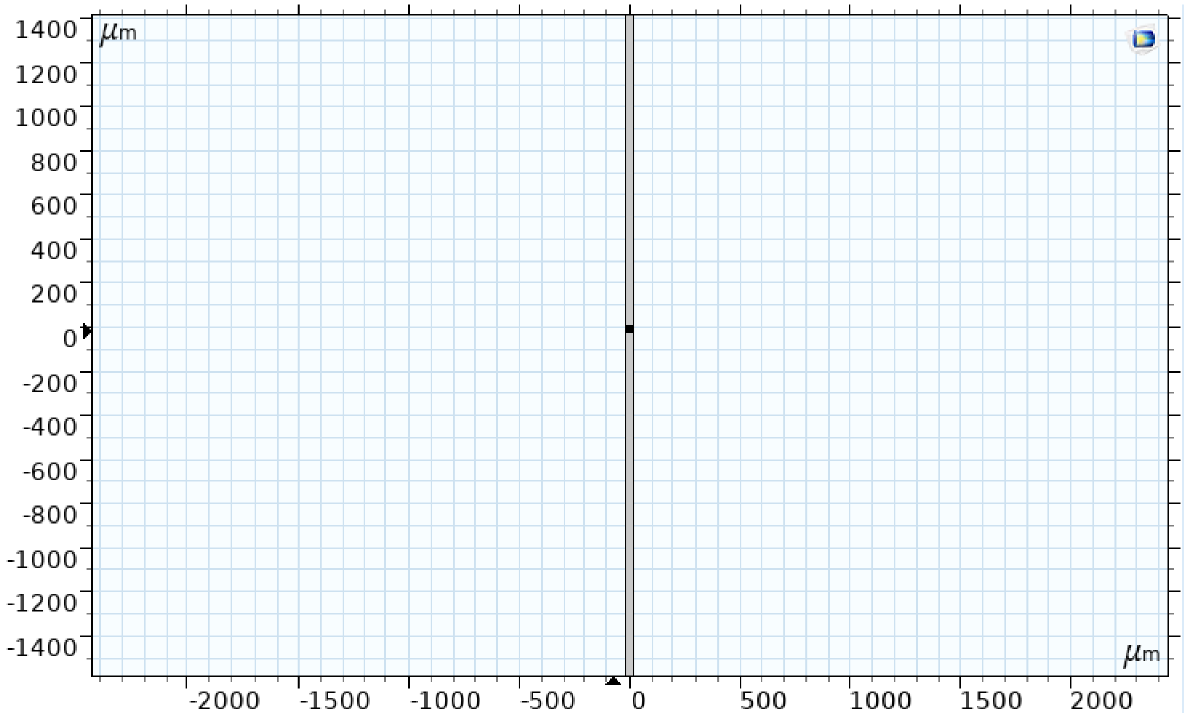


Figure 9: Geometry of the model. the point at the middle is used to measure the temperature at the center of the wire.

6.2.2 Materials subtab

The Materials subtab in COMSOL allows us to define the material properties of the various components in the model and assign materials to the geometry. To assign materials to the geometry, we can select the geometry in the model tree, and then select the desired material from the Materials subtab. Or we can create new materials and define their properties manual. Here we can define the density of the geometry, and assign the heat capacity and the thermal conductivity tables to those of the geometry in the materials subtab.

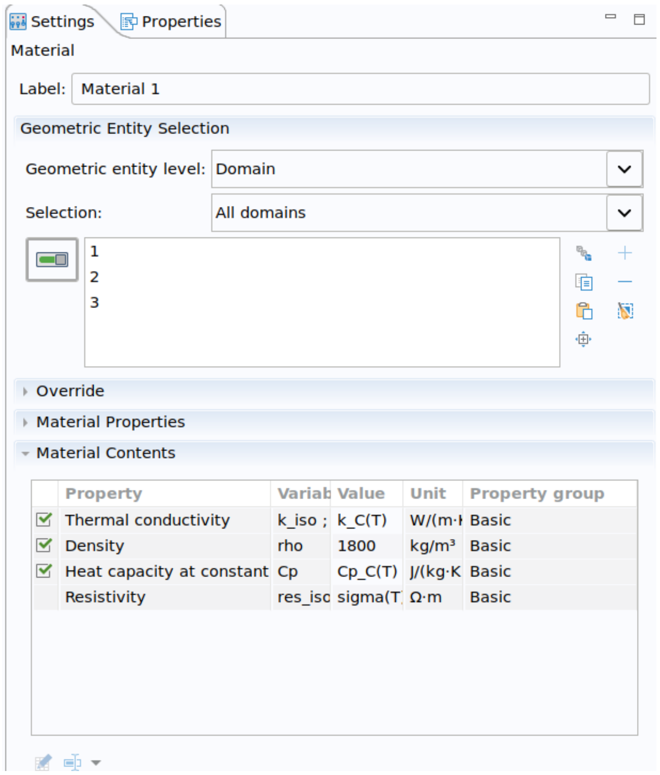


Figure 10: Materials section where different properties are defined

6.2.3 Heat transfer in Solids

The Definition of the heat module in COMSOL's user guide is "The Heat Transfer Module is an optional package that extends the COMSOL modeling environment with customized physics interfaces and for the analysis of heat transfer. It is developed for a wide audience including researchers, developers, teachers, and students".

The heat transfer module contains many physics interfaces that one of them is the heat transfer in solids which is being used in the model. It is an interface used to model heat transfer in solids through conduction, convection, and radiation.

When the interface is added there are nodes defined such as the initial values in which the initial temperature is inserted, Thermal insulation node for which the insulated boundaries of the are added. The Beam heating and the cooling processes are defined in the interface, they can be defined in *Heat Source* node or in *heat* flux node by insert the equations describing them in the nodes analytically.

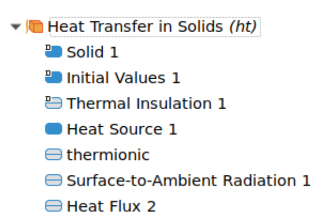


Figure 11: Heat transfer in solids interface and associated nodes

6.3 Mesh tab

After the geometry is formed and the physics is defined , the mesh has to be build as it has the significant role on how the model is solved. The mesh tab defines how the geometry will be divided, the shape and number of the elements forming the geometry. It affects the how long the simulation will take, the memory used to compute the problem, and the accuracy of the solutions.

The mesh can be defined automatically by COMSOL according to the physics is used or manually by the user. In this Model the mesh is defined manually due to the order of magnitudes difference between the dimensions of the geometry. The mesh has to be very small due to micro-size of the wire radius. but since the wire length is longer than the radius by three or four order of magnitudes, the computation will be very large and will consume an enormous amount of memory . To overcome this problem, the geometry is divided into 3 layers, the middle layer which is hit by the beam has a very dense mesh, while the other layers have coarse mesh. The left figure is the mesh tab and associated nodes. The size node is used to determine the size of the mesh, while the other two nodes are used to determine the shape of the mesh and to set the scale of the mesh in each of the layers. the right figure is a visualization of the meshing on the geometry at the boundaries of the upper layer and the Central layer.

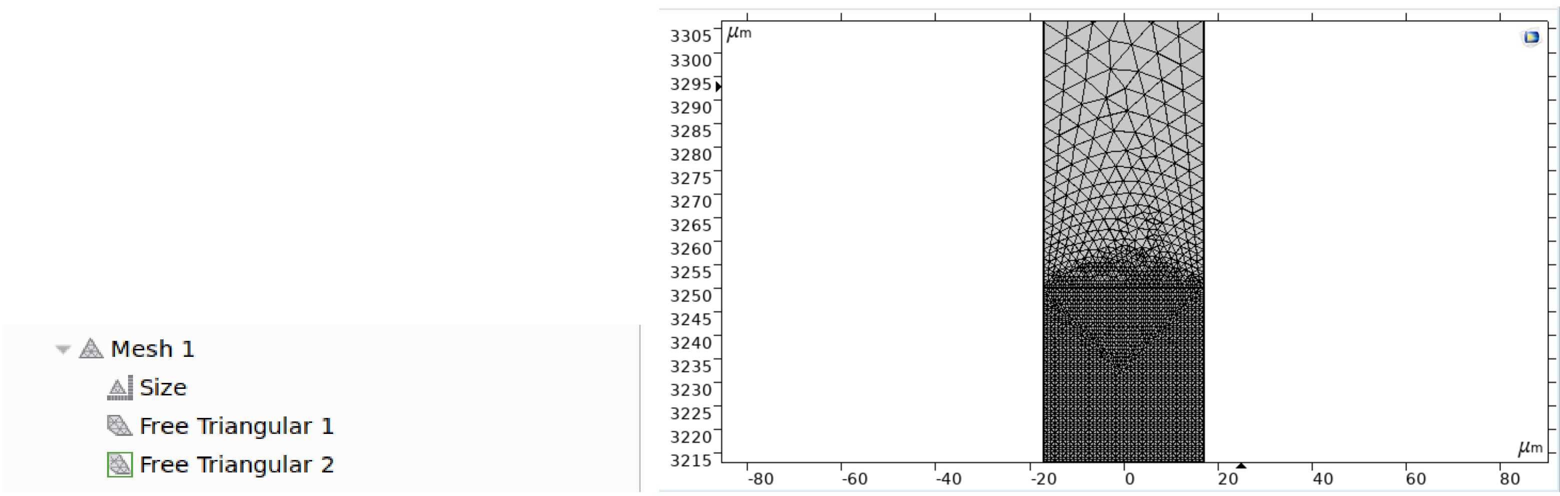


Figure 12: The left figure is the mesh tab and associated nodes. The right figure is the geometry's mesh

6.4 Study tab

The study tab is a tab to control the general parameters of the simulation as the duration of the simulation, the time step, selecting the physics that is used in the simulation from the Model builder and what mesh will be used if more than one are defined. The most important function of the study tab is that it's used to start the simulation. The simulation takes about 40 minutes and consume a considerate amount of memory.

6.5 Result tab

After the simulation is done all the data are stored in the result section. The temperature evolution in the wire scanner at each time step. Tables ad graph of the temperature evolution at a certain point defined in the wire in the geometry subtab can be produced. The data also can be extracted in a .txt files.

A graphical surface heat map of the wire scanner can be visualized and an animation of the dynamics of the system can be produced. in the result tab which is an advantage to COMSOL . Also a summary report about the simulation can be produced in this tab.

Figure 13: A graphical heat map of the wire. Due to the large difference between the dimensions of the wire. the whole wire is can't be displayed in one shoot. The two figures display the center of the wire up to 1.5 mm from the center

7 References

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