SIMULATED BEHAVIOR OF CNT WIRES IRRADIATED IN THE HiRadMat EXPERIMENTAL LINE AT CERN

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Abstract

With the planned increase of luminosity at CERN for HL-LHC and FCC, instruments for beam quality control must meet new challenges. The current wires, made up of plain carbon fibers and gold-plated tungsten would be damaged due to their interactions with the higher luminosity beams. We are currently testing a new and innovative material, with improved performance: carbon nanotube fibers (CNTF). The HiRadMat (High Radiation for Material) experimental line at the output of the SPS is a user facility which can irradiate fix targets up to 440 GeV/c. CNTF with various diameters were irradiated in HiRadMat with different intensities, later imaged with a SEM microscope and tested for their mechanical properties. In addition, simulations have been carried out with the FLUKA particle physics Monte-Carlo code [1], in order to better understand the mechanisms and assess the energy deposition from protons at 440 GeV/c in those CNTF wires, depending mainly on their diameters and densities. This could lead to a good estimation of the CNTF temperature during irradiation. In this contribution, we first present the HiRadMat experimental setup and then we discuss the results of our FLUKA simulations.

INTRODUCTION

The search for performance in particle accelerators and in particular the increase in luminosity [2] pushes the engineering of beam instrumentation to be always at the cutting edge of technology. The precision of the quality control of the beams throughout their acceleration is paramount. Transverse profile monitoring is particularly challenging as it is often based on intercepting devices such as wire-scanners and SEM grids. Operational systems at CERN [3] typically use wire made out of carbon fiber and gold-plated tungsten. These materials in the form of wires are subjected to high mechanical and thermal stresses due to the energy deposited by the particles in the material. The physical properties of those materials have reached their limits for very high beam energies / intensities such as those obtained in the CERN Super Proton Synchrotron (SPS) and Large Hadron Collider (LHC) . The search for new and innovative materials that could be used in all beam conditions has therefore become a necessity. By their exceptional properties, carbon nanotubes, existing in the form of microscopic fibers, seem to be an ideal candidate. This paper presents, together with energy deposition simulations, the setup of an experiment performed at the HiRadMat beam line at CERN for the irradiation of carbon nanotube wires (CNT) with high intensity proton beams at 440 GeV/c [4, 5].

WIRE MANUFACTURING

CNT were produced at the IMDEA by floating catalyst chemical vapor deposition (FCCVD) in a reactor tube of mullite ceramic (SiO_2) heated to 1570 K with toluene (C_7H_8) and ferrocene ($Fe(C_5H_5)_2$) as carbon and iron source respectively. The carrier gas was hydrogen (H_2). The CNT obtained are mainly double or few multiwalls and some hundreds of μm long. The assembly of individual tubes to form a microscopic fiber (CNTF) occurred in the gas phase during growth. CNT entangle and form a dark aerogel which is drawn through and out of the reactor tube. This aerogel of CNT deposits on the winder to produce a fiber [6, 7] (Fig. 1-a and b). The diameter of the final fiber is controlled by varying the spinning rate of the winder, from 7 m/min for the thick diameters, to 28 m/min for the thin diameters.

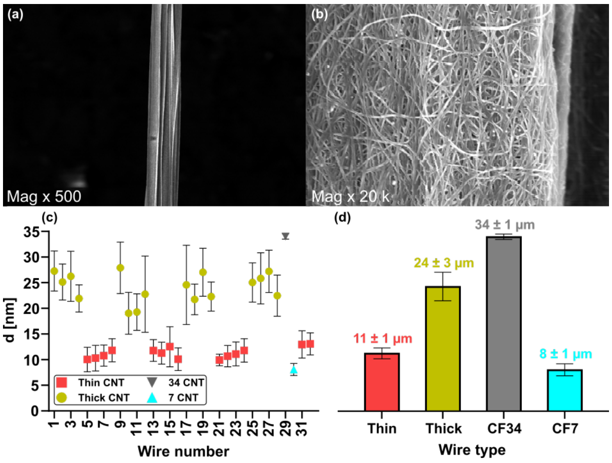

Figure 1: SEM pictures of an as-spun CNTF with a magnification of (a) x500 and (b) x20000; (c) Summary of the average diameters of each sample; (d) mean values in diameter for the thin and thick CNT fibers and average diameter for the 34 and 7 μm carbon fiber. CF stands for Carbon Fiber.

The diameter of the samples was estimated by 30 measurements all along the axis of the wires. Figure 1-d shows the average diameter of the 32 wires with the standard deviation. The red bar represents thin wires and shows an average diameter of 11 μm, the green bar the thick wires with 24 μm diameter and the grey and blue bars the 34 and 7 μm diam-

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eter carbon fiber respectively that are currently considered for wire-scanners.

EXPERIMENTAL SET-UP

Main Purpose

The HiRadMat beam line at CERN offers the possibility of testing and irradiating materials with protons extracted from the SPS. The facility can be tuned to provide a very wide range of beam parameters (momentum (p), beam size (σ_b), number of bunch (N_b), bunch intensity (I_b)) from low to high beam densities.

The purpose of the **CNT Yarn Characterization at High Irradiation** (CYCHI) is to irradiate carbon nanotube fibers and validate up to which extreme conditions they could replace the current carbon wire in Wire Scanners.

Two family of carbon fibers, with 7 and 34 µm were installed and tested using high momentum (440 GeV/c protons and an increasing intensity per beam up to $3.2{\cdot}10^{13}$ protons per beam. After irradiation, the fibers will be tested in tension.

CYCHI was conceived to re-use standard hardware components from the CERN beam instrumentation group (i.e. SEM grid and Beam TeleVision) that will be mounted on a custom vacuum tank closed by CF flanges and glassy carbon windows (Fig. 2).

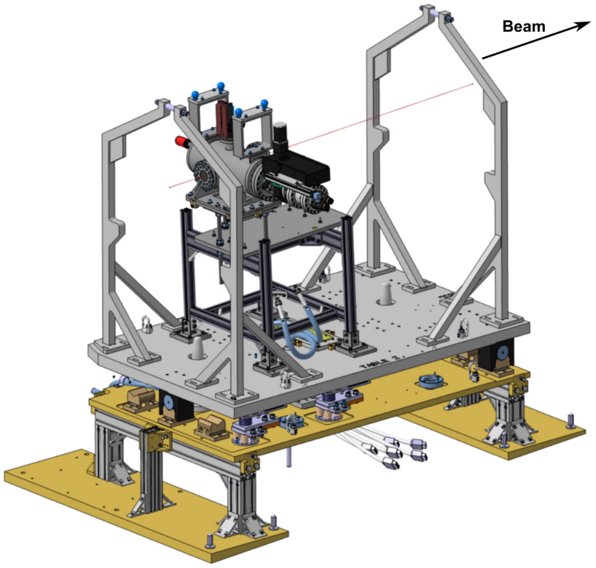

Figure 2: CYCHI experimental setup - (a) CAD model of CYCHI installed on the table B; (b) HiRadMat experimental line in the tunnel.

SEM Grid

Principle: The Secondary Electron Emission grid (SEM) is an instrument commonly used at CERN for measuring transverse beam profiles. The principle is to use a grid of wires spaced by a given distance. When the beam crosses the grid, the interaction between the particles and the wire creates secondary electron emission (SEM). As the diameter of the wires is the same, the number of secondary electrons emitted from each wire is proportional to the number of interacting particles such that a beam profile can be reconstructed by plotting the SEM current for each wire.

In CYCHI, a SEM grid is used as a support to irradiate different CNTFs. The distance between each CNTF is set to 4 mm, a distance large enough compared to the beam size in Hiradmat such that neighboring wires are not impacted during the irradiation test.

Wire support: The design of the grid was conceived not only as mechanical support but it also incorporates an electric circuit. Each wire was connected to a common ground via a 1 MΩ resistor with which it was possible to verify the state of the wire within the vacuum chamber. The support was made out of glass composite material and produced as a PCB (Fig. 3-a). In addition, two polarization plates in stainless steel, crossed by high voltage, are installed on both side of the grids to collect the secondary electrons (Fig. 3-b).

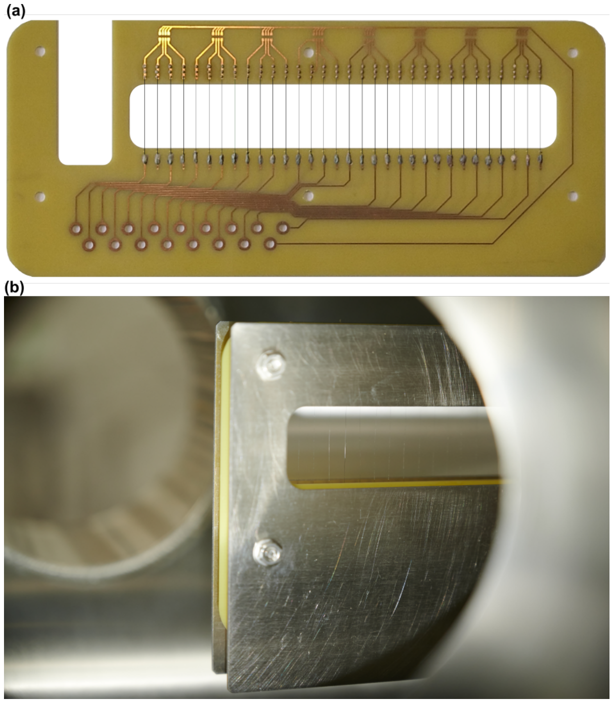

Figure 3: Experimental grid - (a) PCB and electronic outline of the support, tracks and resistors.; (b) Grid with polarisation plates mounted in the vacuum tank.

BTV

A Beam TeleVision (BTV) combines a fluorescent screen oriented at 45° from the beam axis with a camera placed on the top of the screen which captures the light produced by the interaction between the beam and the screen. The screen is composed of Chromox (99.5% of Al_2O_3) and 0.5% of Cr_2O_3), 500 µm thick, mounted on an aluminium support. Four small slits have been machined close to the edges of screen to monitor where its center is and provide a position

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reference for further measurements. By comparing the beam position measured on this screen and on another BTV placed downstream on the beam line, a precise positioning of the wires can be done, ensuring the protons cross the wires in its middle (Fig. 4).

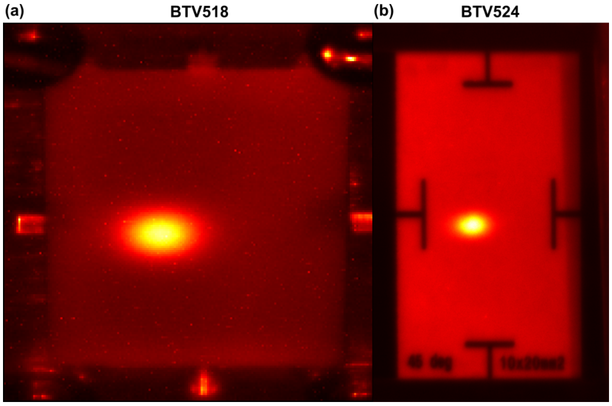

Figure 4: Beam image comparison for alignment - (a) raw BTV518 image; (b) image from reference BTV.

For each wire, the beam intensity was progressively increased from 1 to 10 pulses of 288 bunches, with a nominal number of protons per bunch of 1.1·10^{11}. The beam size on the wire was measured by the BTV. It was chosen to be $\sigma_h = \sigma_v = 0.25$ mm for the first part of the experiment and 0.50 mm for the second part.

Beam-Wire Interaction

This section is a theoretical estimation of the beam-CNTF interaction. Secondary electron emission is a surface phenomenon [8]. The signal measured by the SEM grid is directly function of the number of particles interacting with the wire. The fraction of the beam crossing the wire can be deduced from the horizontal relative alignment of the beam to the wire, the diameter of the wire, the horizontal beam size and the beam intensity. The intensity in the wire is expressed by

$$I_w = I_{beam}\frac{1}{2}\left[\mathrm{erf}\left(\frac{\frac{d_w}{2}-\mu}{\sigma_h\sqrt{2}}\right)+\mathrm{erf}\left(\frac{\frac{d_w}{2}+\mu}{\sigma_h\sqrt{2}}\right)\right], \qquad (1)$$

where d_w is the diameter of the wire, μ the horizontal gaussian center of the beam, σ_h the horizontal beam size and *erf* the error function.

The real beam sizes were measured at 0.28 mm and 0.56 mm and the intensity of the beam between 2.66 and 3·10^{13}. Considering the measured values of beam size and intensity, the average numbers of protons crossing the wire I_w for nominal beam size of 0.25 mm are 4.28·10^{11} ± 3·10^{10} and 8.68·10^{11} ± 1.20·10^{11} for thin and thick wires respectively. The numbers for a nominal beam size of 0.50 mm are 2.21·10^{11} ± 2.69·10^{10} and 4.62·10^{11} ± 4.35·10^{10} for thin and thick wires respectively.

The number of interactions can be calculated by

$$N_{int} = I_w\left(1-\exp\left(-\frac{d_w\pi}{4}\frac{\rho N_A\sigma_i}{M}\right)\right), \qquad (2)$$

where ρ is the density of the material, N_A the Avogadro number, σ_i the inelastic collision cross section (σ_i = 209.8 mbarn) and M the molar mass of the fiber. For CNTF with 10% of iron as a weight fraction, the density was estimated at 1.42 g/cm^3, the molar mass at 13.03 g/mol and the effective Z at 6.47. The average number of interactions is summarized in Table 1.

Table 1: Number of Interactions Proton / Wire

d **[µm]**	**Beam size [mm]** **0.25**	 **0.5**
11	5.21·10^9	2.69·10^9
24	2.29·10^{10}	1.22·10^{10}

ENERGY DEPOSITION IN CNT

FLUKA Calculation

The assessment of energy deposited into the CNTF was performed with the FLUKA Monte-Carlo simulation code. Energy transfer from protons to the material wire at such a momentum (440 GeV/c) cannot be described only with the Bethe-Block formula, but needs to consider high energy secondary electrons, namely delta electrons. In the present case, the maximum energy for these secondaries could reach up to 149 GeV [9], meaning that they can be ejected from a very thin wire and do not contribute to the total energy loss into the material [10]. The threshold for delta ray consideration tracking was set to δ = 1 keV, a useful limit to consider also the influence between wires in a SEM grid configuration and the secondary emission yield (SEY). To illustrate the importance of this threshold, the energy deposition at δ = 1 keV was 4.15 keV, while with δ = 150 GeV the deposited energy was 6.41 keV, showing an increase of about 54%.

We consider a typical density of 1.3 g/cm^3 for this kind of full carbon CNTF. This is significantly lower compared to the one of carbon fiber (1.7 g/cm^3) currently used in wirescanners. In both cases, the energy deposition is considerably reduced compared to a graphite wire from 7.64 keV (ρ = 2 g/cm^3) [11] to 4.15-4.50 keV.

The SEY was calculated using the following relation:

$$\mathrm{SEY} = 0.01 L_s \frac{dE}{dx}\left[1+\frac{1}{1+5.4\cdot 10^{-6}E/M_p}\right], \qquad (3)$$

with $L_s = 3.68\cdot 10^{-17} N Z^{1/3}$ the characteristic length describing the diffusion of low energy electrons, E and M_p the incident energy and mass of protons, N and Z are respectively the number of atoms per unit volume and the atomic number of the material. From the SEY, it is possible to assess the charge generation per incident proton Q(e/H) for a single CNTF, where Q(e/p) = 2SEY. This value multiplied by the real number of protons crossing the wire will be compared with the produced signal in the instrument. The deposited energy and the secondary emission yield obtained by the Fluka simulations for both diameters are summarized in the Table 2.

Table 2: Deposited Energy per Incident Proton into a CNT Wire and Secondary Emission Yield (SEY) for Two Compositions, Carbon and Carbon with 10% Fe as Weight Fraction

	Carbon		**Carbon + 10% Iron**	
	(ρ = 1.30 g/cm^3)		(ρ = 1.42 g/cm^3)	
d [µm]	**dE [eV/p]**	**SEY [/p/cm^2]**	**dE [eV/p]**	**SEY [/p/cm^2]**
11	1987	$4.15 \cdot 10^{-3}$	2151	$4.35 \cdot 10^{-3}$
24	4475	$4.28 \cdot 10^{-3}$	4850	$4.50 \cdot 10^{-3}$

Temperature Calculation

The Fluka simulations give a total deposited energy of 2150 eV with a peak at 1423 eV for a fiber of 11 µm and 4850 eV with a peak at 3514 eV for a fiber of 24 µm (Fig. 5). The maximum temperature, located at the center of the wire, can be conservatively estimated (no cooling consideration) by

$$T_{max} = T_{amb} + \frac{N_{int} E_{dep}}{\rho c_p d_w} \frac{1}{2\pi\sigma_x\sigma_y}, \tag{4}$$

with T_{amb} the ambient temperature setup at 300 K, $N_p = 3.2 \cdot 10^{13}$ the total number of protons and c_p = 1.3 J/g/K for pure carbon and c_p = 0.5 J/g/K for the CNT with iron (average value of the heat capacity between 300 and 1000 K for for both material).

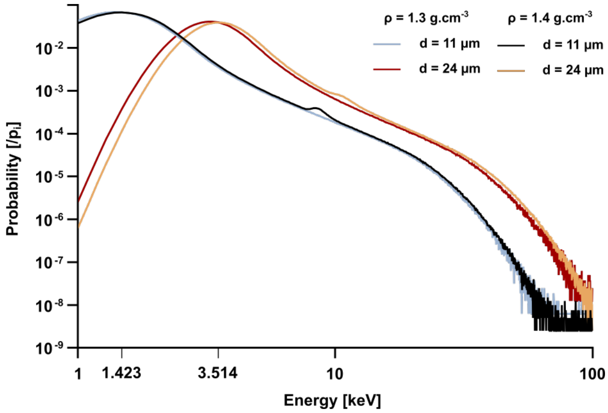

Figure 5: Energy deposition - Probability of a 440 GeV/c incident proton to deposit some energy in wires composed of pure carbon (ρ = 1.3 g/cm^3) in blue and red and composed of carbon and 10% in weight of iron (ρ = 1.42 g/cm^3) in black and orange of 11 and 24 µm in diameter.

The results on the maximum temperature calculated for a beam size of 0.25 mm show a significant impact of the material composition (Table 3). The presence of iron in the material allow a higher deposition of energy, but the main parameter responsible of the increase by a factor 2.2 is the lower heat capacity of iron. This indicates that the presence of few catalytic particles contributes to a massive risk of overheat compared with pure carbon. The comparison between the CNT and the carbon as structural difference is not possible with the fluka code. Thus, only the diameter and the density are variable parameters.

Table 3: Maximum Temperature of Various Samples in Diameter and Density for a Irradiation with a Beam Size of 0.25 mm

d	**Maximum temperature [K]**		
[µm]	**ρ = 1.30**	**ρ = 1.42**	**ρ = 1.70**
11	1694	3813	-
24	1739	3933	-
7	-	-	1665
34	-	-	1756

All these results have to be considered carefully for many reasons : 1- the Monte Carlo simulations needs to have a high number of events to be statistically robust. The simulated deposited energy depends directly from that. 2- The specific heat capacity depends widely on the temperature (from 0.7 to 2.3 J/g/K for temperature between 300 and 4000 K). 3- The cooling mechanisms are complex and depends also on the temperature. 4- The thermal parameters (conductivity, emissivity) of the CNT fibers are incompletely known.

CONCLUSION

The use of carbon nanotubes for beam instrumentation is still in its infancy. The analysis of the physical and mechanical properties after irradiation as a function of the intensity at such energies has never been done. In order to predict the response in terms of secondary electrons produced for the SEM grid signal and the lifetime of the sample due to the increase in temperature, numerical simulations using a Fluka code were performed. It has been shown that the energy deposited in the wire decreases with wire diameter and increases with density. Secondary electron production also increases with increasing diameter and density. We therefore expect to observe a greater signal for thick wires than for thin wires. The simulated temperatures increase drastically for the CNTF with iron, mainly due to the lower heat capacity of iron. These temperatures should induce a change in the structure of the samples without destroying it by sublimation.

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