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LOW DENSITY WIRES FOR BEAM HALO MONITORING

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Abstract

Beam halo monitoring is crucial for high-intensity machines such as the HL-LHC. Carbon Nanotube (CNT) wires offer a promising alternative to conventional carbon fibre scanners due to their lower density, improved thermal properties, and reduced beam interaction. This work evaluates their thermal performance and survivability through simulations at SPS and HL-LHC beam conditions.

Results indicate that CNT wires can tolerate HL-LHC beam-induced heating in dynamic scanning mode for halo measurements in the 3.5–6.5 σ range, remaining below the 1600 K sublimation threshold. In contrast, stationary operation closer to the core produces sustained heating and higher thermal risk. While challenges remain in manufacturing, post-processing, and property variability, CNT wires show strong potential for non-destructive halo diagnostics, provided long-term performance can be optimised.

INTRODUCTION

The HL-LHC will operate at unprecedented beam intensities, increasing the importance of precise and reliable beam-halo diagnostics. The halo, defined as particles beyond 3.5 σ from the beam core, must be characterised with better than 1 % precision in its relative fraction and contrast sensitivity down to 10^{-3} in a Gaussian beam [1].

Existing diagnostics such as the Beam Wire Scanners (BWS) and Synchrotron Radiation Telescopes (BSRT) are limited by excessive invasiveness, speed, or resolution. Wire-based beam scan methods, while offering good transverse resolution, are typically destructive or limited in terms of operational conditions. Current Carbon Fibers (CF) wires cannot withstand the maximum integrated intensity at the Super Proton Synchrotron (SPS). This limitation is primarily due to the sublimation of the carbon wire when exposed to high energy deposition [2].

Carbon nanotube (CNT) wires are emerging as promising candidates for more resilient beam wire scanners (BWS), owing to their combination of low density, high thermal conductivity, and reduced diameters, which together minimise beam interaction and enhance heat dissipation. Whereas conventional carbon fibre wires exhibit densities around 1.8 g/cm^3 with diameters near 7 µm, CNT yarns typically show densities close to 1 g/cm^3 and can be manufactured with diameters as small as 2 µm [3]. These properties significantly reduce energy deposition. Nonetheless, their performance under HL-LHC beam halo conditions requires thorough investigation before they can be adopted operationally.

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Despite the lower (about 30 % when compared to CF) signal-to-noise ratio exhibited by CNT wire scanners, they were able to successfully record beam profiles of 450 GeV proton beam at the SPS. They were tested up to SPS intensity of 3.4×10^{13} protons, where they failed due to metallic inclusions inherent to the manufacturing procedure [4, 5].

This article focuses on thermal simulations of CNT wires beyond SPS energies, extending to the HL-LHC, where temperature rises are expected to scale by a factor of ~150. It assesses their survivability, feasibility, and potential for use in non-destructive beam halo monitors.

SIMULATION SETUP

Carbon nanotubes (CNTs) are broadly divided into single-walled (SWCNTs) and multi-walled (MWCNTs) types. SWCNTs are a single rolled graphene sheet, typically 1–10 nm in diameter (see Fig. 1), whereas MWCNTs are formed from several concentric tubes, which enhances their structural robustness. Individual CNTs exhibit exceptional intrinsic properties, including Young's moduli approaching 1 TPa or tensile strengths exceeding 50 GPa. These combined characteristics underpin their promise as materials for demanding high-performance applications [3].

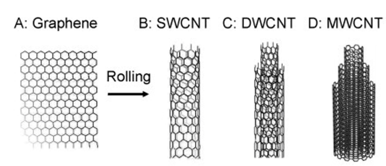

Figure 1: Different CNT structures [6].

To transition from the nanoscale to macroscopic scale, CNTs must be processed into aligned and continuous forms such as wires. This typically involves wet-spinning or other fibre-forming techniques where dispersed CNTs are assembled into bundles and then drawn into cohesive, conductive strands [3, 7]. The wires used in this study, produced by Dexmat, represent such a transformation, combining individual CNTs into low-density wires. Initial microscopy and density measurements of these samples revealed substantial batch-to-batch variability. Average values were therefore adopted for all analyses in this study, as they are the most representative. The wires exhibited diameters of about 10 µm (±1 µm) and densities close to 1.0 g/cm^3 (±0.2 g/cm³).

Beam Parameters

The simulations were set up for beam profiles and parameters of the SPS and HL-LHC. Thermal simulations were performed assuming a Gaussian beam profile at 450 GeV and 7 TeV, with intensities up to 5.7×10^{14} protons. For

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halo profiles, the simulations assumed a perfectly Gaussian beam cores with exponentially decaying tails.

Wire Properties

In the simulations, CNT wires were modelled as uniform cylindrical structures. Their thermophysical parameters—specific heat capacity and thermal conductivity—were taken from experimental data [5]. While individual CNTs can achieve extraordinary intrinsic values, macroscopic CNT wires display more modest and variable properties: tensile strengths of 0.5–3 GPa, Young's moduli of 20–120 GPa, and thermal conductivities of 100–1000 W/mK. Densities vary with processing and batch [3]. The wires simulated here, fabricated using Chemical Vapour Deposition (CVD) followed by wet spinning and a nitric acid immersion to remove residual metallic catalyst, showed average densities close to 1 g/cm^3 with diameters of about 8 µm, with impurity content reduced from roughly 8 % to about 1 % after purification. These values were adopted for the present analysis.

Simulation Conditions

Simulations were used to evaluate beam exposure, assuming quasi-instantaneous heating and limited lateral heat diffusion. In particular, a thermal model accounting for multiple mechanisms influencing the wire temperature during and after beam interaction was implemented. Heating is driven by the energy deposited from the incident particle beam, converted into internal energy based on the wire's specific heat and density [8]. Impurities present in the material are considered in the energy deposition simulations and included in the effective density, which is averaged to account for their contribution and results in a slightly increased value. Heat conduction along the wire was included but has a limited effect due to the short exposure times. Cooling processes were represented by both radiative emission to the environment and thermal conduction toward the wire supports. At higher temperatures, energy loss due to thermionic electron emission becomes relevant and was incorporated into the model. Finally, sublimation was introduced once the material reaches critical temperature thresholds, and is implemented by modelling mass loss and associated energy consumption. This last effect is particularly significant, as it is the main factor limiting the use of CF wires in high-intensity beams [9, 10].

The resulting PyTT simulation code [11] was used to implement a 1D finite-difference heat diffusion model. This includes ionisation energy loss following the Bethe–Bloch formalism, as well as CNT-specific thermal parameters such as thermal conductivity, anisotropy and temperature-dependent emissivity. The setup predicts wire temperature profiles and potential failure points but has not yet been experimentally benchmarked.

BEAM HALO MEASUREMENT STRATEGIES

The functional specification for the HL-LHC beam halo monitoring sets out stringent performance requirements relating to collimation control, machine protection, and beam–beam interactions [1].

The system must measure halo populations from 3.5–6.5 σ (potentially up to 8.5 σ), operate without perturbing the beam, and sustain measurements for over 10 seconds.

This study evaluates two CNT-based halo measurement strategies based on earlier simulations:

1. **Stationary monitoring:** The wire remains fixed at 3.5 σ for an extended period, enabling continuous measurement but requiring enhanced thermal resilience (Fig. 2 a).

2. **Dynamic probing:** The wire is driven to a radial position corresponding to 3.5 σ and subsequently retracted. This approach minimises dwell time in the halo region, reducing thermal exposure (Fig. 2 b).

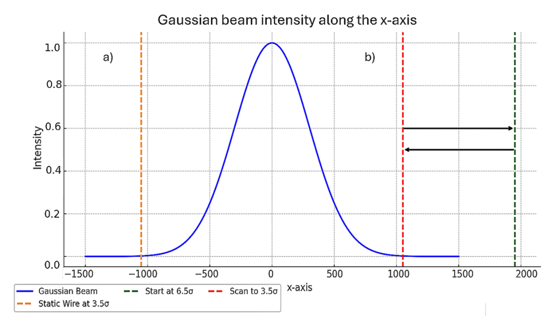

Figure 2: Beam halo wire strategies: a) stationary; b) scanning.

RESULTS AND DISCUSSION

The sublimation threshold of approximately 1600 K is adopted here as a reference limit for assessing wire survivability. This value originates from beam tests performed in 2010 on conventional carbon fibre wires, where observed damage thresholds were translated into an equivalent temperature using dedicated thermal simulations tailored to the specific beam and wire parameters [2].

Temperature Evolution for LHC and SPS

To evaluate thermal performance under SPS safe beam conditions (450 GeV, $\sigma = 350$ µm, 1.02×10^{13} protons, wire speed 9 m/s), we compared CNT wires with conventional CF wires. Specifically, CNT34 and CF34 were selected to isolate material effects, as both share the same diameter and density. This enables direct cooling behaviour comparison. The CNT8 wire, on the other hand, was included to illustrate the performance of our final low-density CNT wire design.

Figure 3 shows the temperature evolution during scans across the beam core for wires with diameters of 34 µm (CNT34 and CF34) and 8 µm (CNT8). CNT wires exhibited faster cooling, a key factor in reducing the time spent near sublimation temperatures. Notably, the CNT8 wire remained well below the 1600 K sublimation threshold relevant for HL-LHC beam halo operation. These results show how diameter, density, and material affect thermal performance during beam-core crossing.

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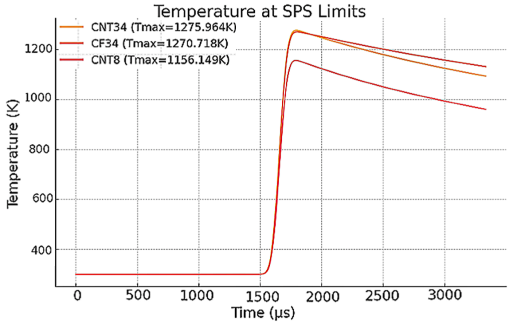

Figure 3: Simulation of the temperature evolution of CF and CNT wires (SPS).

Impact of Measurement Strategies

For the evaluation of stationary and scanning wires, simulations were performed using HL-LHC beam-parameters at 7 TeV energies and total intensity of 5.7×10^{14} protons. Different transverse beam sizes were considered to cover the expected halo conditions. The wire scanning cases assumed a speed of 1 m/s, which corresponds to the maximum scan velocity available in the LHC, while the stationary cases represented a fixed insertion at the same locations.

Figure 4 shows the temperature evolution of a stationary wire positioned at 3.5 σ from the beam centre for beam sizes of σ = 200 µm and σ = 300 µm. Under stationary conditions, continuous energy deposition leads to elevated maximum temperatures. For σ = 200 µm, the wire temperature rises rapidly, surpassing 2200 K, well above the 1600 K sublimation threshold, whereas for σ = 300 µm, it reaches only 1600 K. These results highlight the thermal hazard of keeping the wire fixed close to the beam core at high intensities.

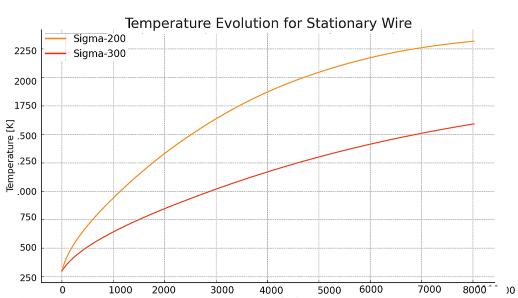

Figure 4: Simulation of the temperature evolution of a stationary 8 µm CNT wire for HL-LHC beam parameters.

In contrast, Fig. 5 shows the temperature profiles for a scanning wire that pauses briefly at the maximum halo extent (3.5 σ) before retracting, under the same beam conditions. Unlike the sustained heating in stationary wires, this dynamic approach results in much lower peak temperatures, about 420 K for σ = 200 µm and 385 K for σ = 300 µm. These values are well below the 1600 K sublimation threshold, confirming that short-term exposure during scanning provides a considerably safer operational margin than fixed positioning.

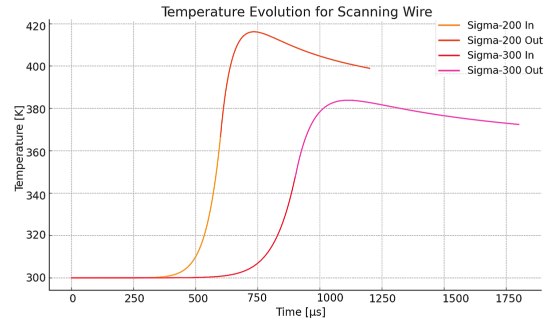

Figure 5: Simulation of the temperature evolution of a scanning 8 µm CNT wire for HL-LHC beam parameters.

Material Comparison

The CNT wires used in this study combine low density with moderate thermal resilience, making them attractive for beam-intercepting applications requiring minimal perturbation and fast thermal response. Compared to dense tungsten or less conductive carbon fibre, CNT wires offer a favourable trade-off. Their behaviour broadly follows Ashby indices optimised for high thermal conductivity-to-density and specific heat-to-density ratios [12]. While not suitable for prolonged exposure near the beam core, they remain stable below the 1600 K sublimation limit, supporting their use in dynamic diagnostics.

CONCLUSIONS AND FUTURE WORK

CNT-based BWS demonstrate strong potential for precise and reliable beam halo monitoring at high intensities and energies. Their low density and diameter reduce beam interaction, offering advantages over conventional CF wires. Preliminary thermal simulations suggest that CNT wires can tolerate HL-LHC beam-induced heating in the halo region, supporting their integration into next-generation linear BWS systems.

Future work will focus on mechanical integration, support design, and effective heat dissipation. Resistivity measurements under HiRadMat irradiation conditions aim to validate simulation results by linking observed temperature rises to changes in electrical conductivity. Scalability and batch-to-batch property variability remain important manufacturing challenges.The present work assumes adequate CNT purity after post-processing, but systematic validation is needed to confirm achieved levels and ensure consistency.

Further experimental testing at the SPS facility will assess thermal and mechanical robustness under realistic beam conditions. While existing BWS systems provide sufficient contrast for 1D profiles, advanced applications such as bunch-by-bunch diagnostics or tomoscopy will require additional development.

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