ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO13

DEVELOPMENT OF LOW DENSITY MATERIALS FOR BEAM INTERCEPTING INSTRUMENTS

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Abstract

Materials with a minimal interaction with particle beams are widely used in accelerators in interceptive instruments such as screens, secondary emission grids and wire scanners. Material damage limits are already exceeded in energy frontier and high brightness machines. A new generation of 'low density' materials with nano-structures are becoming available at scales of interest for use in beam instrumentation. Specifications are increasingly of use but still with fundamental issues that limit their application. This paper will demonstrate the potential for this class of materials for beam intercepting materials. It will outline the current limitations and ongoing research to overcome them both in the short and long-term.

INTRODUCTION

Beam instruments can be divided into two categories: those that do not intercept the beam (non-interceptive), using properties such as emission of light (synchrotron light emission or electro-magnetic coupling; others where the beam physically intercepts some material, either gas or solid, causing an effect which is measured such as particle scattering, emission of light (scintillation, fluorescence, OTR) or emission of secondary particles.

Interceptive instruments have limitations in their field of use due to the nature of their interactions. Intercepting the beam with too much material (mainly an issue for solid interceptors) results in excessive beam-loss, causing irradiation of components, potentially magnet quench in superconducting machines or rendering the instrument 'destructive' of the beam, so only useable in set-up conditions such as in the observation screens 'BTV' in the CERN proton LINAC [1]. Beam-material interactions can also damage or destroy the interacting material in energy frontier machines such as the wire scanner (BWS) in the LHC [2].

Gaseous detectors (either using background or injected gas) can overcome many of these limitations. However, residual beam-gas signals tend to be too low without some amplification such as in the new beam-gas ionisation (BGI) in the CERN PS [3] and injected gas detectors can lead to beam loss such as the Beam-Gas Vertex (BGV) [4] and Beam-Gas Curtain (BGC) [5] in the CERN LHC due to the diffusion of gas along the beam axis.

It is interesting at this point to compare the quantity of material actually intercepted by the beam for commonly used instruments. The number of matter particles intercepted, n is defined in (1):

$$n = \rho L \; [mol.m^{-2}], \qquad (1)$$

where ρ is the mass density of the intercepting material and L is the detected length of the intercepting material (the diameter for a wire). For gaseous detectors, the mass density is calculated at the pressure of operation.

This value n allows us to compare the number of matter atoms intercepted by the beam for both solid and gaseous detectors and is plotted in Fig. 1 for some common instruments with typical design characteristics in use at CERN. As the interactions measured are often elastic collisions, the atomic mass is also plotted.

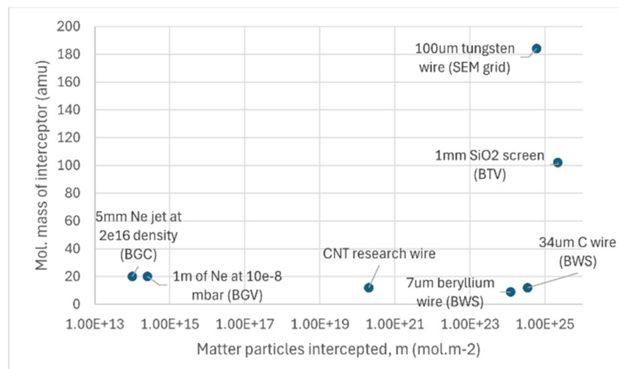

Figure 1: Matter particles intercepted by the beam and atomic mass for common interceptive instruments.

Ignoring for the moment the 'CNT (Carbon Nano-Tube) Research Wire' it is clear by inspection that the intercepting mass groups divide into solids and gases, with a difference of some 10 orders of magnitude in the number of particles intercepted by the detector materials. This expansive 'valley' explains much of the inherent limitations in the two types of interceptors: The solids tend to intercept too much beam and the gases not enough. Even the most highly optimised solid interceptors such as a 7 µm beryllium wire used in the CERN PS wire scanner in the 1980s [6] shows little variation from other solids on this log scale just as with the focussed gas jet in the BGC detector.

WHAT MATERIAL WOULD MAKE AN IDEAL INTERCEPTOR?

Solid or Gas?

Gases have the advantage of being inherently indestructible by the beam. However, they will diffuse into the accelerator vacuum system so the pressure that can be achieved is limited. Detectors such as the BGI [3] use beam-gas ionisation with focussing and amplification of

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ISBN: 978-3-95450-262-2 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2025-TUPMO13

ionised particles to enhance the inherently low beam-gas signal rate.

There are advantages of solid interceptors over gases. The material is all in a defined location, allowing the detector to scan the structure of the beam. It is also easy to integrate into a compact, moveable instrument.

Solid Interceptor Material Optimisation

To take advantage of the defined position in moving instruments such as wire scanners, solid interceptors must have a high mechanical strength (σ_f) to density (ρ) ratio. Resisting beam heating implies a high heat capacity (c_p) to limit temperature rise along with a high maximum temperature of use (T_m).

Candidate materials have been plotted together using these criteria to rank them for this application in Fig. 2.

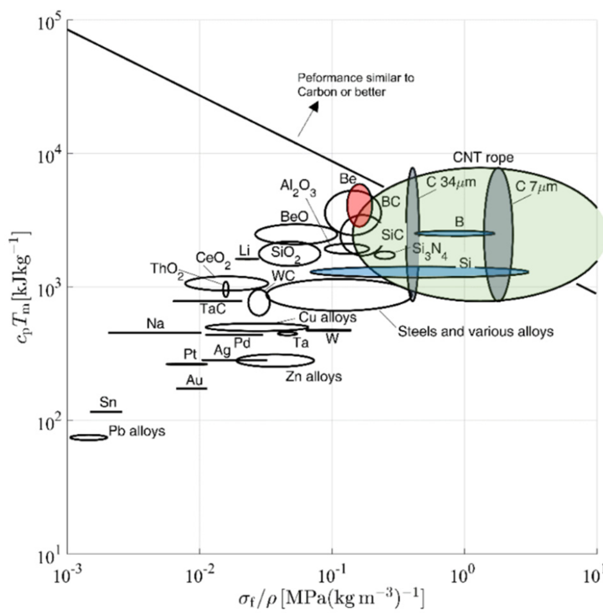

Figure 2: Materials selection chart for moving beam intercepting devices [7].

It can be seen that carbon and boron materials rank highly and as such are widely used in these applications. However, these are already at their limits for energy frontier machines such as the SPS and LHC at CERN [2, 8].

Physical properties such as heat capacity and melting temperature are difficult to improve, however, ultimate strength and density come from the material structure.

AVAILABLE MATERIALS

Novel forms of carbon based on a hexagonal lattice of mono-atomic thickness either in 2D sheets of graphene or rolled into 1D (although strictly 3D, this expression is used as properties are principally defined along the axis) nanotubes have the potential to improve both density and ultimate strength. The strength of single nano-tubes can be orders of magnitude greater than steel. The effective density, as seen by a particle beam, of a hollow tube of carbon atoms is also low (although difficult to define and measure).

Comparing CNT with Existing Materials

It is interesting to compare the potential of CNTs with existing interceptor materials. A realistic upper limit for the strength of a Single-Walled Nano-Tube (SWNT) with defects of 120 GPa can be taken [9]. Mass density is more difficult to evaluate. There is significant variation in the literature and defining a value that is relevant for beam-matter interaction is not obvious. Products are available on the market with a density of 200 kg.m^{-3} which is taken here.

The amount of material needed will depend on the application. Current CERN fast wire scanners use 34 μm carbon filaments with 800 MPa tensile strength giving a breaking load of ~0.3 N which is desirable for manual installation and manipulation. Assuming (conservatively) that this same load would be required gives a CNT wire diameter of 0.88 μm. This results in an interacted matter quantity $n = 2 \times 10^{20}$ mol.m^{-2}. Adding this to Fig. 1 (CNT research wire) shows the potential for an intercepting material that spans the valley between solid and gaseous interceptors, with ~4 orders of magnitude less material than the best beryllium scanner wires.

Limitations of Current Materials

The value of n that could be achieved with a SWNT demonstrates the interest in developing this material for interceptive detectors. However, SWNTs with lengths useable for accelerator instruments (~10 cm) are not yet available on an industrial scale.

A review of applications and state-of-the-art in the field was held at CERN in 2023 [10]. Commercial CNT production currently makes tubes of μm scale length [11]. The most widespread methodology for producing practical lengths for beam intercepting wires involves drawing CNT ropes from short, vertically aligned CNT 'forests' and twisting them (see Fig. 3) to produce ropes or wires of indefinite length.

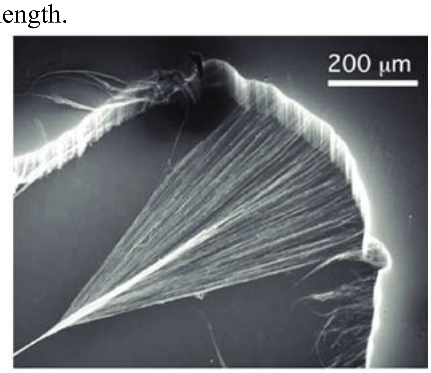

Figure 3: Micrograph showing production of CNT ropes [12].

There are three principal limitations coming from current material production methods. Firstly, using ropes (CNTY) rather than single long CNT strands limits the strength, as it relies on van der Waals forces between individual strands of nanotubes, with failure due to strand separation (see Fig. 4). This limits the failure strength to no more than 1.1 GPa [13], 100 times lower than the SWNT strength.

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Secondly, industrial production methods tend not to produce pure SWNT, but Multi-Wall Nano-Tubes (MWNT) which are structures formed from multiple concentric layers of SWNT. This significantly increases the effective material density seen by the beam.

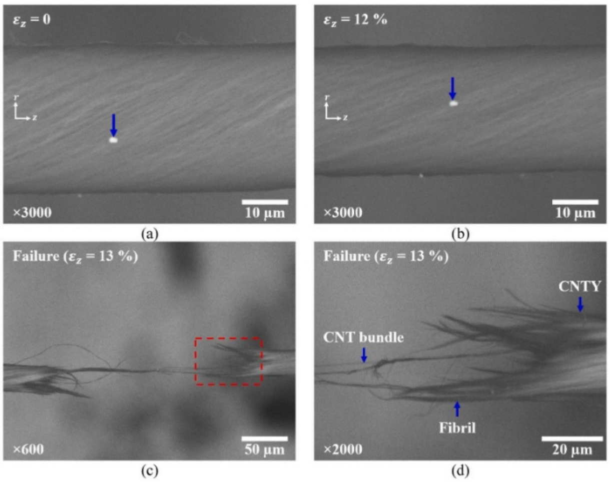

Figure 4: Micrograph of a CNT rope showing failure by separation of the strands (Courtesy CERN microscopy service) + In situ SEM of a CNTY during tensile testing. (a) CNTY at εz = 0, (b) CNTY at εz = 12 %, (c) CNTY at failure (εz = 13 %), (d) close-up of the CNTY at failure, indicated by a dashed rectangle in Fig. 4c from [14].

Finally, current production methods use metal catalysts, normally iron or aluminium. This leaves a residue of up to 8 % embedded in the final material. When the material is exposed to extremely high temperature and thermal shock in the beam, these residues evaporate and can damage the geometry and structure of the material [15].

CURRENT APPLICATIONS

The requirements and limitations of existing materials for wire scanners at CERN was outlined in 2018 in [16]. Since then, development has continued to simulate and then qualify the behaviour of materials in beams with tests in the HiRadMat facility [17].

More recent studies [18] demonstrated that reducing the catalyst impurity content to the ~1 % level while keeping a similar density would make it less interactive with the beam and therefore more suitable for this purpose.. In addition, as CNT ropes can more easily be made in a variety of diameters, significant optimisation can be made with smaller ~8 µm diameter wires.

Materials from this generation which have been purified to the 1 % level are planned for test with beam in the CERN accelerator complex in 2026.

FUTURE TRENDS

Although these current materials can have a use in replacing wires in the LHC injector chain up to the SPS, they are not useable in the LHC ring. Existing wire scanners in the LHC are limited to a small number of the total bunches both to prevent wire damage and limit energy deposition into downstream superconducting magnets and CNT wires do not yet have the properties required for this application.

Another possible application for CNT intercepting materials would be as a monitor for the stored energy in the transverse tails of the beam (beam halo), which is presented in this conference [18].

Both of these applications would require properties of the interceptor closer to the ideal case shown in Fig. 1.

Although such materials are not yet on the market, there are research materials with extremely long MWNT forests of up to 140 mm [19] which suggests that techniques to develop such materials could soon be available.

Considering this, the current upgrade for the LHC wire scanner is being designed such that it can be retrofitted with sub-micron diameter wires using nano-manipulation techniques.

Although this article has focussed on wire materials, 2D materials for beam observation screens would also see a major extension into higher brightness applications by using graphene-based materials assuming current limitations ue to photon yield and surface quality can be addressed.

CONCLUSION

Carbon nano-tubes and graphene have a great potential in interceptive instrumentation, bridging the valley between solid and gaseous detectors.

Materials are now on the market that start to exceed the performance of current carbon-fibre based alternatives and will see installation in CERN accelerators in the coming months. Research in production techniques is advancing rapidly towards a next generation of lighter, stronger materials.

The volume of the market for these materials in instrumentation is unlikely to allow for dedicated industrial production. Strategy is therefore directed to collaboration with smaller, research facilities and to following the market trends for this new and exciting material.

ACKNOWLEDGEMENTS

The authors would like to thank: Marius Sapinski at PSI for valuable discussions and help; The CERN materials service for microscopy and materials testing help; Alexandre Mariet who performed much of the early work for this study.

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