HiLumi
HL-LHC PROJECT

Low Density Wires: Development for beam halo monitoring - status and plans

G. Aliana Cervera, C. Pasquino, R. Veness (CERN)
A. Lunt, D. Mattia (University of Bath)

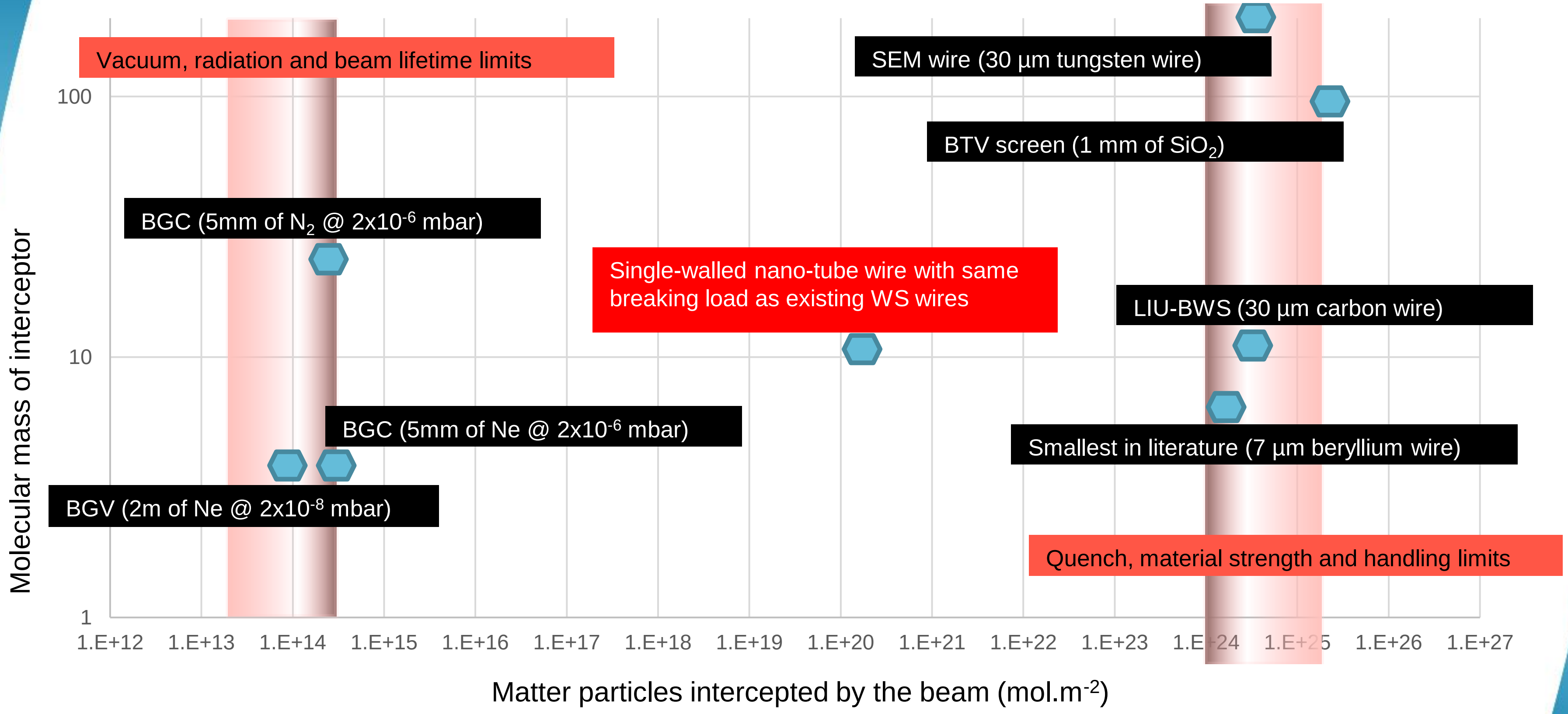
HL-LHC Beam Halo Review

Summary

Presentations focus: Evaluate results and benefits of carbon nanotube (CNT) wires for beam halo monitoring

- **Key properties of Carbon Nanotubes**
- **Practical considerations**
- **Potential operational impact**
- **Thermal studies**
- **Quenching studies**

Intercepted material for gaseous and solid devices



(1) Slide provided by R. Veness

Key properties of Carbon Nanotubes

- Allotropic form of carbon.
- **Graphene sheet** coiled in a specific direction.
- One or several walls (SWCNT – MWCNT)
- Long and hollow **nanometric** structure

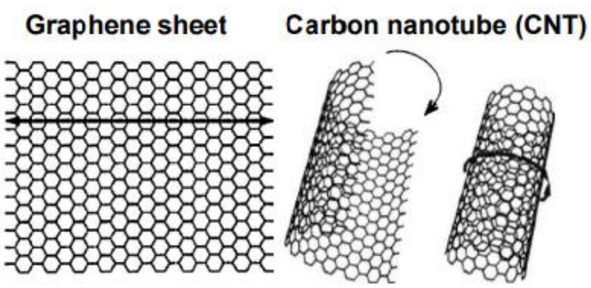


Figure 1. Carbon nanotube structure

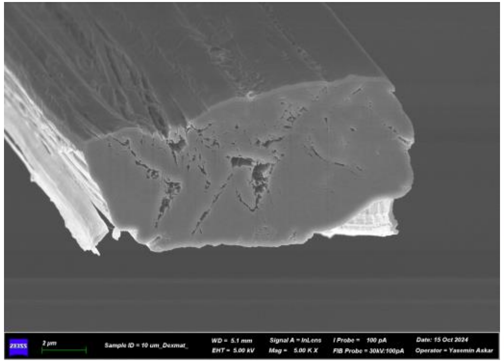


Figure 2. SEM image of our Dexmat CNT structure

Exceptional properties

		CNT	CNT wire	Carbon fiber	Stainless steel
Density [g/cm³]		0.8-1.4	0.8 – 4 g/cm³	1.7-2.5	7.7-8
Mechanical properties	Tensile strength [GPa]	11-63	1-3	2-7	0.5-1.6
	Young modulus [GPa]	1000	200-800	230-600	190-210
Thermal conductivity [W/m k]		3000	600-800	5-15	16-30

(2)

Practical considerations

- **High variability of performance.**
  - Each batch of wires needs to be tested on its own to ensure its characteristics.
- Few available suppliers.
- **Required postprocessing.**

Expected characteristics after treatment

Diameter(⌀) – 8 µm

Density (ρ)– 1 g/cm3

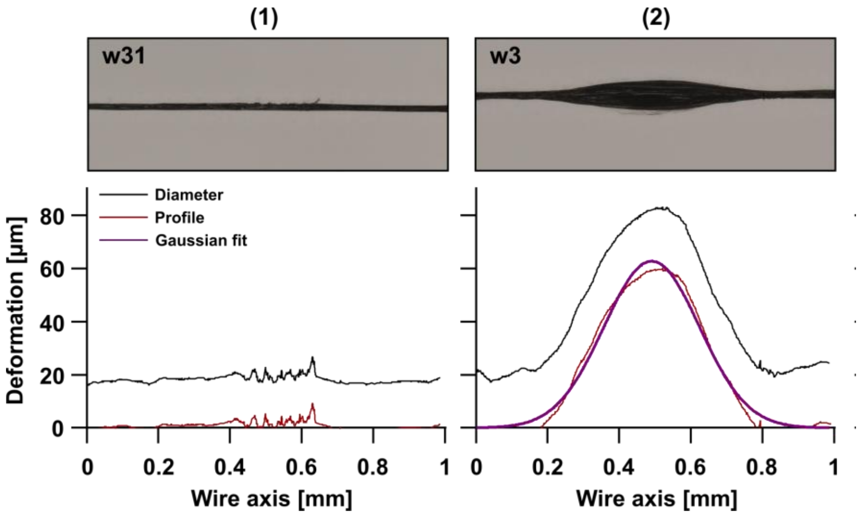


Figure 3. Optical microscopic images of CNT wire samples after irradiation. Profile of the deformation after image treatment with Gaussian fit (3)

No direct relation with the dose deposited

Obvious change of shape → Residual iron particles melted

Potential operational impact

- **Capable of reading full intensity and energy of SPS beam.**
- **Signal decrease** compared to other wires.
- **Noise increase** compared to other materials

PS conditions

- CNT wire 30 µm
- CF wire 34 µm
- Energy 26 GeV

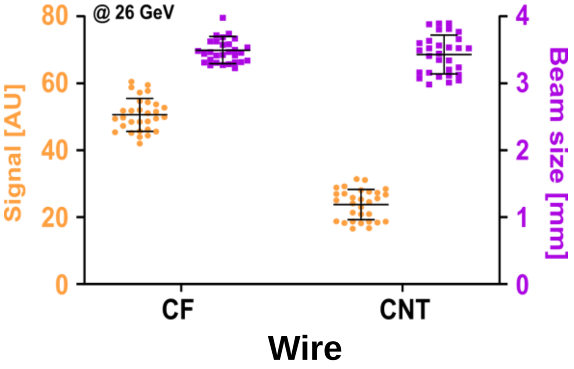


Figure 4. Summary of integral signals and beam sizes for scans with CF and CNT wires at 26 GeV (3)

PSI conditions

- CNT wire 20 µm
- Molybdenum wire 25 µm
- Energy 2.5 GeV

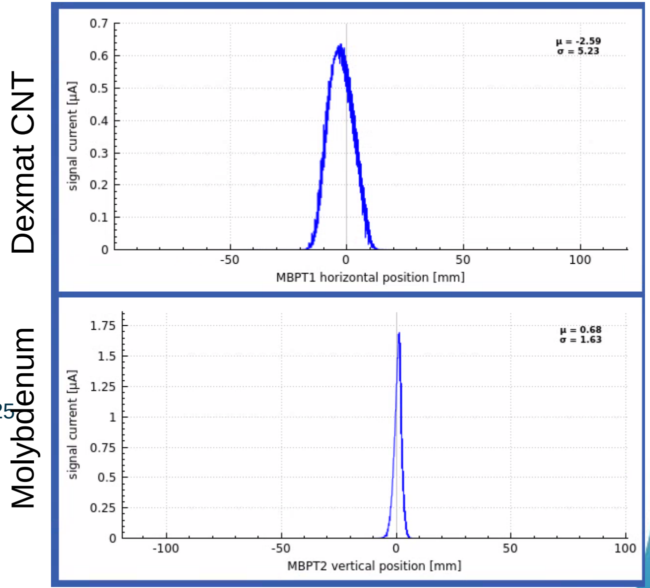


Figure 5. Example of a signal acquired using CNT wire at PSI compared to molybdenum wire. Provided by M. Sapinski (PSI)

Thermal studies – Comparison with CF

Thin target detectors temperature equation

$$\left(\frac{\partial T}{\partial t}\right)_{tot} = \frac{\Phi(x,y,t)}{C_p(T).\rho}.\left\langle\frac{dE}{dx}\right\rangle - \frac{k(T)}{C_p(T).\rho}\nabla^2 T - \frac{S.\sigma_{SB}.\epsilon.(T^4-T_0^4)}{V.C_p(T).\rho} - S.(\phi+2k_B T).\frac{J_{th}}{V.C_p(T).\rho} - \frac{H_{sub}}{m_{mol}}.\frac{S.W_{sub}}{V.C_p(T).\rho}$$ [1]

Total temperature change rate

Beam heating: Direct heating due to beam energy deposition

Conductive cooling: Temperature gradient, has small effect due to BWS small diameter

Radiative cooling: Thermal radiation. The dominant cooling process up to 2400 K.

Thermionic cooling: Electron emitted when they acquire energy exceeding the works function. Dominant at high temperature.

Sublimation cooling: Amount of the material get enough energy to sublimate. It is dominant if BWS is being sublimated

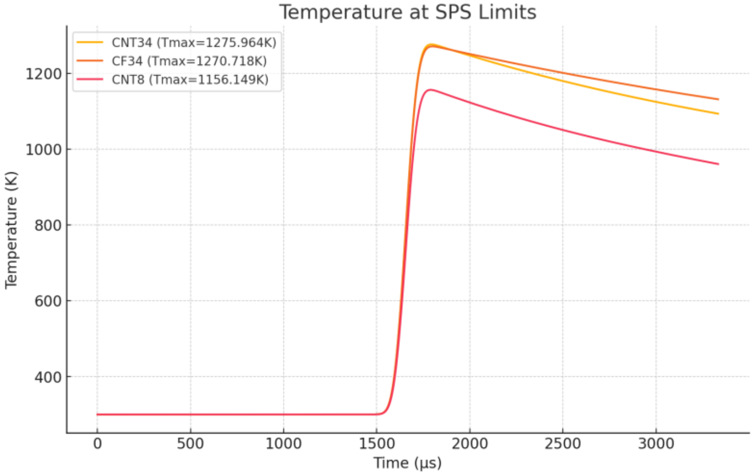


Figure 7. Temperature evolution of 34 μm CF and CNT wire at CF experimental beam limits in the SPS. Current expected 8 μm CNT wire temperature evolution under the same conditions.

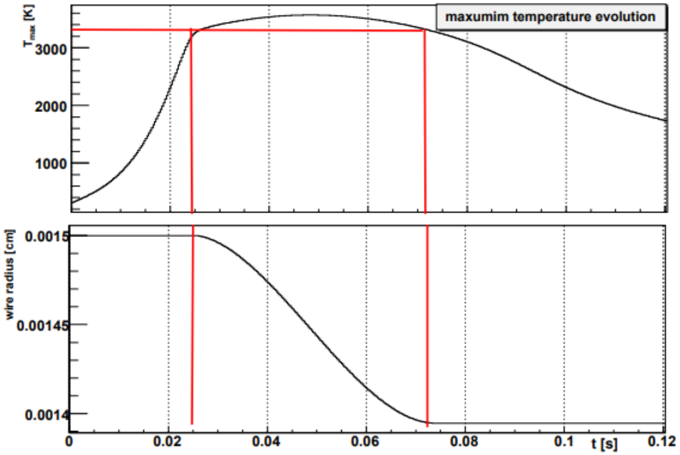
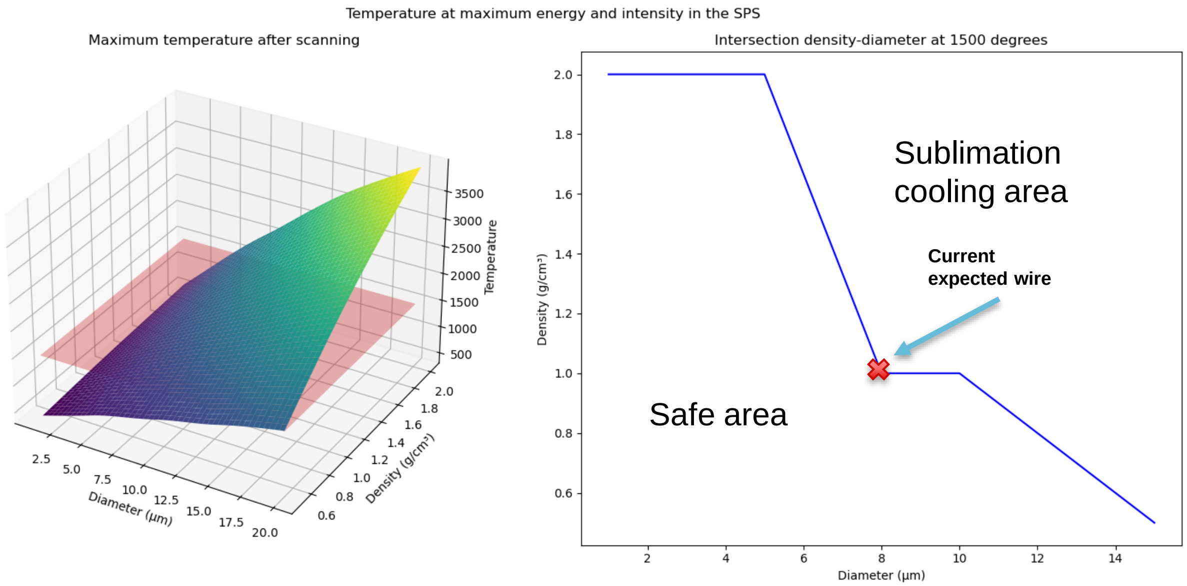


Figure 6. Sublimation conditions in a WS (4)

(4)

Thermal studies - Wire heating in SPS

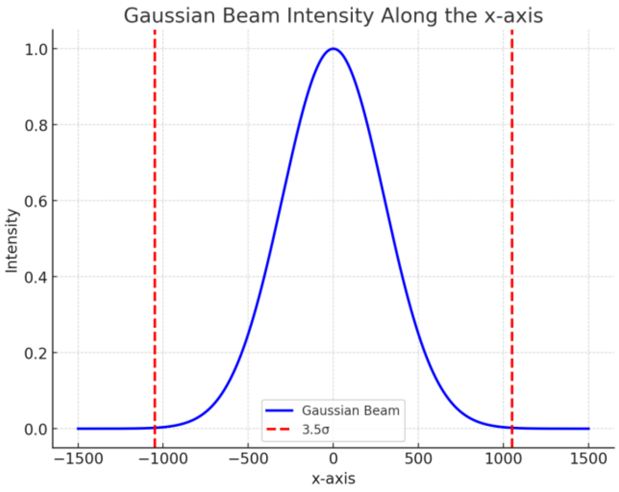


Simulation conditions

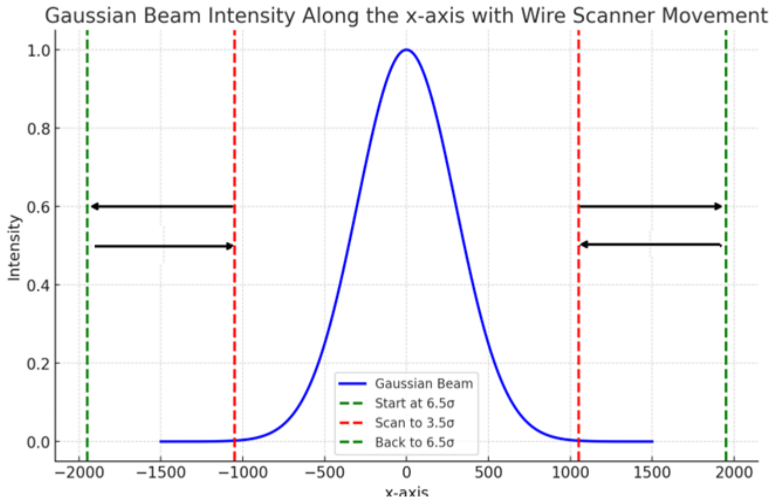
- Gaussian beam
- Energy – 450 GeV
- Intensity – 5,7e13
- Scanning speed – 15 m/s
- Temperature limits – 1500 degrees
- Beam size of 1 mm

Beam Halo Monitoring approach to 3.5σ

Stationary wire



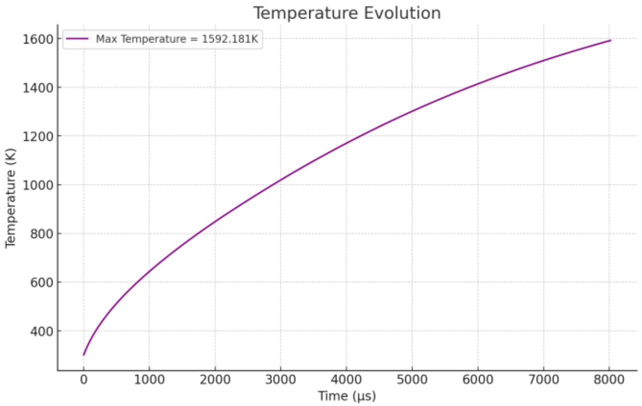
Scanning wire

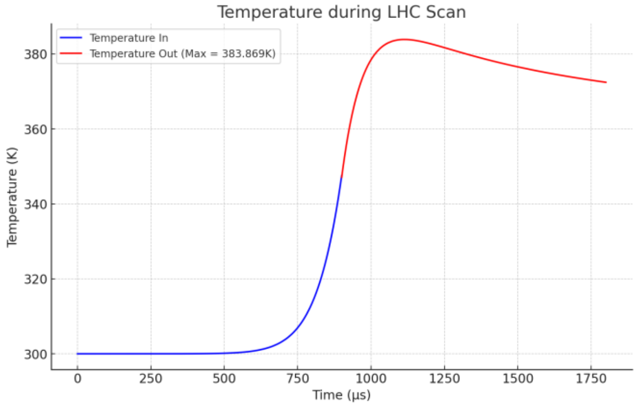


Thermal studies – Current wire in the BHM (3.5σ)

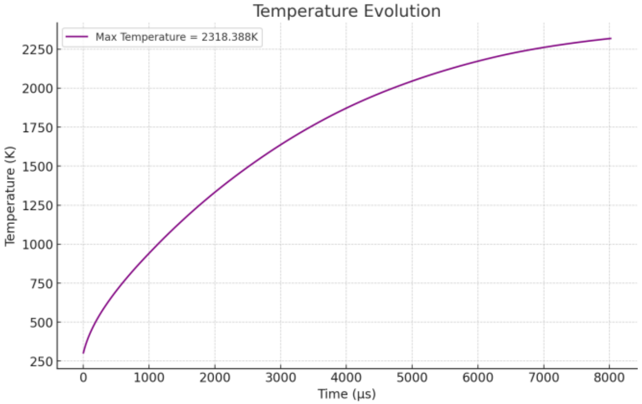
Beam size | **Stationary wire** | **Scanning wire**

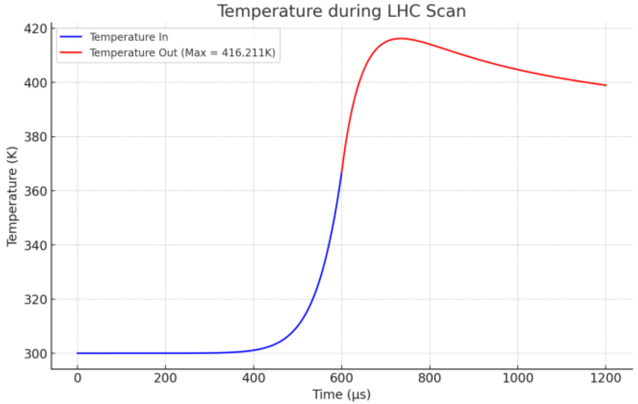
300 µm





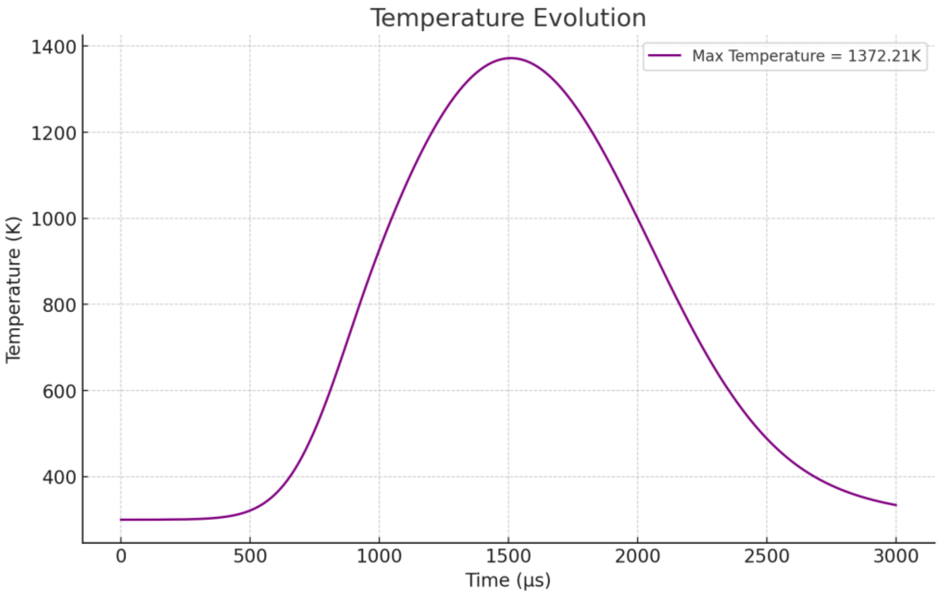
200 µm





w/ Collaboration of A. Abouelenain

Thermal studies – Physical limits



Simulation Characteristics

- Energy of 7 TeV – Intensity of 5.7e14

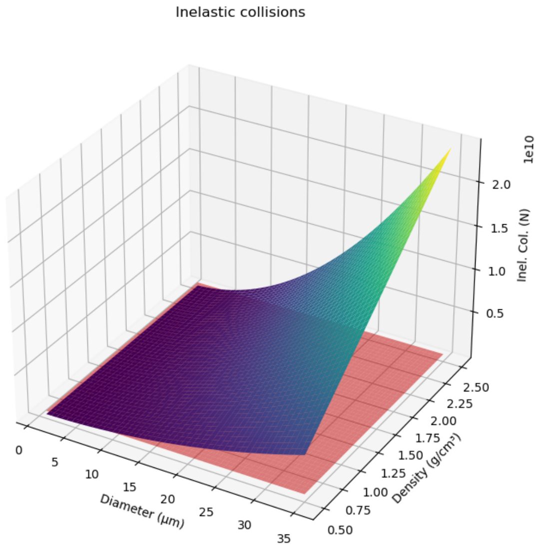
Limitations

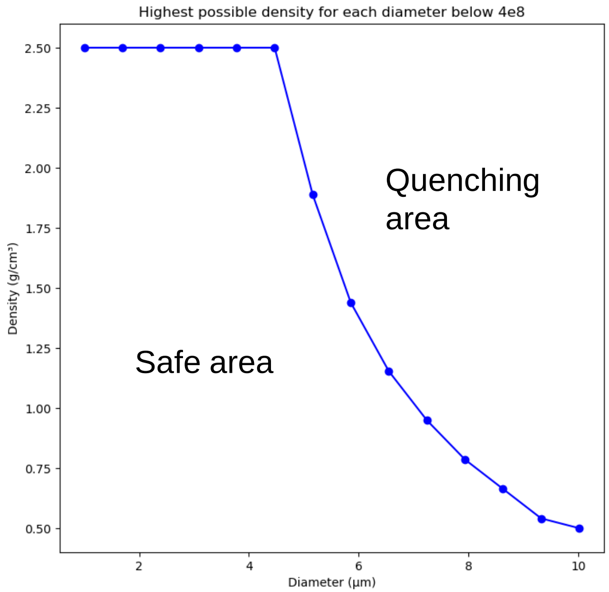
- Carbon atoms being knocked out have been neglected.
- Wire defects have not been considered

Wire characteristics

- 0.01 µm of diameter .
- Density of 0,8 g/cm3

Inelastic collisions studies





Simulation conditions

- Energy – 6,5 TeV
- Intensity – 5,7e14
- Scanning speed – 1 m/s
- Quench limit – 4e8

(5)

Conclusions

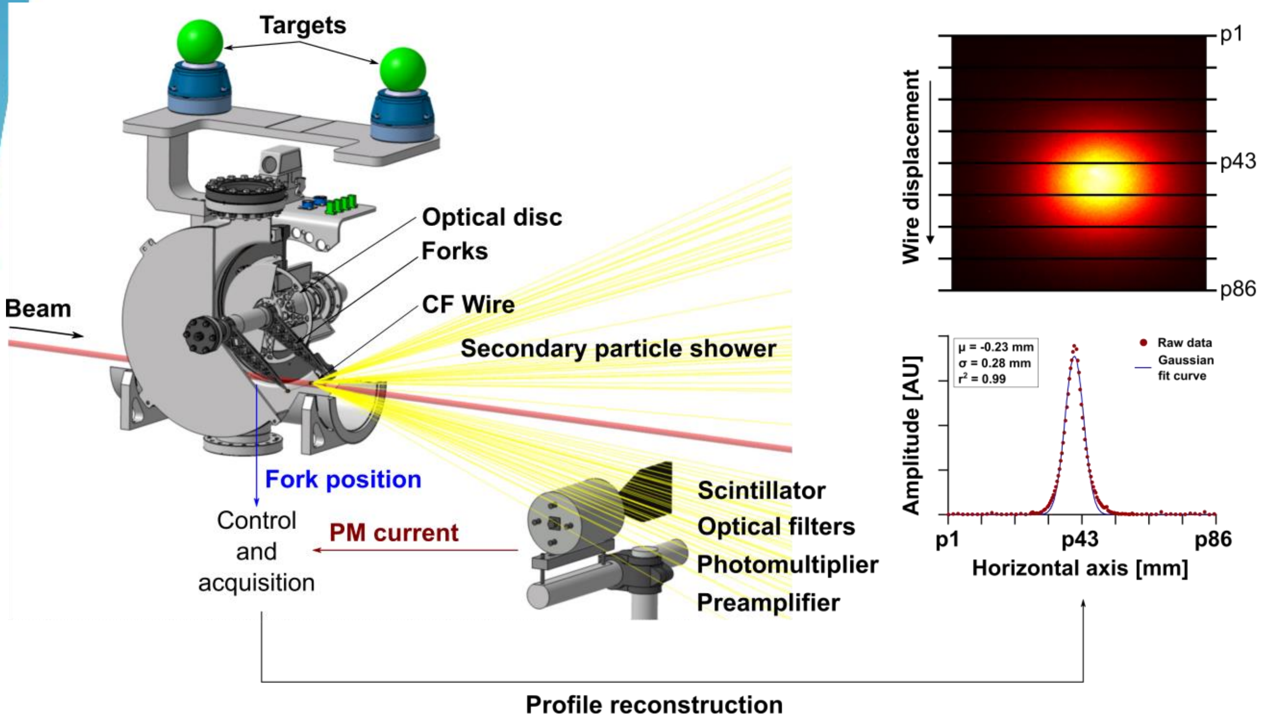
- CNT-based Beam Wire Scanners (BWS) could enable precise and reliable monitoring of the beam halo, even at high intensities and energies.
  - The low-density nature and small diameters of CNT wires reduce beam interaction, preserving beam quality.
  - CNT wires exhibit improved properties over the current Carbon Fiber wire.
- Streamlined integration with the next generation of linear beam wire scanner.
- State-of-the-art advancements driven by active R&D, with key contributions from our collaborations with leading partners
  - 20-21 June 2023 Workshop - Low density materials for Beam Instrumentation
- Further testing and characterization is required to ensure an adequate performance.
- Concerning expected accuracy, contrast, signal levels, a BH monitor via wires needs more studies and simulations. Basic information can be inferred from standard BWS are:
  - Present BWS flying at 1m/s -> achievable contrast in the range 1e-3 to 1e-2
  - 1D profile only (unless tomoscopy via multiple BWS can be implemented)
  - Bunch per bunch possibility (may need to be integrated over many turns)

Thank you for your attention

Any questions?

CERN

Wire-scanners (WS)



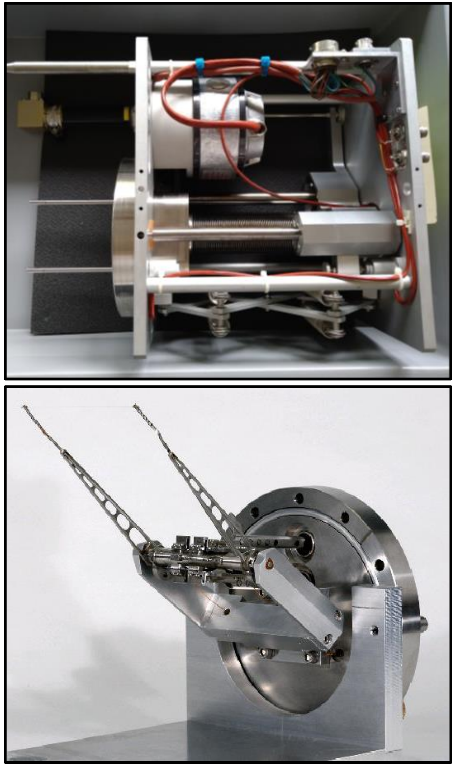


Figure 6. Linear and rotary Wire Scanners

A. Mariet (2023) [3]

Wire scanners challenges

Wire degradation

Today, the ageing of Carbon Fiber wires is a limitation

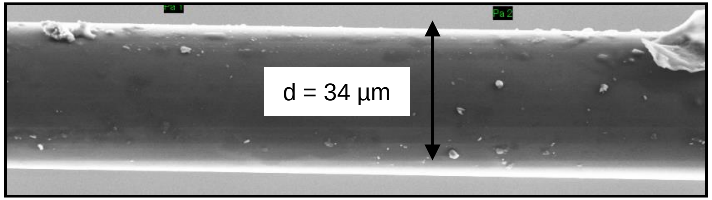


Figure 7. Pristine 34 µm Carbon Fiber (CF) before irradiation [3]

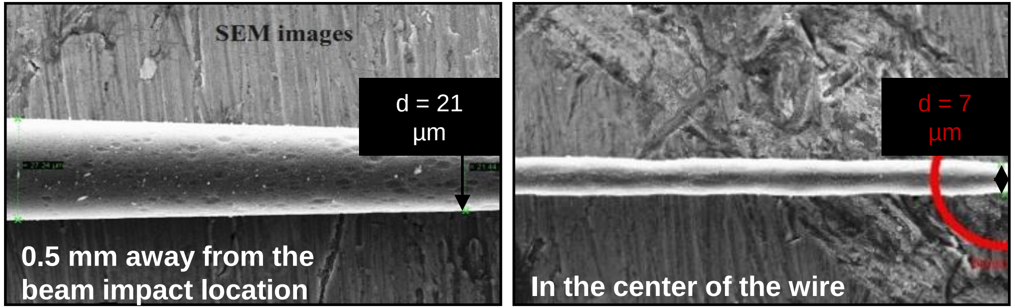


Figure 8. Aging Carbon Fiber (CF) after irradiation [3]

Future challenges of intercepting devices [4]

Machines	SPS	LHC	FCC
Beam energy	450 GeV	7 TeV	50 TeV
Beam size	2 mm	200 µm	20 µm
Max intensity (N_p)	~ 5.10^{13}	~ 3.10^{14}	~ 1.10^{15}

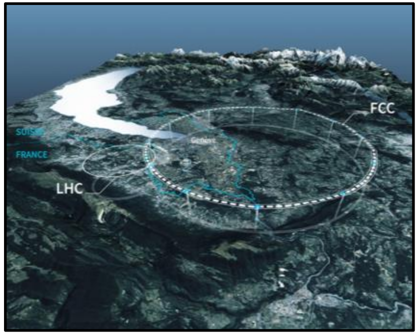


Figure 9. Future Circular Collider project representation

CNT manufacturing

CNT manufacturing methodologies [6]

Electric-arc discharge

Laser ablation

Chemical Vapor Deposition (CVD)

Types of chemical vapor deposition for our purpose:

- Thermal CVD (TCVD)
- Plasma-enhanced CVD (PECVD)
- Floating Catalyst CVD (FCCVD)
- Catalyst-Supported CVD (Cat-CVD)
  - Davide Mattia – University of Bath
- Photo-Thermal CVD

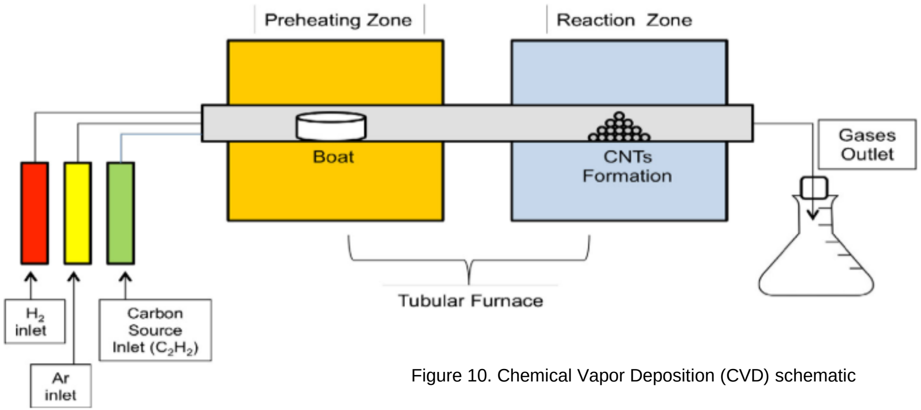


Figure 10. Chemical Vapor Deposition (CVD) schematic

Figure 11. Ultra-long CNT forest created by CVD [7]

CNT wire manufacturing

CNT rope manufacturing methodologies [7]

Wet spinning

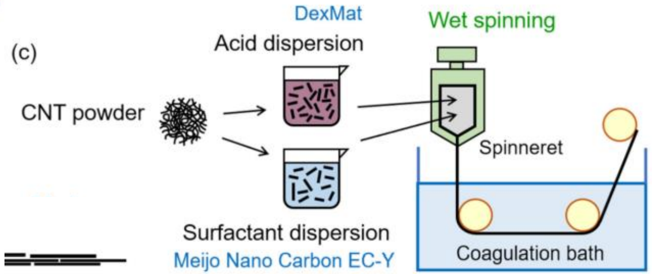


Figure 12. Wet spinning procedure schematics

Dry spinning (solid-state)

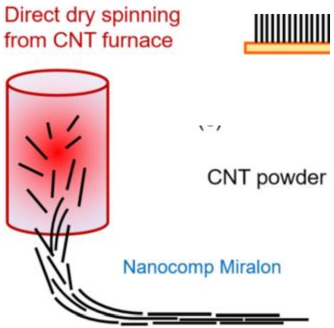


Figure 13. Dry spinning SS procedure schematics

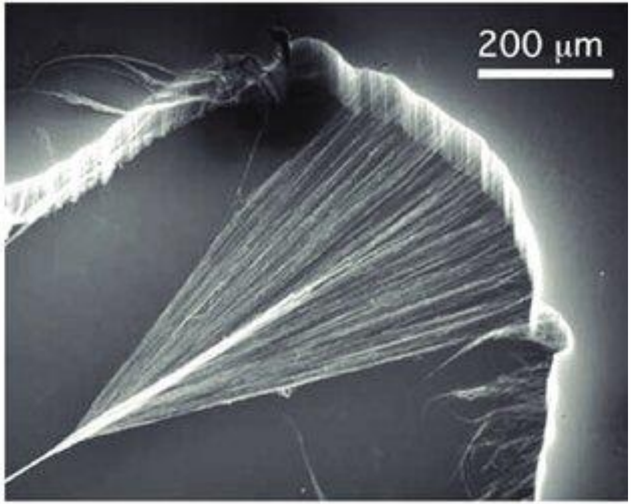


Figure 15. Dry spinning from a CNT forest

Dry spinning from a CNT forest

Figure 14. Dry spinning from a forest procedure schematics

Proof of concept

Treatment applied

- 12 h nitric bath (2.8 M concentration) at 125 degrees.
- Neutralisation of the acid and dry overnight

Figure 16. Treatment done at University of Bath

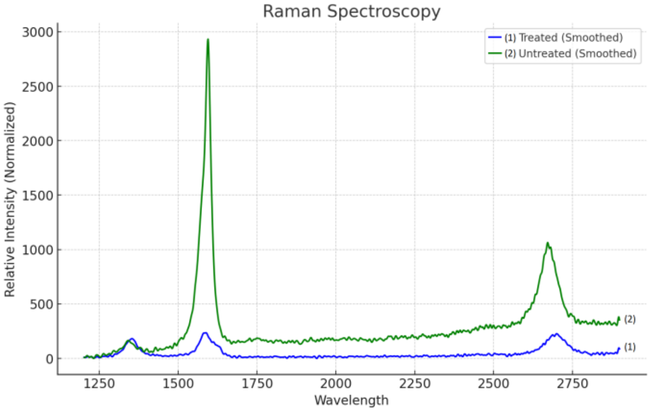


Figure 17. Raman spectroscopy result from both wires

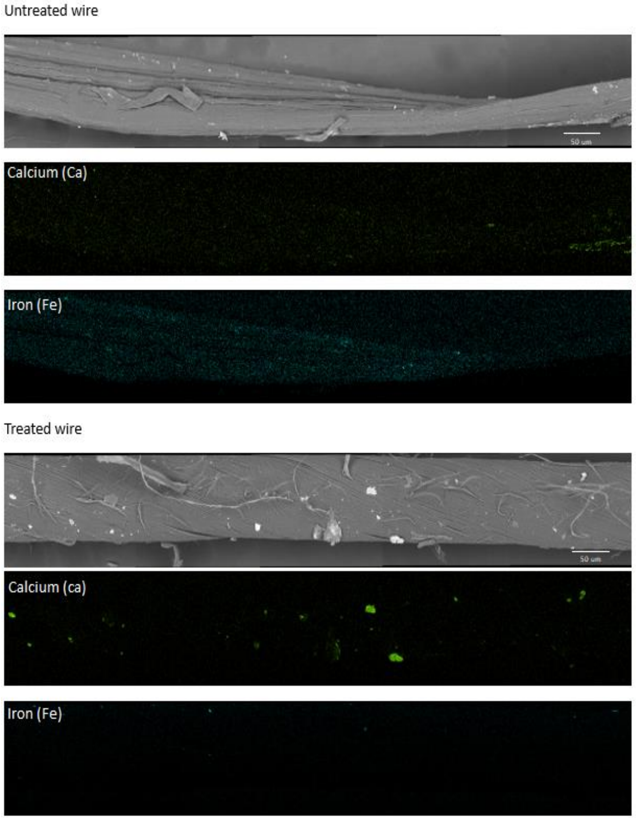


Figure 18. EdX and SEM images of both wires, treated and untreated