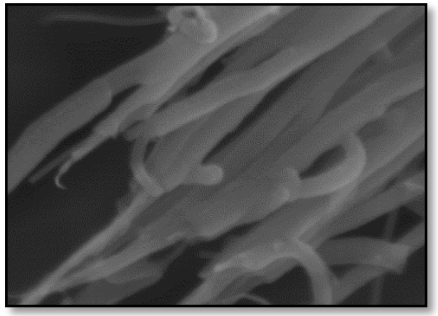
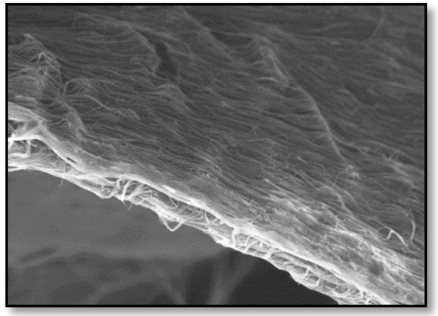
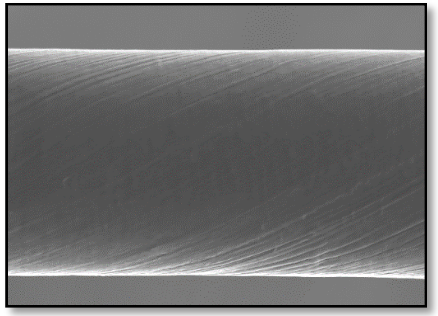
Tests and simulations on Carbon Nanotube yarns as a material for beam intercepting instruments in HiRadMat

- General introduction
- Carbon Nanotubes
  - Description
  - Properties
  - Yarn structure
- HiRadMat experiment
  - Objectives
  - Experiment
  - Simulations
  - Preliminary results



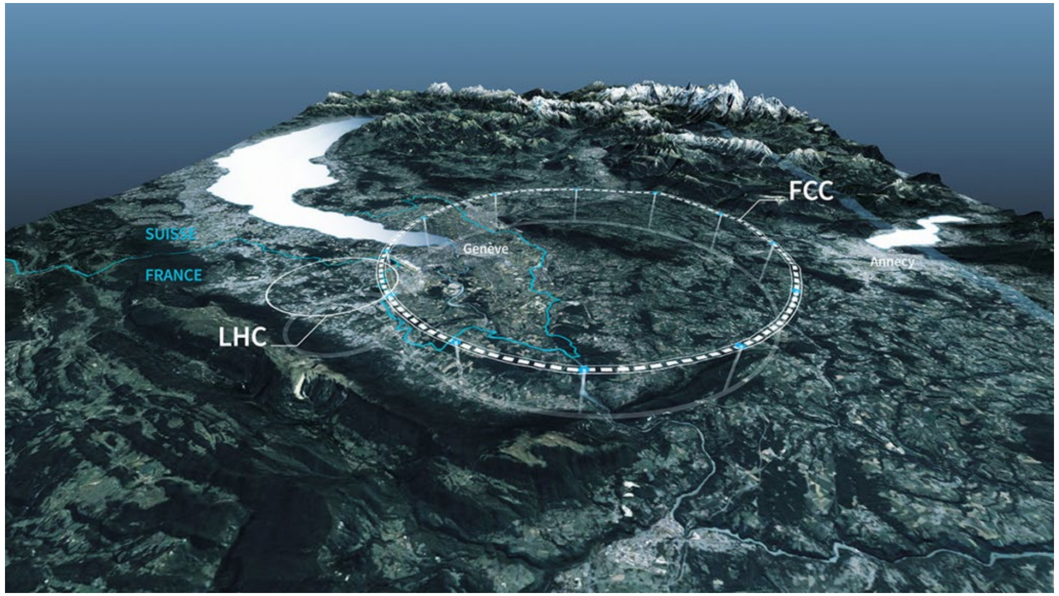




Challenge for beam intercepting devices

1 - …..Towards higher beam intensities

Machine @ CERN	SPS	LHC	HL-LHC	FCC-hh
Max total intensity [N_p]	~ $5x10^{13}$	~ $3x10^{14}$	$6.2x10^{14}$	$1.1x10^{15}$

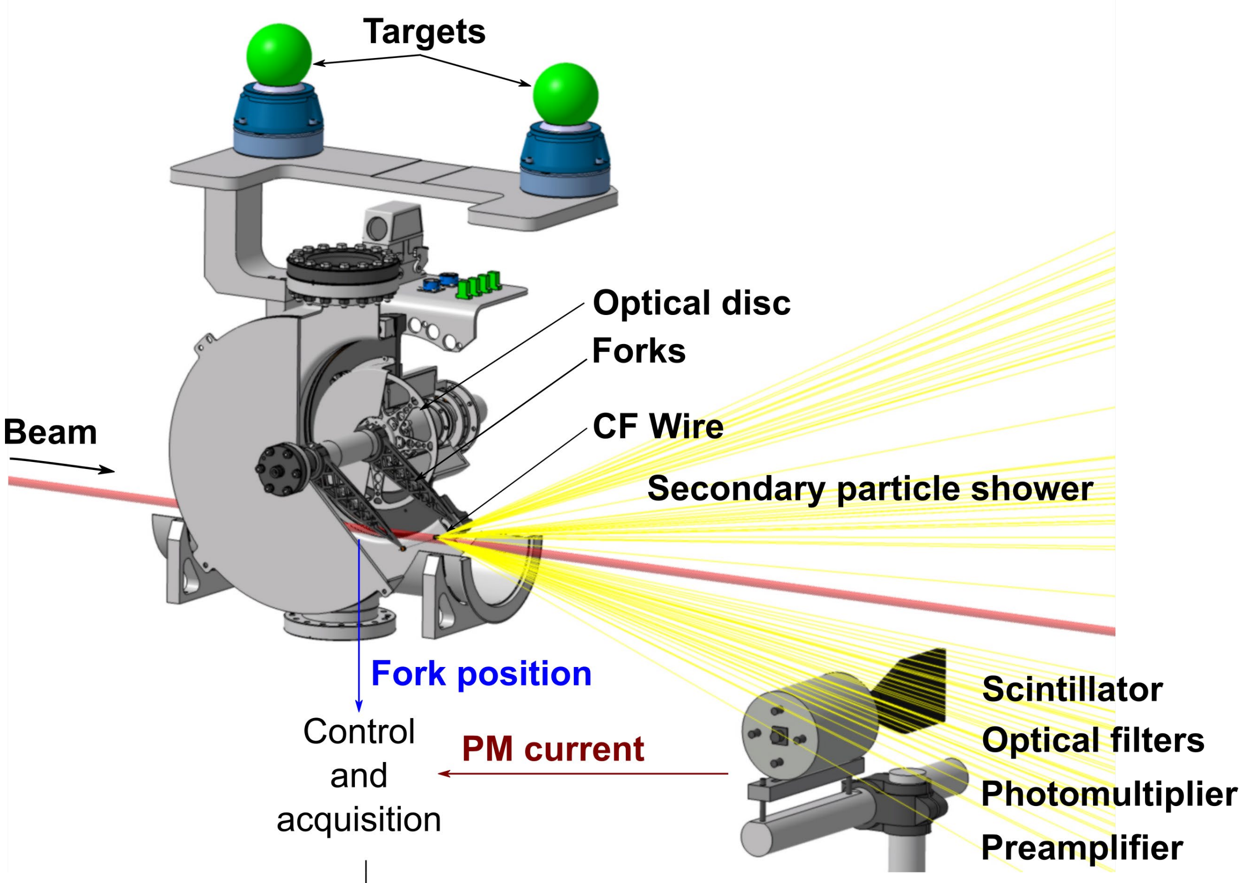


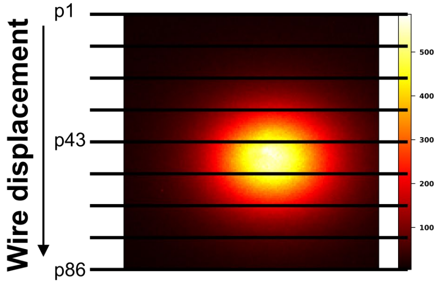
2 - Smaller beam size at higher beam energies

	SPS	FCC	LHC
Beam energy	**450 GeV**	**50 TeV**	**T TeV**
Beam size	**2 mm**	**20 µm**	**200 µm**

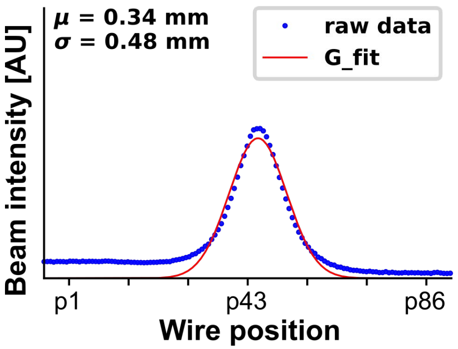
→ **Extreme beam densities**

Wire-Scanners for transverse profile monitoring





Moving a thin wire across the beam.



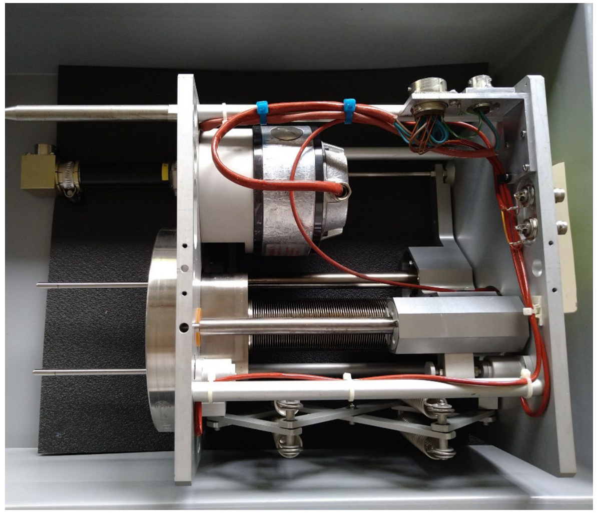
Measuring the intensity of the secondary particle shower induced as function of wire position with a Scintillator and Photomultiplier tube.

Profile reconstruction

Challenge for Wire-Scanners

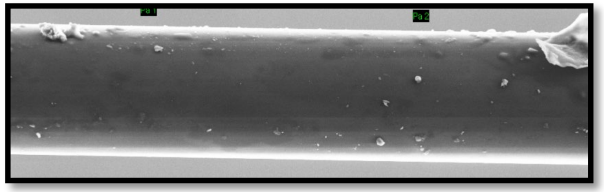
Today, **the ageing of wires is a limitation**

Linear Wire-Scanner in the SPS



Scan speed [$m.s^{-1}$]	Momentum [$GeV.c^{-1}$]	Intensity	σ_l [mm]	σ_l [mm]
0.5	400	$2.41.10^{13}$	0.57	0.73

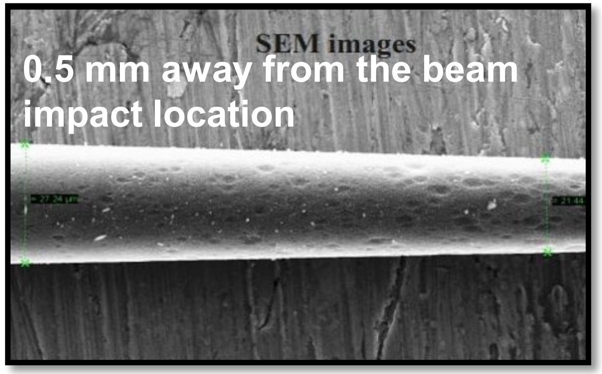
New



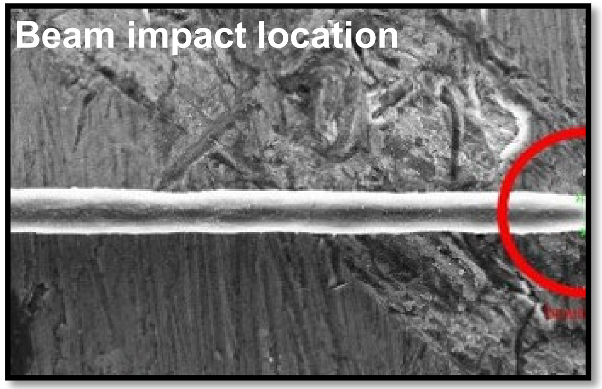
34 µm carbon fiber

Wire sublimation [1]

Aged



d = 21 µm

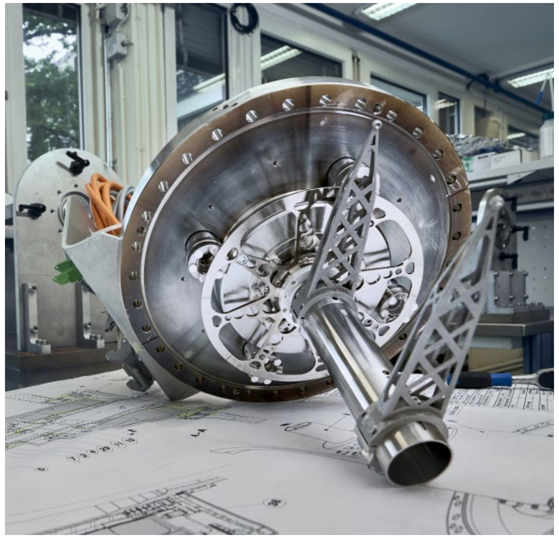


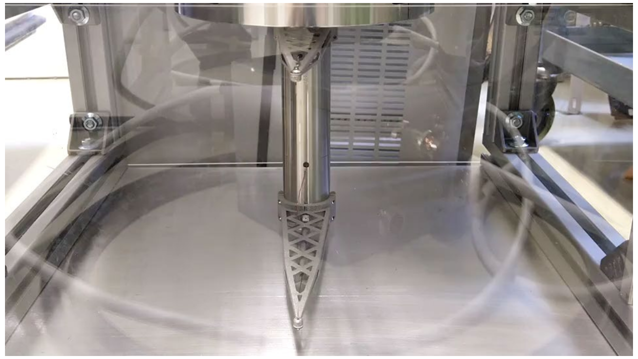
Diameter down to 7 µm

[1] M. Sapinski, B. Dehning, A. Guerrero, J. Koopman, E. Metral, Carbon fiber breakage experiment on SPS, 2010

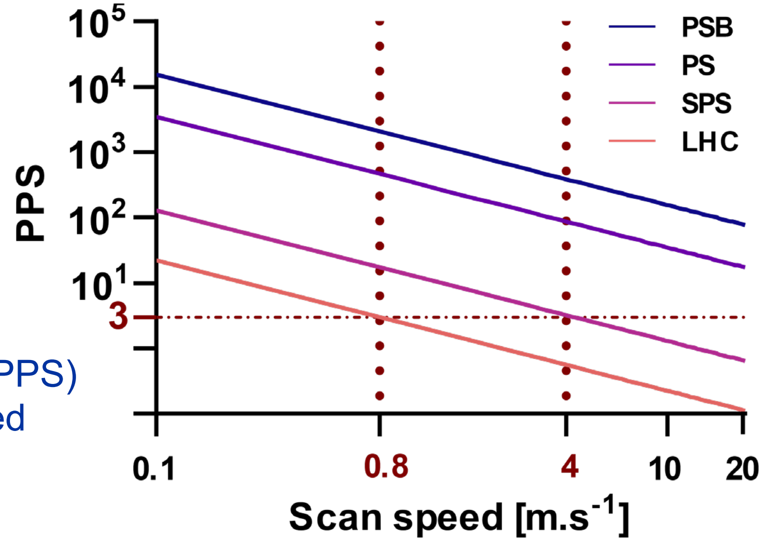
Challenge for Wire-Scanners

To cope the ever-increasing beam densities, scanning fast is a good option.





20 m.s^{-1} fast rotating wire scanner deployed at CERN in 2020 in Injector Complex (PSB, PS, SPS)



Number of points per sigma (PPS) as a function of the scan speed

To get the required resolution :

@ SPS $v_{scan\ max}$ = 4 m.s^{-1}

@ LHC $v_{scan\ max}$ = 0.8 m.s^{-1}

@ LHC $N_{bunch\ max}$ = 8 (vs 2808 max)

Challenge for Wire-Scanners

To cope the ever-increasing beam densities, scanning fast is a good option.

We need better Wire, better Material

- Mechanical properties : **high strength, low density**
- Thermal properties : **high conductivity**

- Resist to **Radioactive environment**
- Compatible with **Ultra-High Vacuum environment**

anner deployed at
ex (PSB, PS, SPS)

e required resolution :

$v_{scan\ max} = 4\ m.s^{-1}$

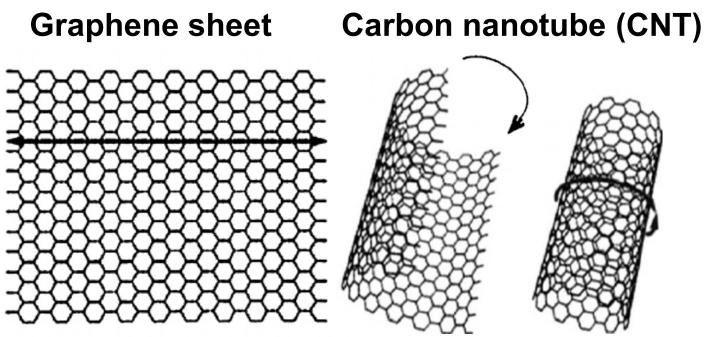
@ LHC $v_{scan\ max} = 0.8\ m.s^{-1}$

@ LHC $N_{bunch\ max} = 8$
(vs 2808 max)

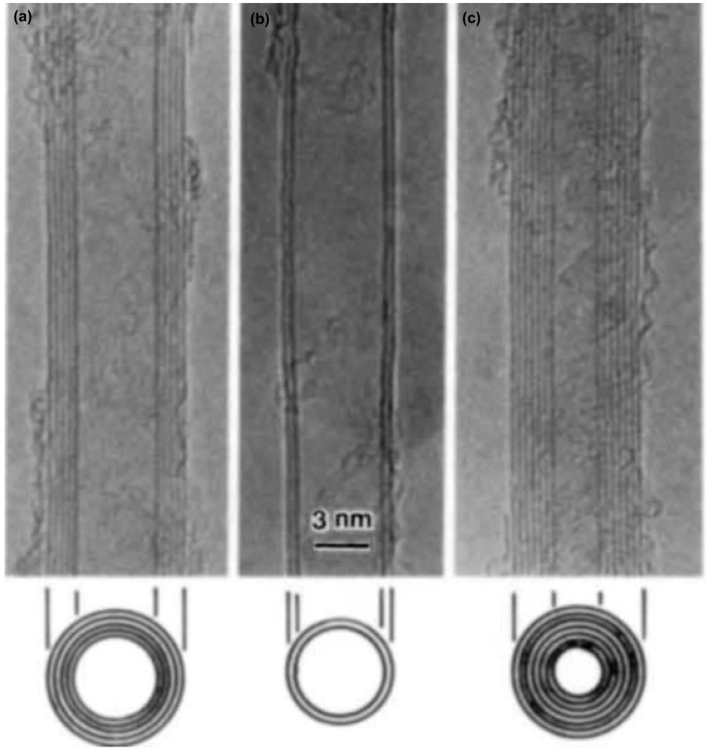
Number of points per sigma (PPS)
as a function of the scan speed

Carbon Nanotubes (CNT)

- Allotropic form of carbon
- Formed by sheet(s) of graphene coiled in a specific direction (axe of chirality)
- Composed of one or several walls (SWCNT, DWCNT, MWCNT)
- Long and hollow nanometric structure



From graphene to CNT [1]



Electron micrographs of CNT by Iijima [2]

[1] S. Sheshmani, A. Ashori, et M. Arab Fashapoyeh, « Wood plastic composite using graphene nanoplatelets », International Journal of Biological Macromolecules, vol. 58, p. 1-6, 2013.
[2] S. Iijima, "Helical microtubules of graphitic carbon," Nature, vol. 354, p. 56, 1991.

Mechanical and thermal properties

For comparison

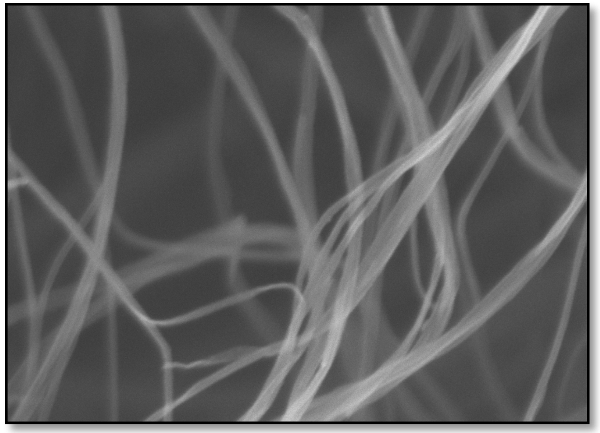
	Carbon fiber	Stainless steel
Density :		
• walls and diameter function		
• density : 0.02 - 4 $g.cm^{-3}$ [1]	1.7 - 2.5 $g.cm^{-3}$	7.8 $g.cm^{-3}$
Mechanical properties :	**Mechanical properties**	
• modulus : 1 - 5 TPa [2]	60 - 500 GPa	200 GPa
• strength : up to 120 GPa [2]	600 - 4500 MPa	500 - 600 MPa
Thermal properties :	**Thermal properties**	
• conductivity : 3 - 6 $kW.m^{-1}.K^{-1}$ [3]	0.140 $kW.m^{-1}.K^{-1}$	0.015 – 0.030 $kW.m^{-1}.K^{-1}$
• heat capacity : 700 $J.kg^{-1}.K^{-1}$	720 $J.kg^{-1}.K^{-1}$	430 - 500 $J.kg^{-1}.K^{-1}$
• transition temperature : 4100 K	4100 K	1600 K

Best properties in every domain

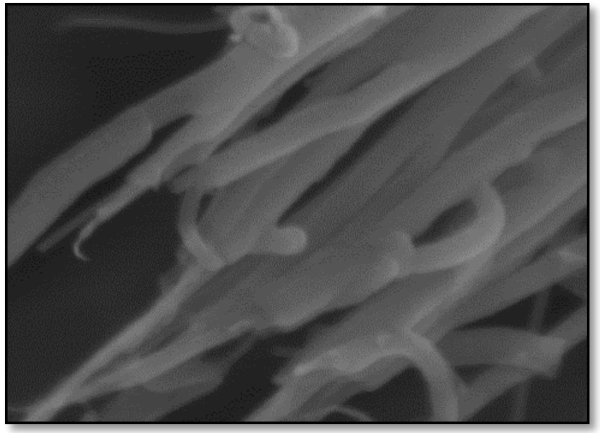
[1] Ch. Laurent, E. Flahaut, et A. Peigney, « The weight and density of carbon nanotubes versus the number of walls and diameter », *Carbon*, vol. 48, nº 10, p. 2994-2996, 2010.
[2] Jhon, Young *et al,* «Tensile Characterization of Single-Walled Carbon Nanotubes with Helical Structural Defects », *Scientific Reports*, 2016.
[3] S. Berber, Y.-K. Kwon, et D. Tománek, « Unusually High Thermal Conductivity of Carbon Nanotubes », *Phys. Rev. Lett.*, vol. 84, nº 20, p. 4613-4616, 2000.

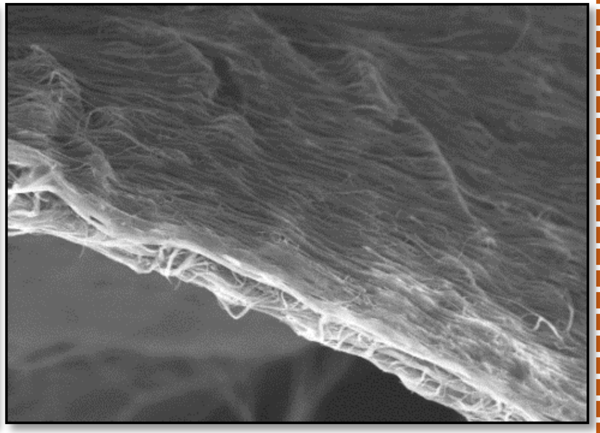
Carbon Nanotube Yarns

5 nm — 50 nm — 500 nm — 30 µm

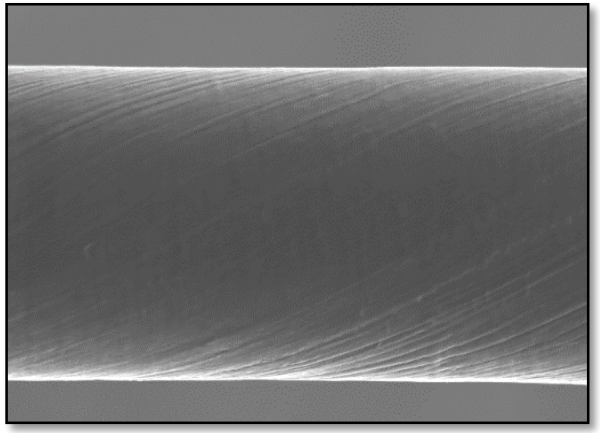

CNT (x 120k)

Strong covalent bonds between C atoms in CNT


Bundles (x 127k)


Layer (x 10.5k)

Weak van der Waals bonds between CNT in clusters / bundles

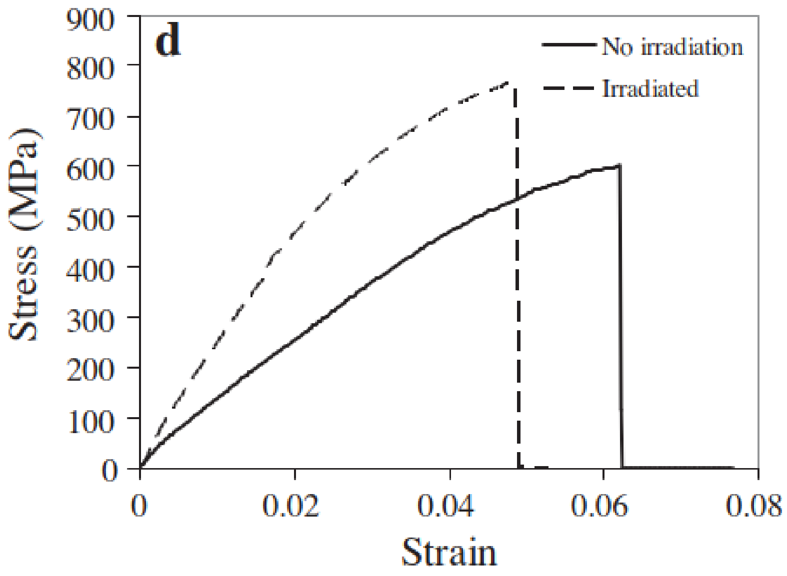

Yarns (x 230)

Large degradation of the yarn properties

HiRadMat experiment

Objective : Study the change of CNTY mechanical properties after irradiation

Tensile test of CNTY before and after gamma irradiation (from [1])



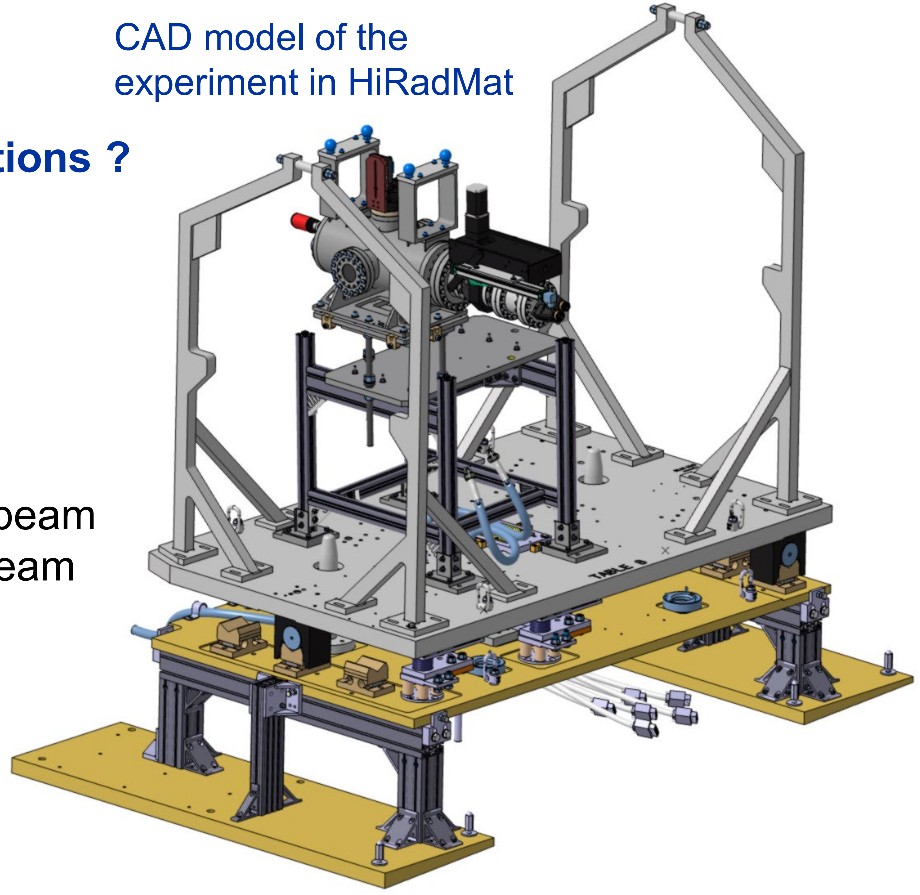
- Gamma irradiation of CNTY
- Creation of constructive defects
- Creation of covalent bonds
- Increase of the strength by 20 %

CAD model of the experiment in HiRadMat

True with these conditions ?

Beam :

- Proton
- E = 440 GeV
- σ_x = 0.25 mm
  0.50 mm
- 288 bunches / beam
- I_{tot} = 3.2e13 / beam

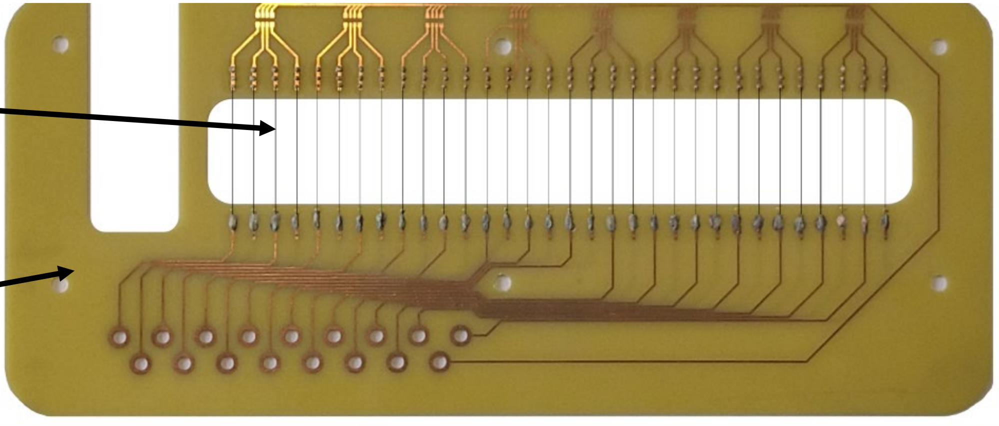


[1] Miao, Menghe *et al*, « Effect of gamma-irradiation on the mechanical properties of carbon nanotube yarns, irradiation », *Carbon,* 2011

Material and conditions

Samples (CNT + CF)

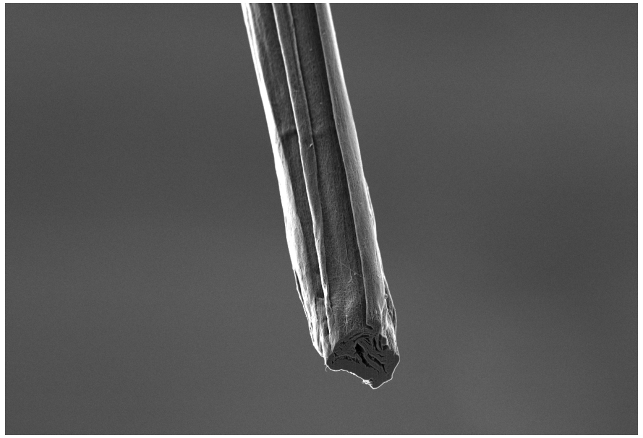
Support grid



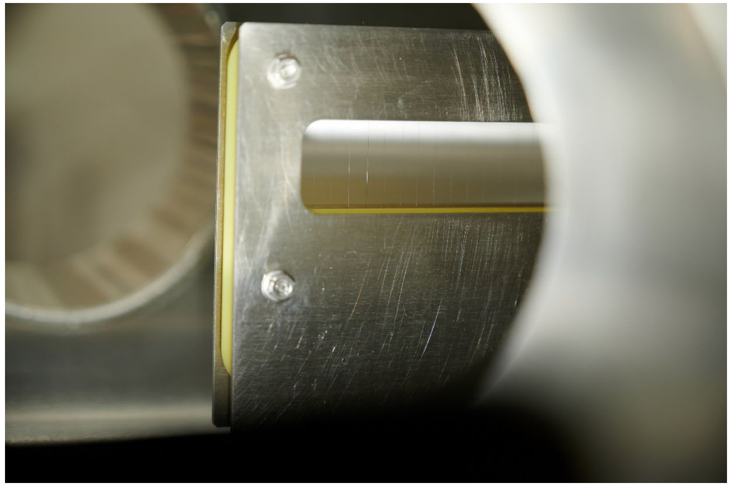
Material :

- 30 CNTY (thin and thick)
- CF (7 and 34 µm)

With the courtesy of A. Perez Fontenla



Cross section of a thick CNTY irradiated in HiRadMat



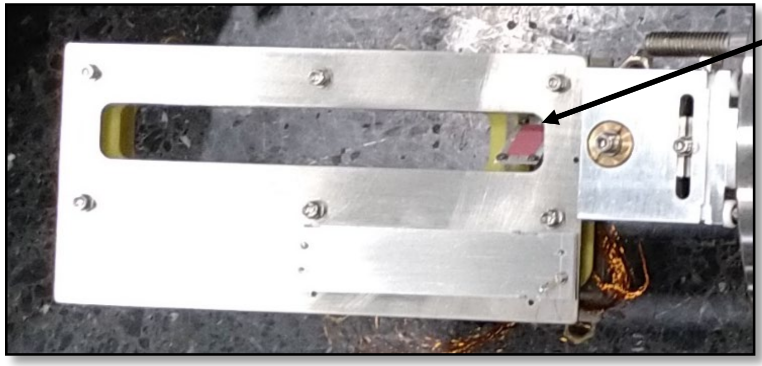
Grid assembly in the tank

Yarn parameters :

- C : 90% C + 10% Fe
- d_{thin} = 11 +/- 2 µm
- d_{thick} = 24 +/- 4 µm
- $\lambda_{lin\text{-}thin}$ = 0.04 +/- 0.004 tex (g.km^{-1})
- $\lambda_{lin\text{-}thick}$ = 0.11 +/- 0.023 tex

Irradiation of the wires one by one

Experimental challenge



BTV screen

Challenge : ensure the alignment between the beam and the samples

In-situ screen Ref BTV

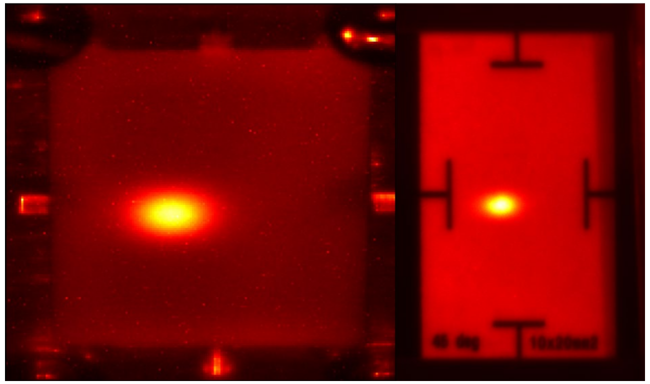
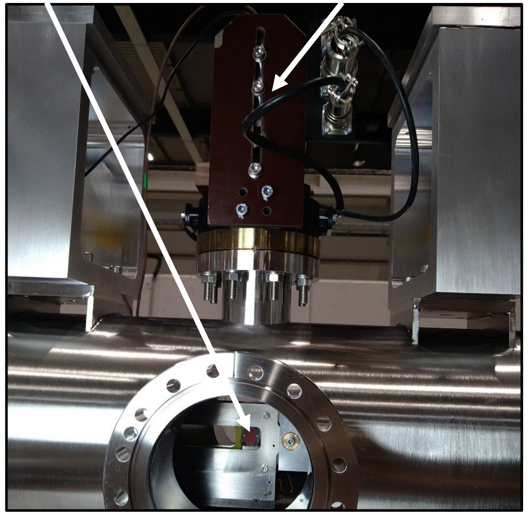


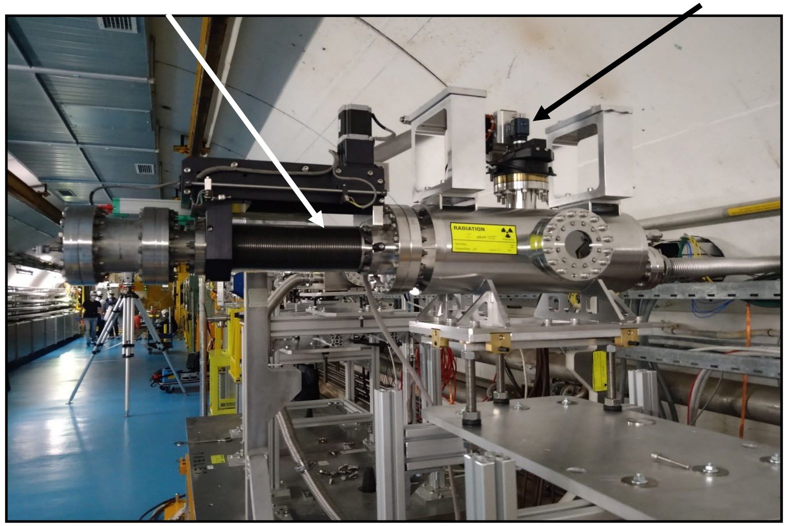
Image comparison

BTV screen BTV Camera



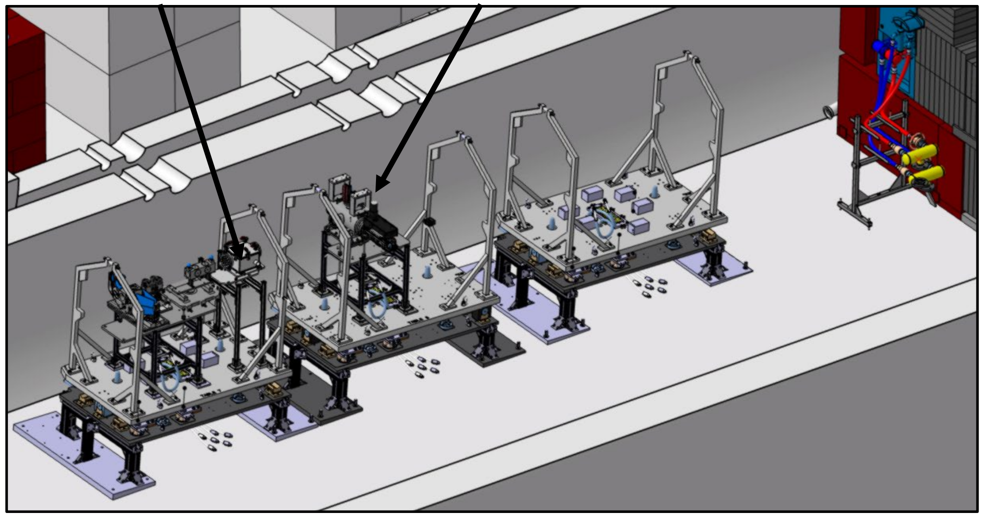
Wire position calibration

SEM mechanism BTV Camera



CYCHI experiment in HiRadMat

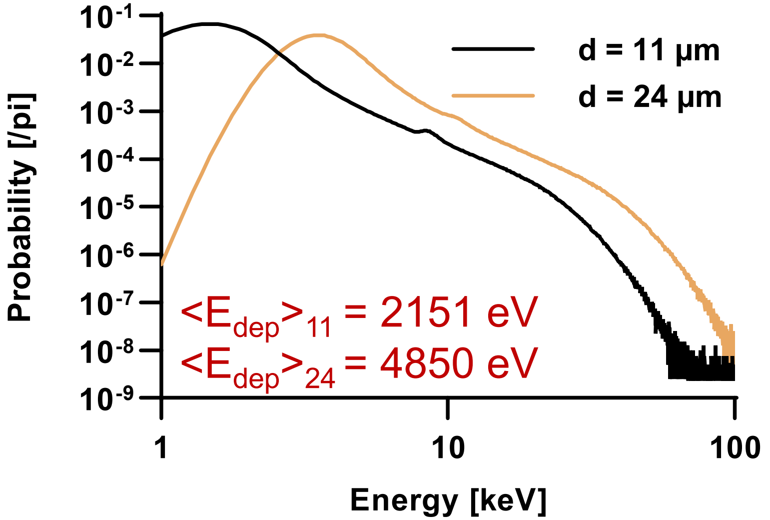
Reference BTV Experiment



HiRadMat experimental line

Energy deposition and thermal simulations

Fluka simulations



Probability for an incident proton to deposit some energy in carbon with 10% in weight of iron.

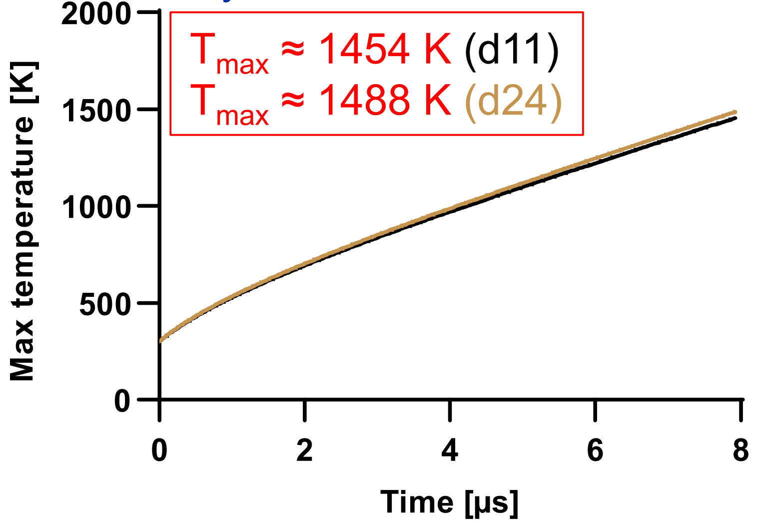
Thermal simulation parameters

$c_p = 0.9c_{p\text{-}C} + 0.1c_{p\text{-}Fe}$
Variation of c_p with the temperature
Cooling mechanisms :

- Radiation
- Conduction
- Thermionic emission

Expectation of a modification of the structure

Python code simulation*



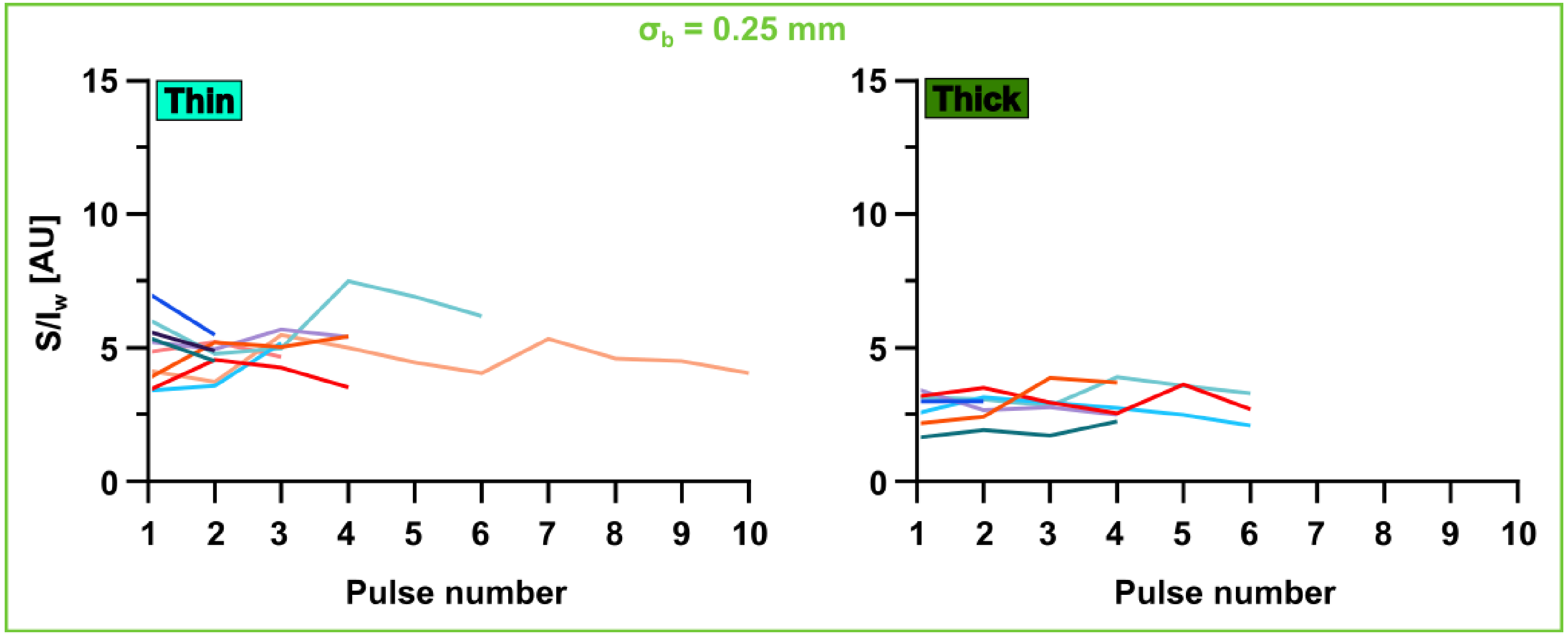
Evolution of the temperature at the center of the wire as a function of the time.

* Code provided by A. Navarro Fernandez (CERN)

In-situ test : Secondary electron emission

Normalized by:

- the intensity (BCT measurement)
- the position (BTV image)

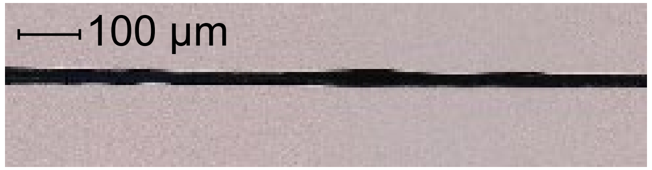


- Beam size of 0.25 mm
- Pulses from 2 to 10
- Cumulated intensity per wire from :
    - $7.7 10^{11}$ to $4.2.10^{12}$ (thin)
    - $1.0.10^{12}$ to $5.5.10^{12}$ (thick)

- No obvious evolution of the signal with the increase of the number of pulses.
  ⟶ **No modification of the surface**
- Larger dispersion for thin wires than for thick wires.

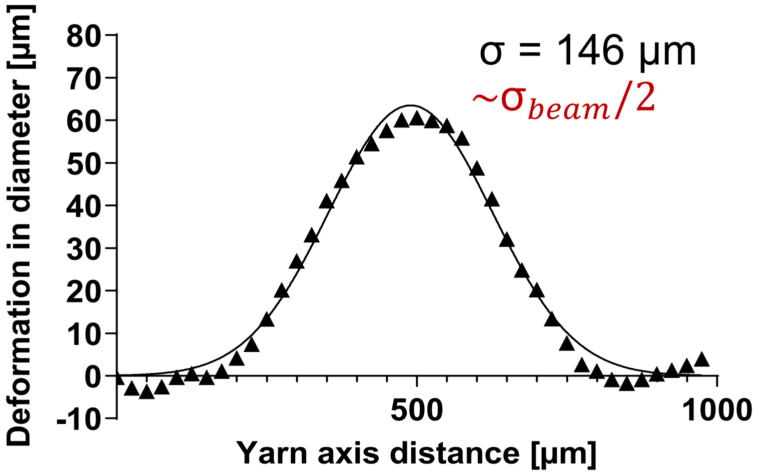
Evolution of the normalized signal with the increase in pulse for a beam size of 0.25 mm and both types.

Post-irradiation test : Raman spectroscopy

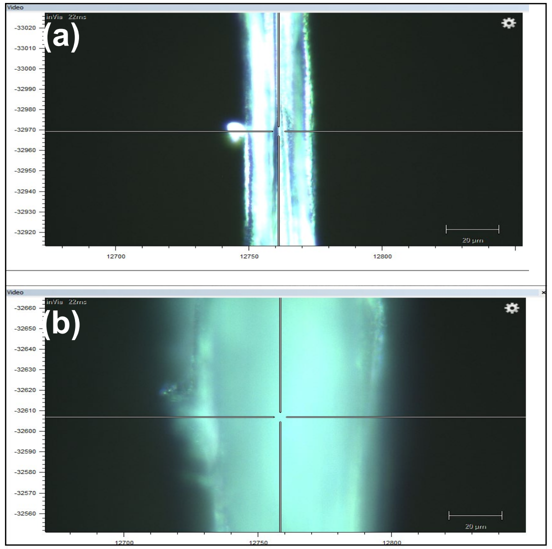


CNT yarn before irradiation

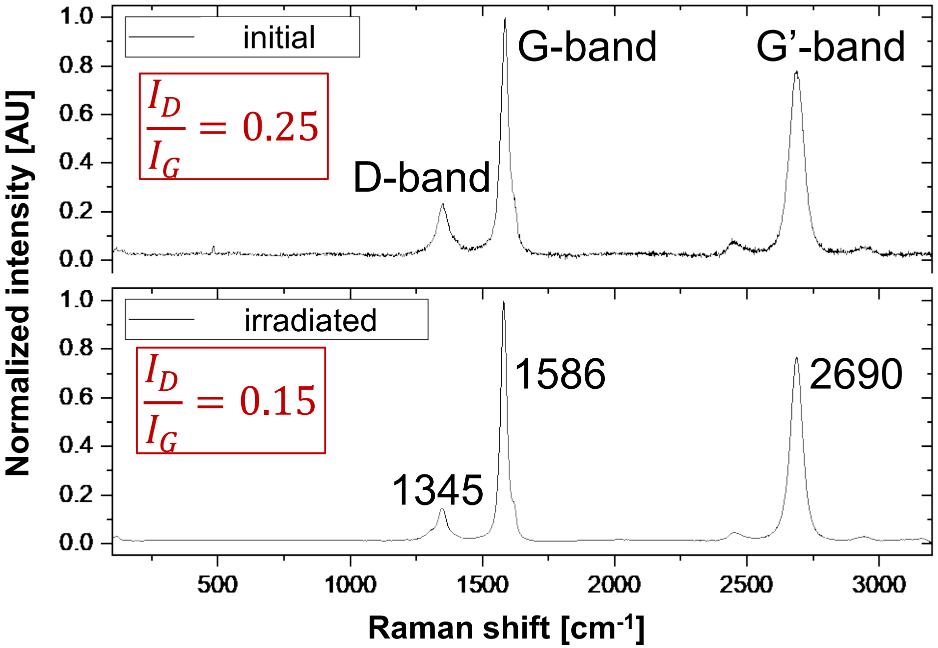
CNT yarn after irradiation



Shape of the irradiated area deformation



Sample enlightened by the Raman laser at two positions : (a) initial; (b) irradiated

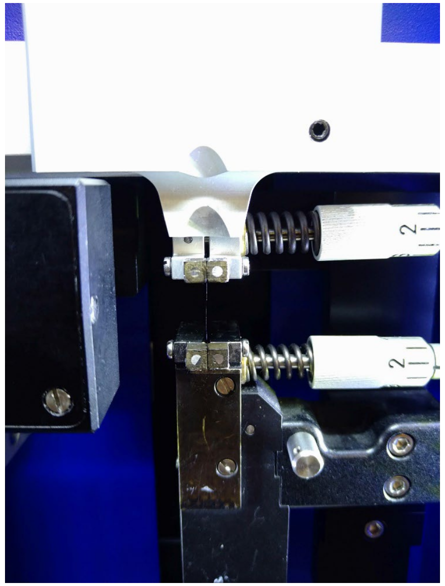


Raman spectra of pristine and irradiated area

Modification of the shape, but no degradation of the structure !!!

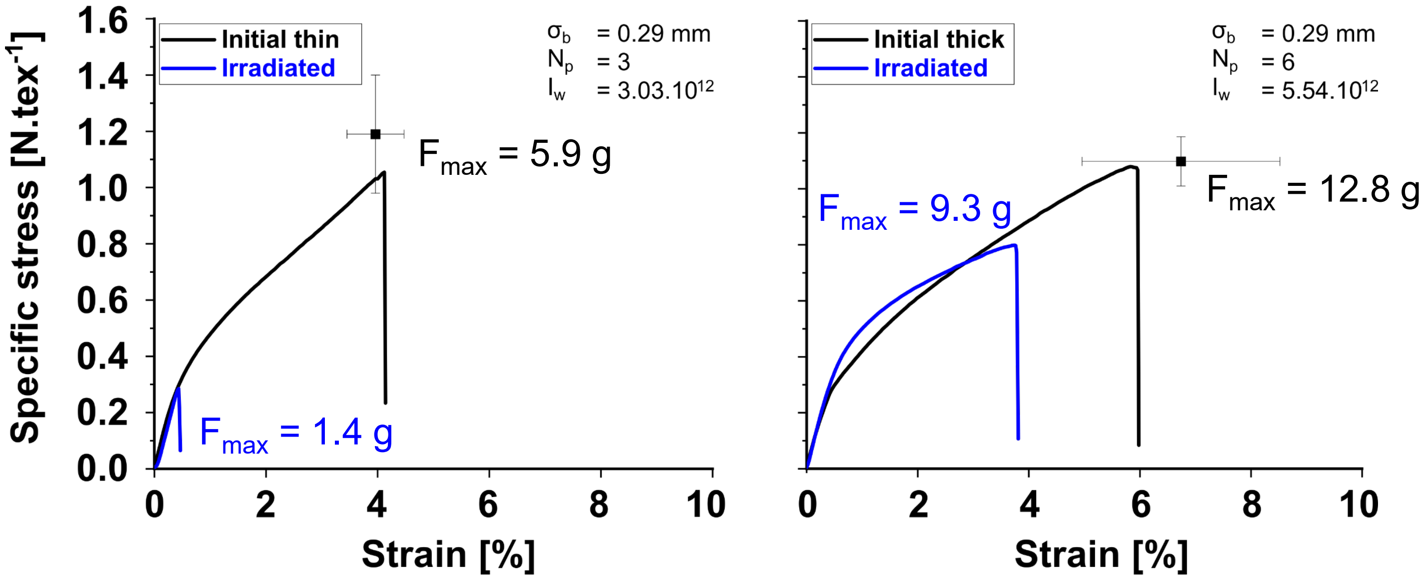
Hypothesis : overpressure in the yarn structure due to the residual catalytic particles

Post-irradiation test : Mechanical tests



Tensile machine
Load cell 1N

With the courtesy of A. Mikhalchan (IMDEA)



Fracture area of a thick yarn

Larger degradation of the specific strength and strain to failure for thin wire despite the smallest number protons crossing the wire

Conclusion

- Carbon Fiber wires have to be replaced to meet new requirements
- Materials available today have properties far from the maximal potential of CNT
- Development of an experimental setup to allow the tests of low-density materials at high beam densities and secondary emission yield using low intensity beams
- First results obtained in HiRadMat in 2021 showed than the CNT wires loose mechanical properties after proton irradiation
- Full data analysis still ongoing
- Purity of materials due to production methods is clearly an issue
- CNT productions is a very active field of research and it is important to keep cross links with the manufacturers
- Preliminary tests with operational instruments in the SPS are in progress

a lot more still needs to be done …

Acknowledgments

This work was supported by:

- Ray Veness, Thibaut Lefevre, Federico Roncarolo, Benjamin Moser, Michel Duraffourg, Stéphane Burger, Araceli Navarro Fernandez, Thomas Virazels, Clémence Salomon, Ana Teresa Perez Fontenla **(CERN)**
- Pascal Simon, Nikolaos Charitonidis, Aboubakr Ebn Rahmoun **(HiRadMat team)**
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