Large-diameter carbon nanotube fiber for H-/proton beam diagnostics: fabrication, test and implementation at CSNS accelerator

Zhijun Lu, **Chunjie Xie**, Biao Zhang, Fang Li, Renjun Yang, Huachang Liu, Xiao Li, Xin Qi, Sheng Wang, CSNS/IHEP, Dongguan, China

Liming Zhao, Yutao Niu, Zhao He, Yongyi Zhang, SINANO, Suzhou, China

Muqiang Qian, Jiankun Huang, Jin Zhang, Peking University, Beijing, China

31/08/2026

Whistler, Canada

New Materials for high-intensity beam monitor

Challenge for interceptive profile monitors

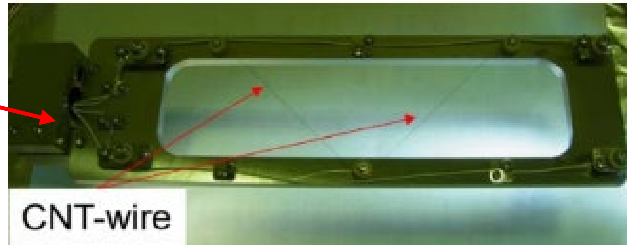
- Conventional wires face increasing thermal and radiation loads in high-intensity beams.
- Beam-induced heating can limit pulse length, repetition rate, and wire lifetime.

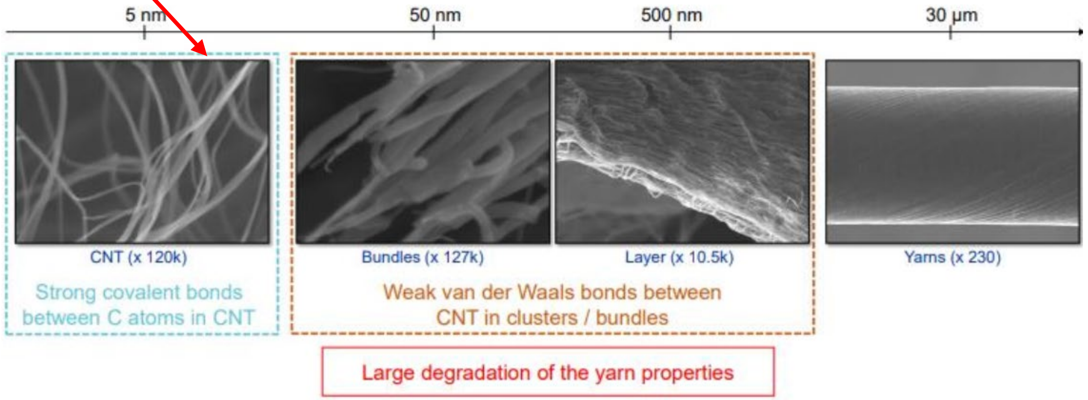
Why carbon nanotube fibers(CNTFs)?

- Low density reduces beam-induced heating.
- Thermal endurance and mechanical flexibility.
- Adequate secondary-emission signal for profile measurement.

Parameters of the wires for beam monitor

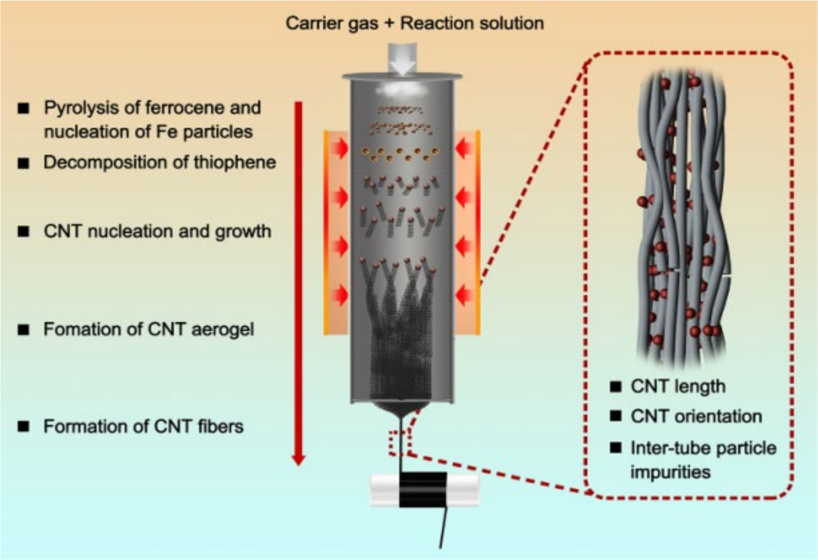
Material	CNTF	CF	W	SiC
Diameter [um]	100	33	33	75
Density [g/cm^3]	1.08	1.8	19.35	2.89
Thermal conductivity [W/m·K]	350	24	173	340
Tensile Strength [Gpa]	1.79	3	1	5.9
Work Temperature [K]	<2000	<2000	<2000	<1500

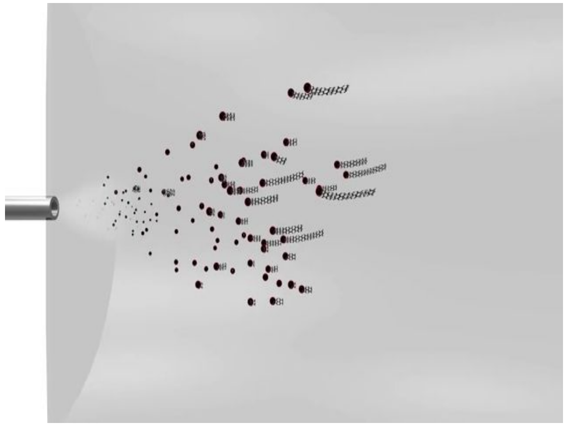




[1] A. MARIET, Low density material for beam instrumentation(2023), CERN
[2] A. Miura, et. al, Application of carbon nanotube wire for beam profile measurement of negative hydrogen ion beam (2018), KEK
[3] G. A. Cervera, Development and characterization of CNT-based wires for beam wire scanners (2024), CERN

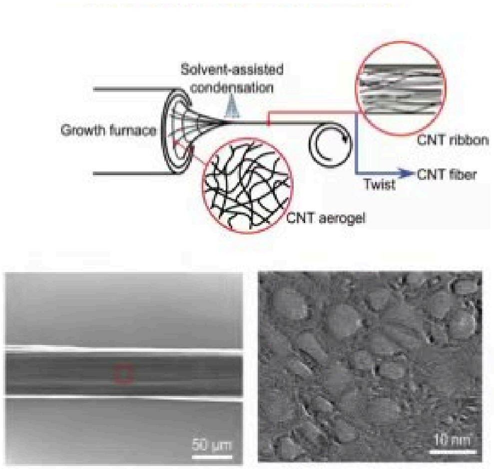
Controlled growth of CNTF wire



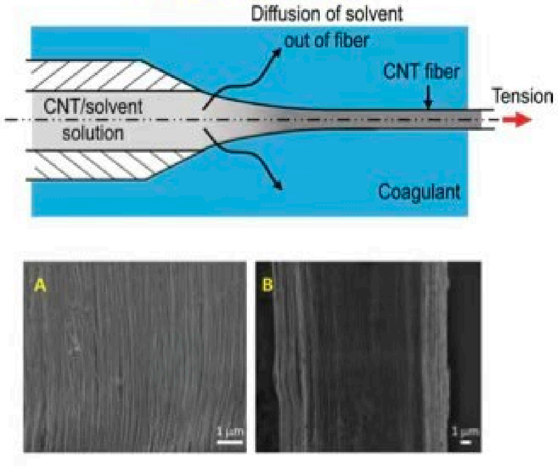


- Two main CNTF fabrication methods:
  - **FCCVD direct spinning:** Integrates CNT synthesis and fiber formation in a single process, enabling continuous production of CNTFs
  - **Wet spinning:** Uses pre-synthesized CNTs to form a spinning dope, decoupling CNT synthesis from fiber formation and offering compatibility with conventional fiber-processing technologies

FCCVD direct spinning



Wet Spinning Method



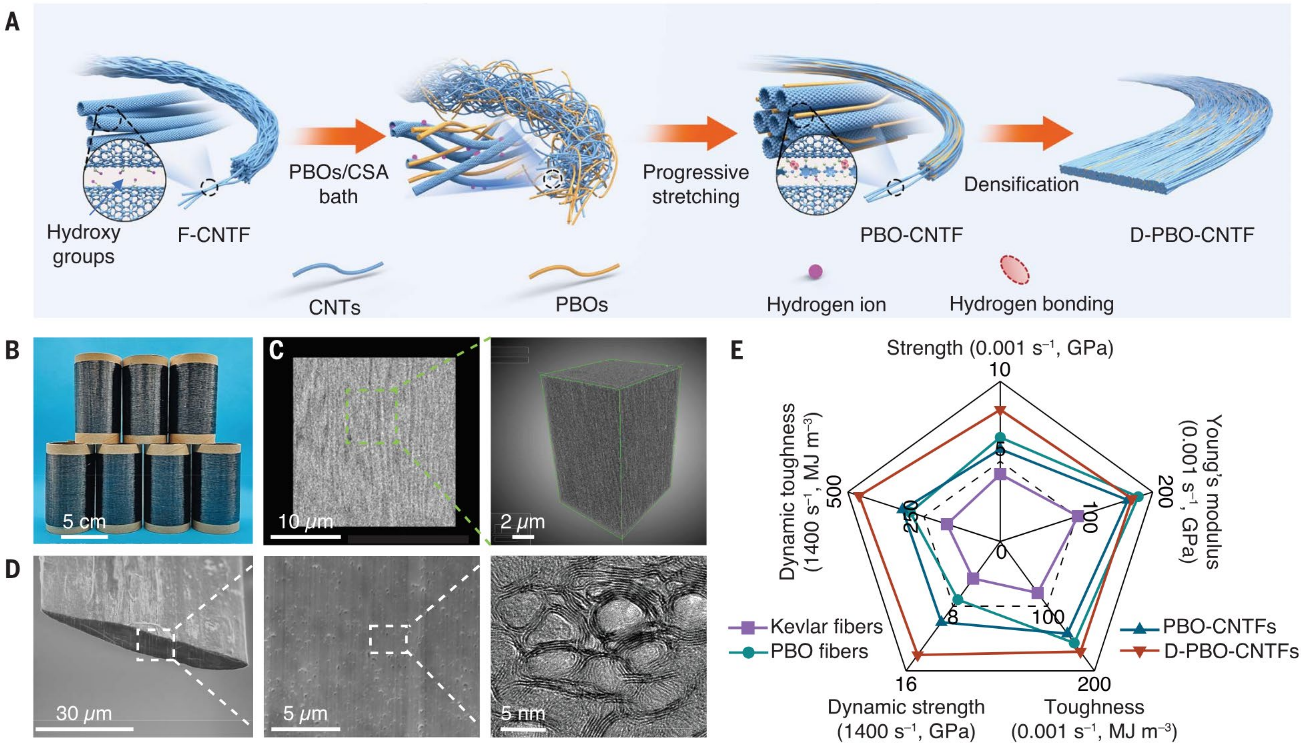
[1] Y. L. Li et al., Science 304, 276–278 (2004)
[2] N. Behabtu et al., Science 339, 182–186 (2013)
[3] Y. Niu et al., Nano Research 18, 949 (2025)

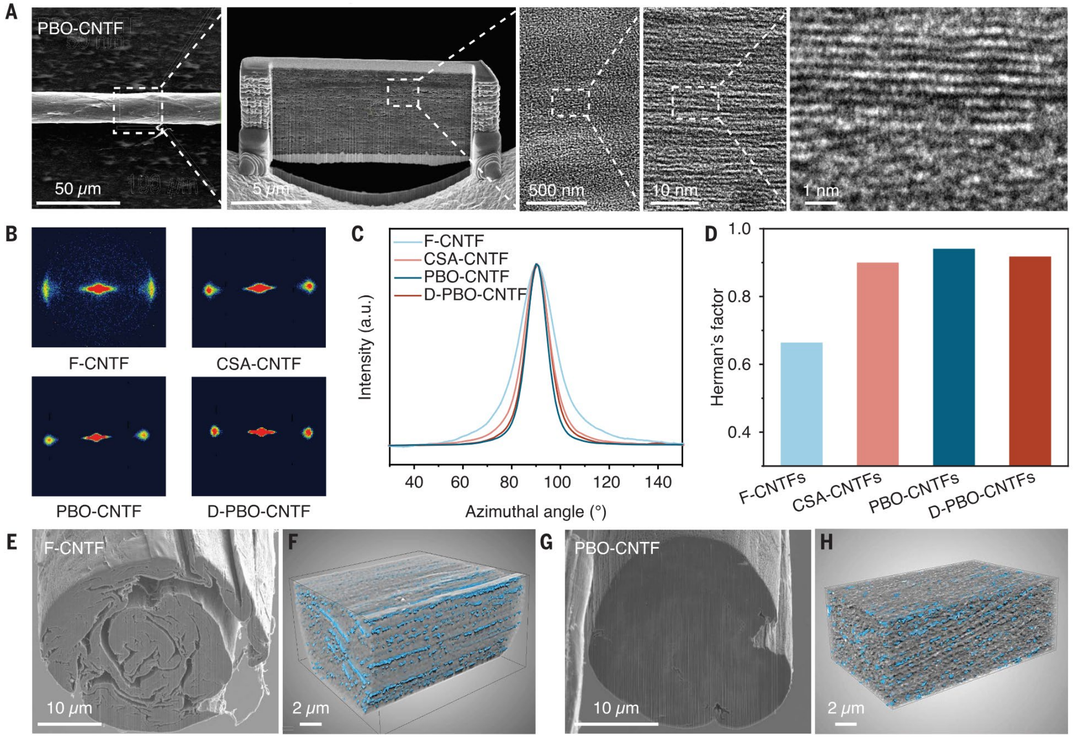
Both methods have been employed for our 60~100 μm CNTF samples

An example of CNTF manufactory

PKU-IHEP-SINANO collaboration on CNTF wire

- D-PBO-CNTFs exceptional mechanical performance: 8.2 GPa quasi-static tensile strength and 14.0 GPa record-high dynamic tensile strength (~1400 s^{-1}).
- Highly aligned and densified structure (SEM/TEM/WAXS/nano-CT) : herman orientation factor 0.66 → 0.92; porosity 4.8% → 1.0%

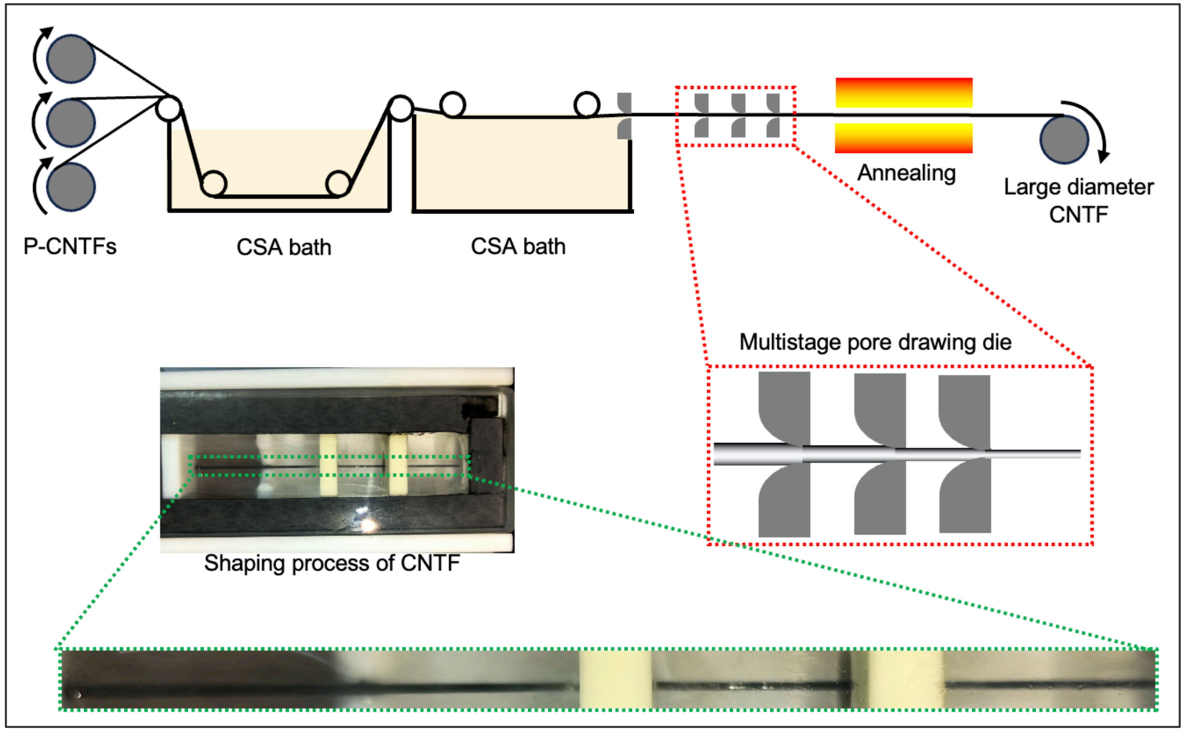


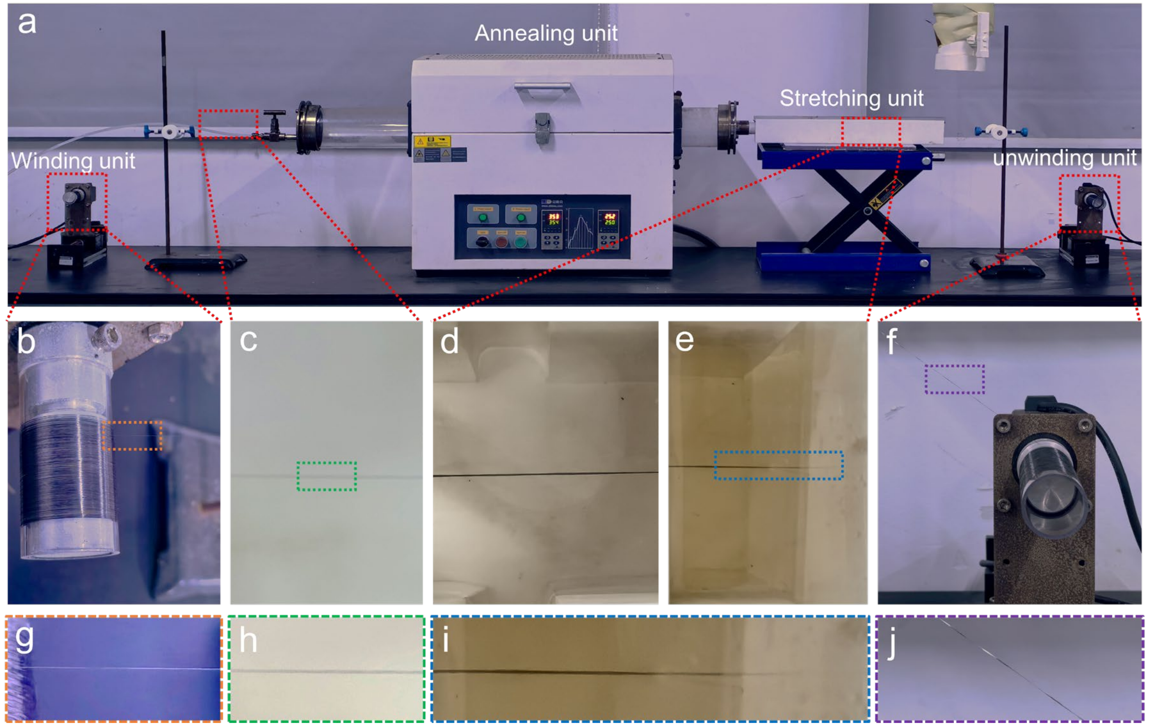


[1] X. Zhang et al., Science 384:6702, 2024

A novel large-diameter CNTF-wire fabrication scheme

- Hybrid carbon source, water, and drawing ratio enable continuous high-strength CNT precursor fibers
- A kilometer-scale continuous processing line for high-performance fibers has been built, integrating unwinding, CSA-assisted stretching, washing, annealing, and winding

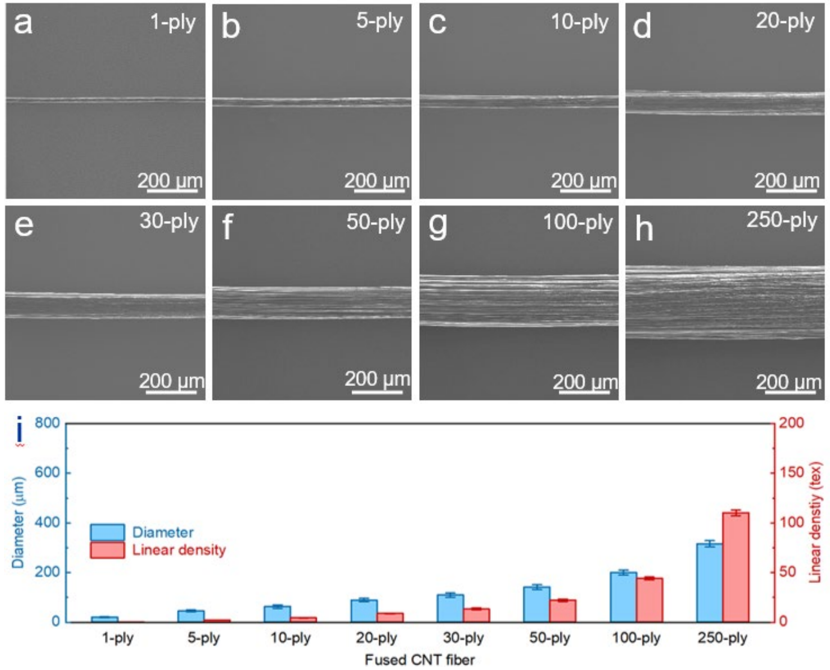




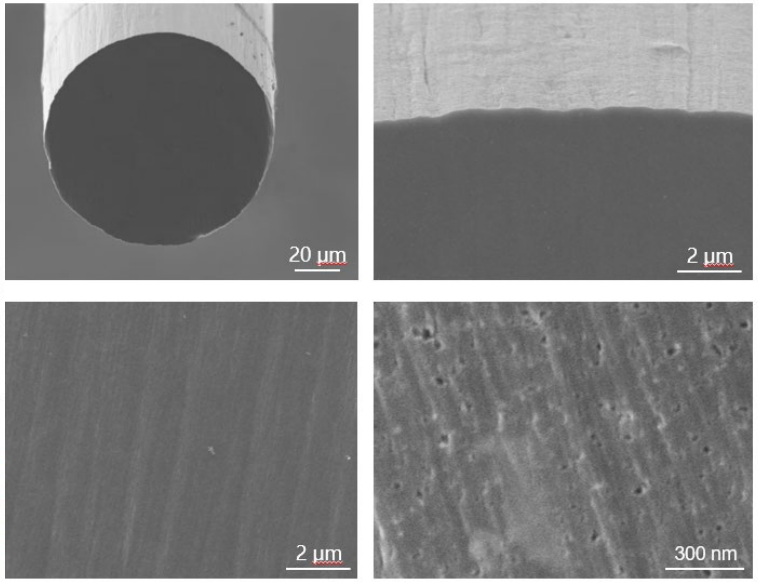
[1] Y. Niu et al, Nano Research, 18:949, 2025: L. Zhao et al., Nat. Commun. manuscript in preparation

Characterization of the CNTF-wire samples

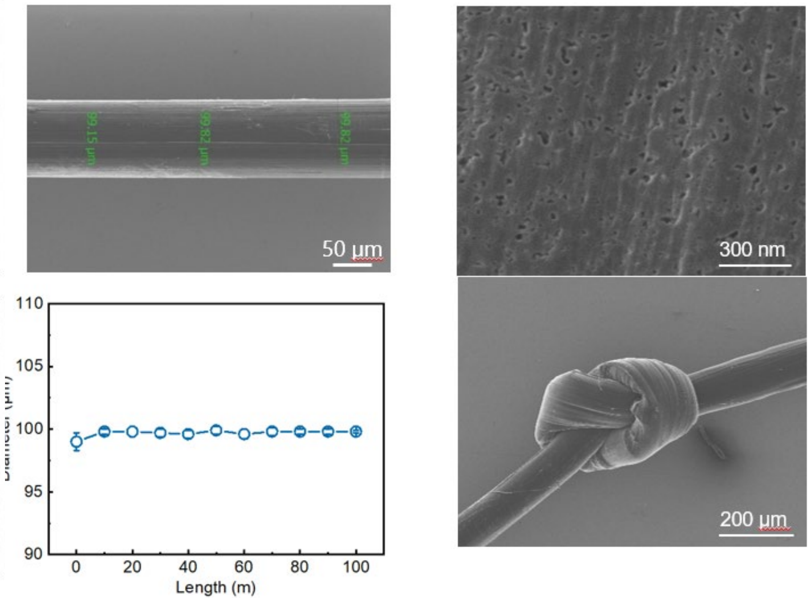
- Continuous production: hundred-meter level high-performance CNT fibers with a uniform diameter
- Tunable diameter: 20–300 μm by varying the number of precursor filaments
- Controlled geometry: adjustable roundness and surface roughness through drawing-die optimization, enabling ~100 μm-diameter fibers



Fiber cross-section and magnified view



Surface morphology and diameter statistics



The fibers exhibit excellent flexibility and can be tied into knots

CNTF-wire samples fabricated in 2025-2026

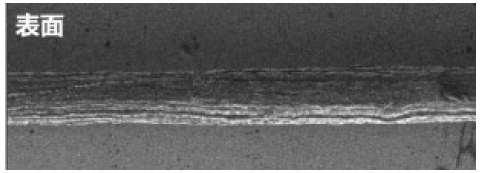
- 60, 80, 100 μm different diameter CNTFs production methods have been carried out at SINANO & PKU
- Process optimization and experimental testing are currently in progress

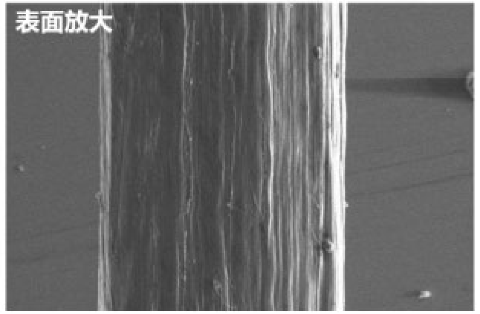
Parameters of the CNTF samples

Material	CNTF-I	CNTF-II	CNTF-III
Diameter [um]	100	80	60
Density [g/cm^3]	1.07	0.97	1.39
Thermal conductivity [W/m·K]	350/24	350/24	350/24
Tensile Strength [Gpa]	1.79	1.9~2.0	1.8
Conductivity [MS/m]	0.58	0.57	3.5

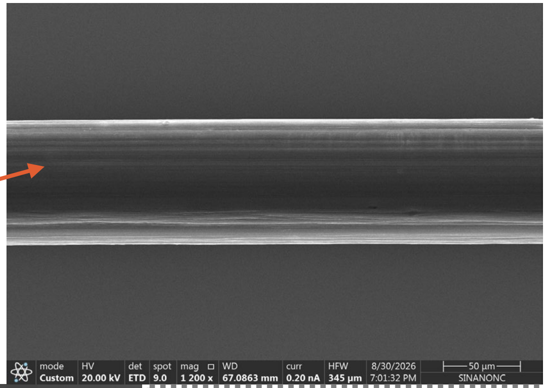
Carbon Nanomaterials & spectroscope group in Peking Univ.
http://jinzhanggroup.pku.edu.cn/index.html

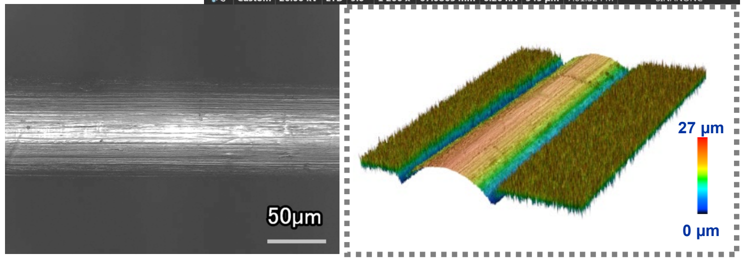
60 um CNTF





80 um CNTF

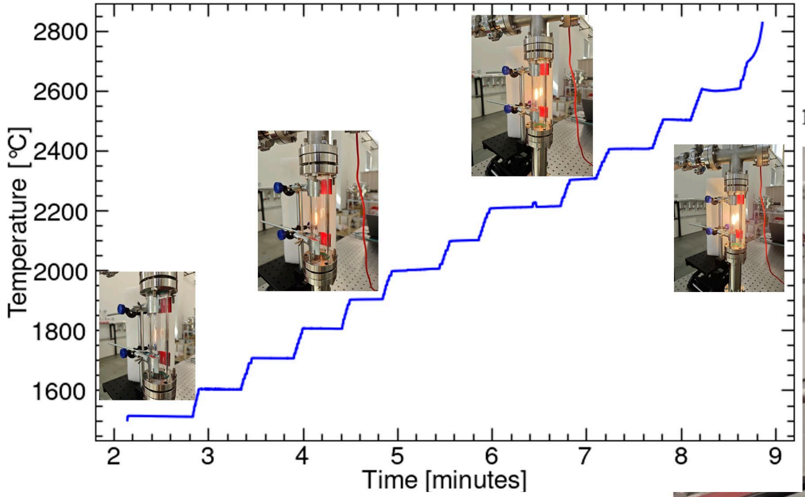


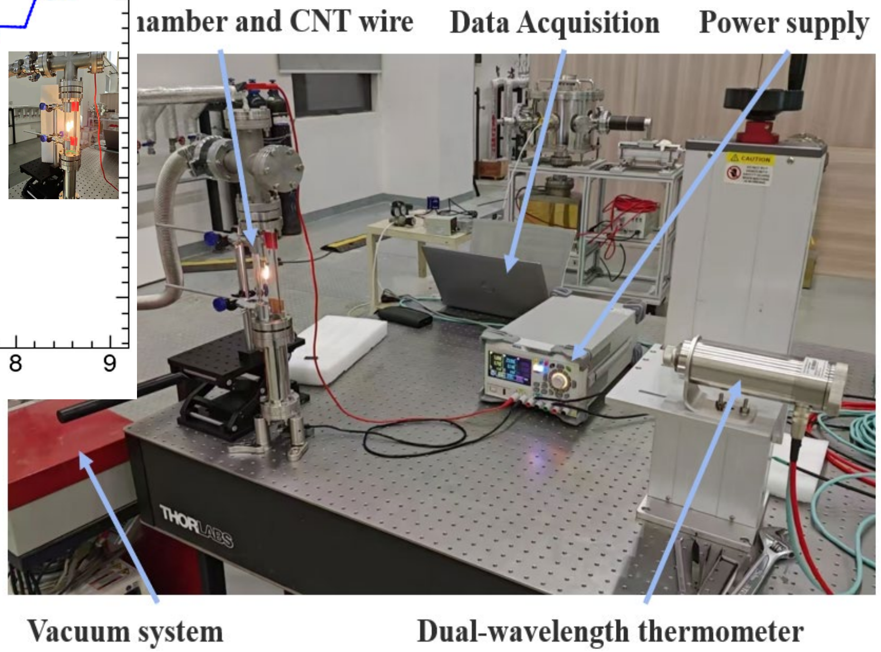


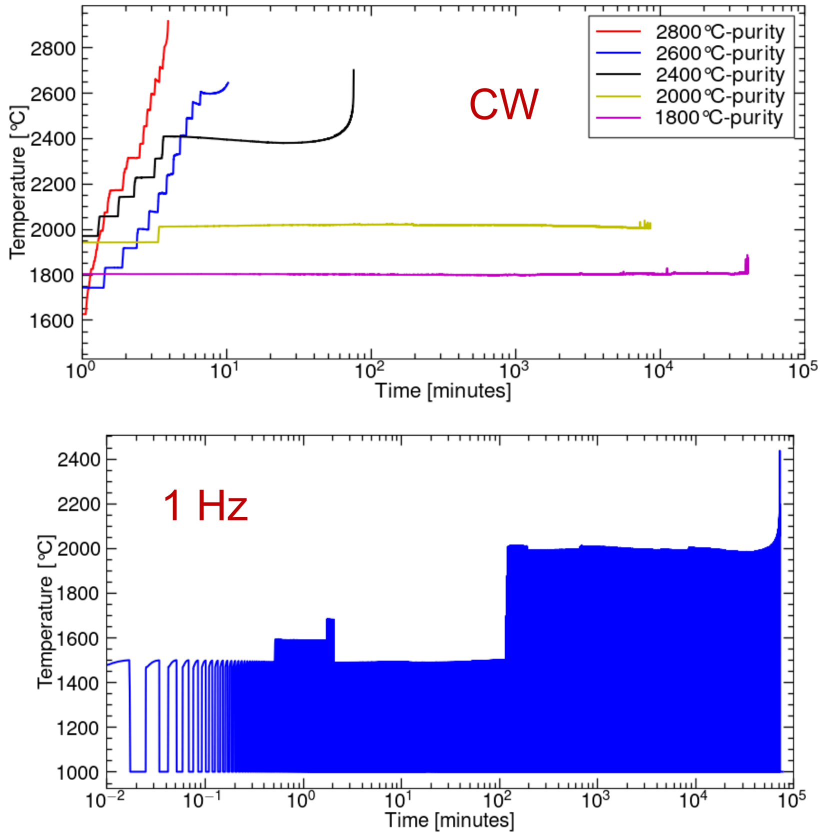
Thermal resistance test at CSNS

- The d100 µm CNTF wire w/ continue heating: >300 h@2270K & >700 h@2070 K (~5×10^{-5} Pa)
- With a pulsed PS, the wire resists for >1000 h at 2270 K@1 Hz
  => for WS/SEM-grid for beam commissioning (~10 h/year), no replacement more than 10 years!

First heating experiment in vacuum at IHEP





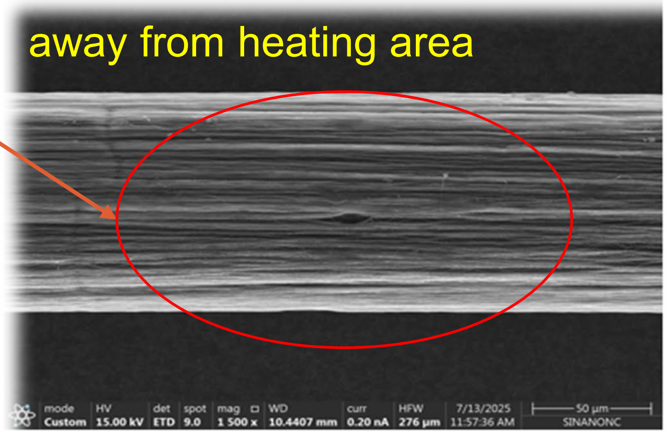


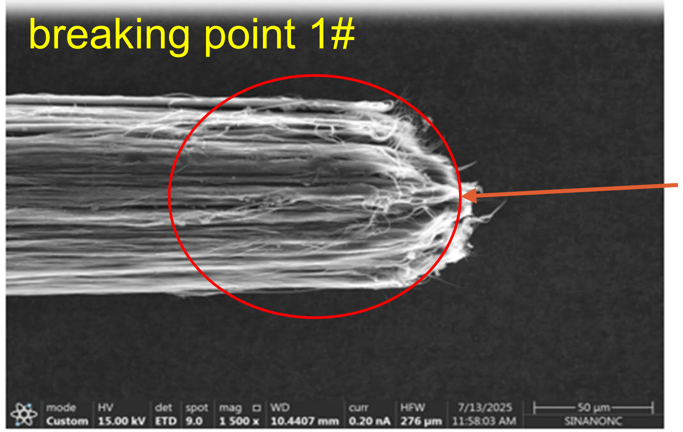
Thermal damage – surface morphology

Continue heating for 700+ h

- Clear separation of CNTF is observed near the fracture surface (SEM microscope)
- The fracture morphology is regular, with only a small number of filaments around the fracture

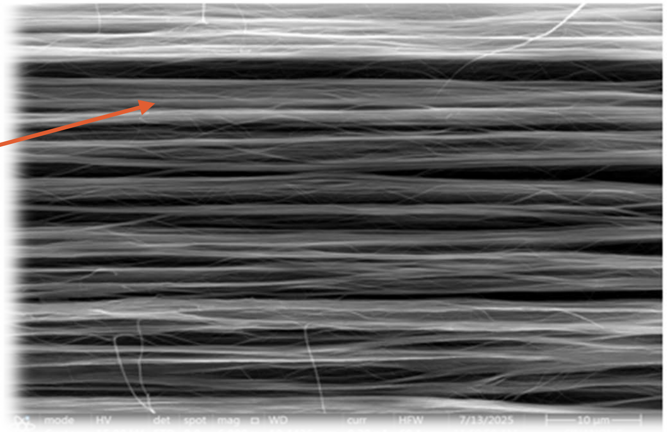
Normal CNTF wire close to fracture

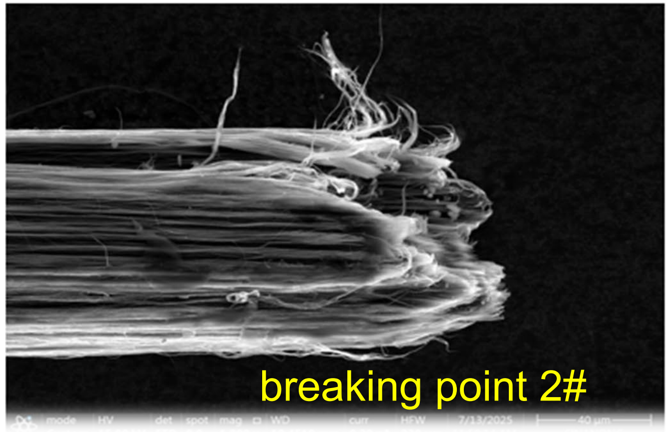




Fracture point become thinner

Normal CNTF wire close to fracture





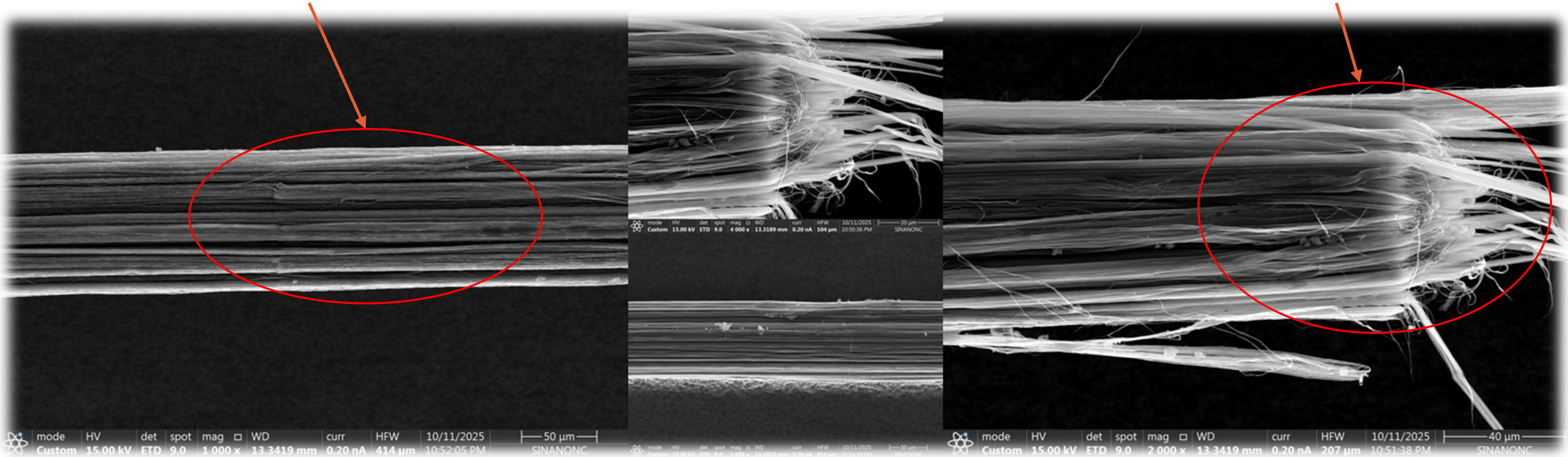
Thermal damage – surface morphology

Pulsed heating for 1000+ h

- The fracture morphology is similar to that observed after prolonged heating, with clearly exposed CNTF bundles near the fracture region
- Progressive necking and diameter reduction are observed toward the fracture point
- High-temperature sublimation is observed, indicating severe thermally induced material degradation

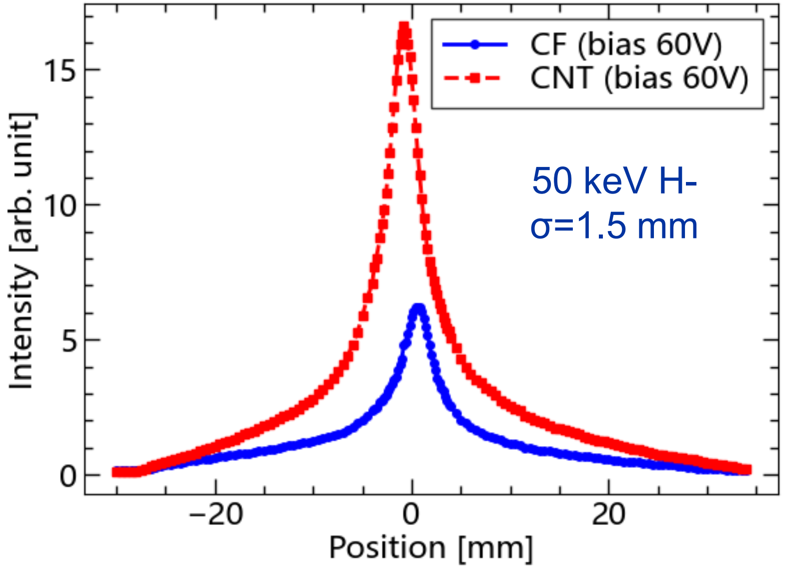
Normal CNTF wire close to fracture

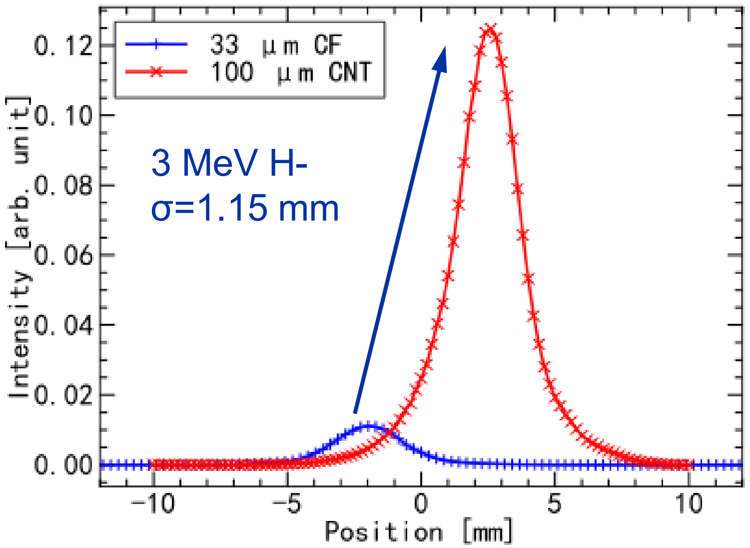
Fracture point become thinner

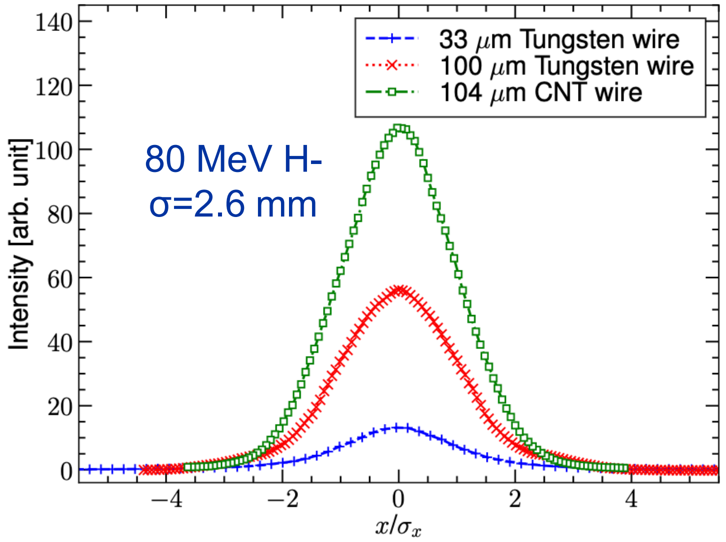


Secondary emission signal for low-energy H- beam

- The secondary emission signal of the d100 μm CNTF and d33μm CF/d100 μm W wire
  50 keV@IS, 3 MeV@MEBT, 80 MeV@LRBT
- 50 keV (15 mA, 85 us, σ = 1.5 mm): 3X signal enhancement when all of beam been intercept
- 3 MeV (15 mA, 85 us, σ = 1.15 mm): 11X signal enhancement thanks to a large diameter—a longer electron range
- 80 MeV (15 mA, 85 us, σ = 2.6 mm): 2X of the d100 um tungsten wire; ~8X of CF d33μm wire

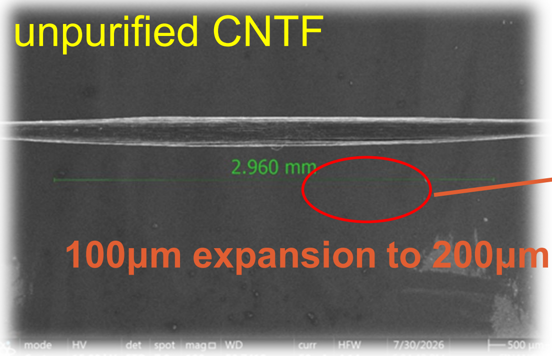


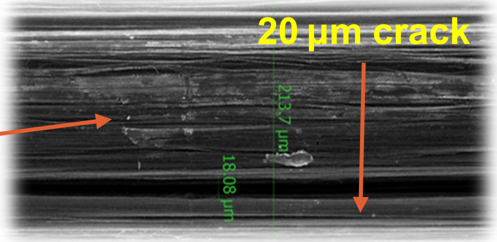




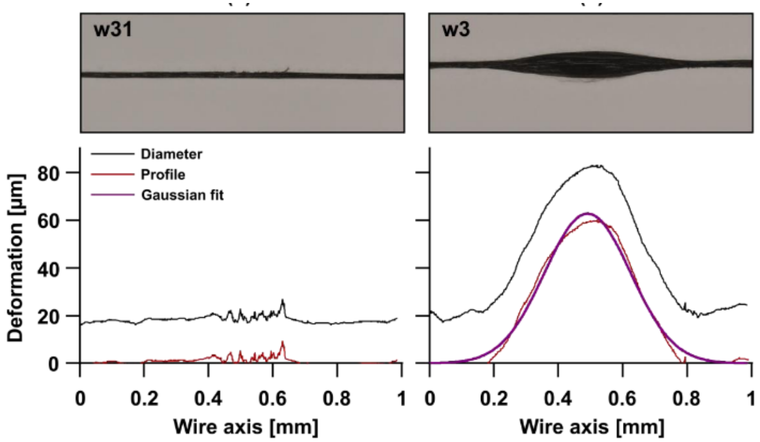
H- beam damage @ 3 MeV (one-year operation)

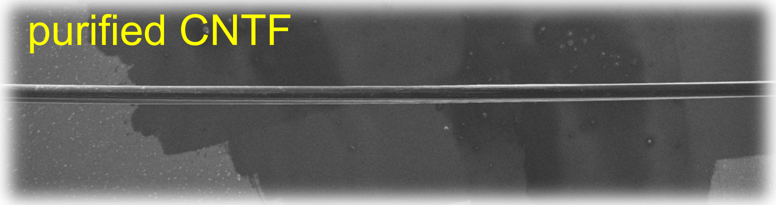
- The CNTF wires without vacuum annealing for residual Fe removal found to be expanded, which same as CERN research result; the expanded region is accompanied by cracks, with crack widths typically ranging from 10 to 20 μm
- The CNTF wires with vacuum annealing for residual Fe removal show no expansion
  Fiber roundness/surface smoothness are preserved

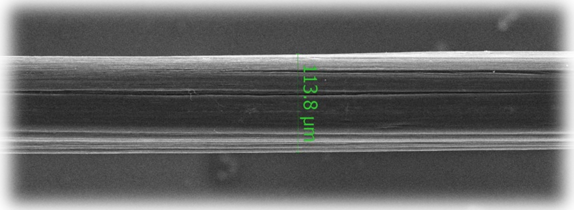




CERN SPS results





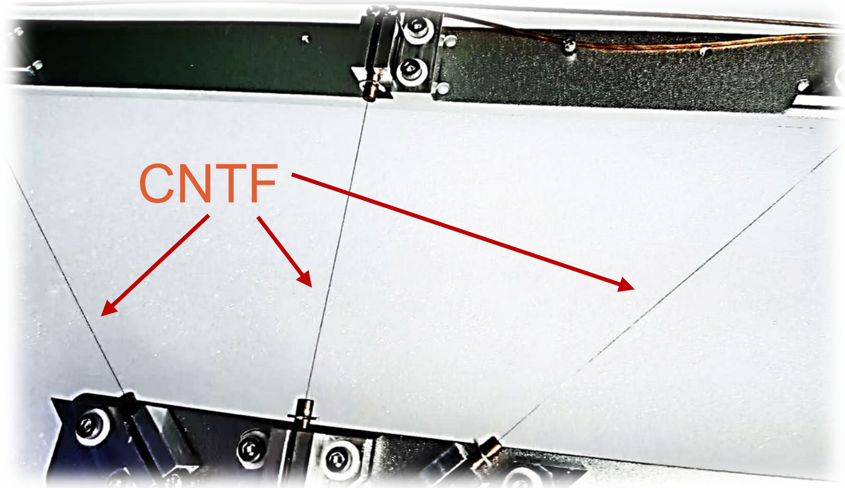


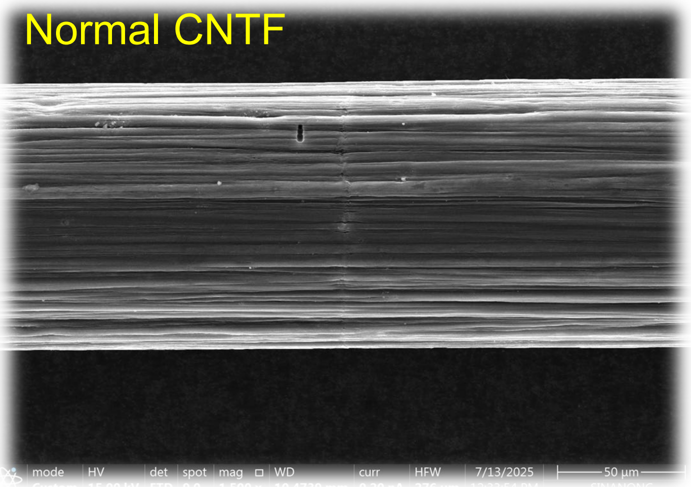
Vacuum annealing for residual Fe is crucial and successful

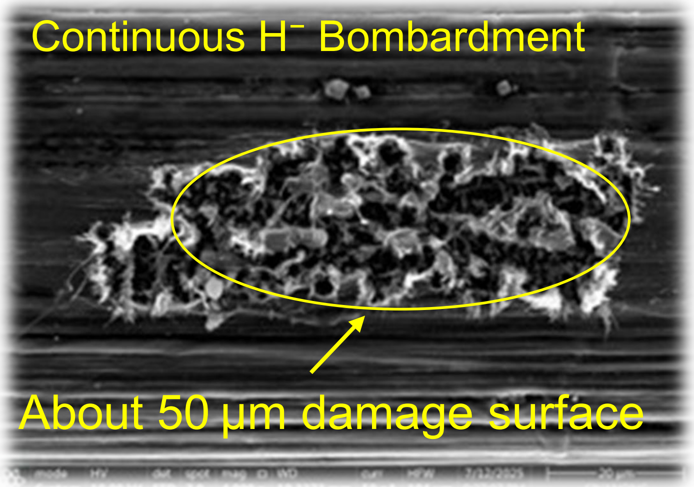
[1] A. MARIET, Low density material for beam instrumentation (2023), CERN

H- beam damage @ 80 MeV

- First experiment (2025)
  - 80MeV, 15mA, 560us, σx,y≈ 2.6 mm @ 5 Hz (30 mins, ~1620 K, ANSYS simulation)
  - damage surface morphology, about 50 μm, probably cause by particles or impurities in fibers
- Recent experiment with newly optimized CNTF (2026)
  - 80 MeV, 15mA, 590us, σx,y≈2.6mm @ 12.5 Hz (30 mins, >2100 K, ANSYS simulation)
  - No visible damage by eye, SEM measurement is ongoing







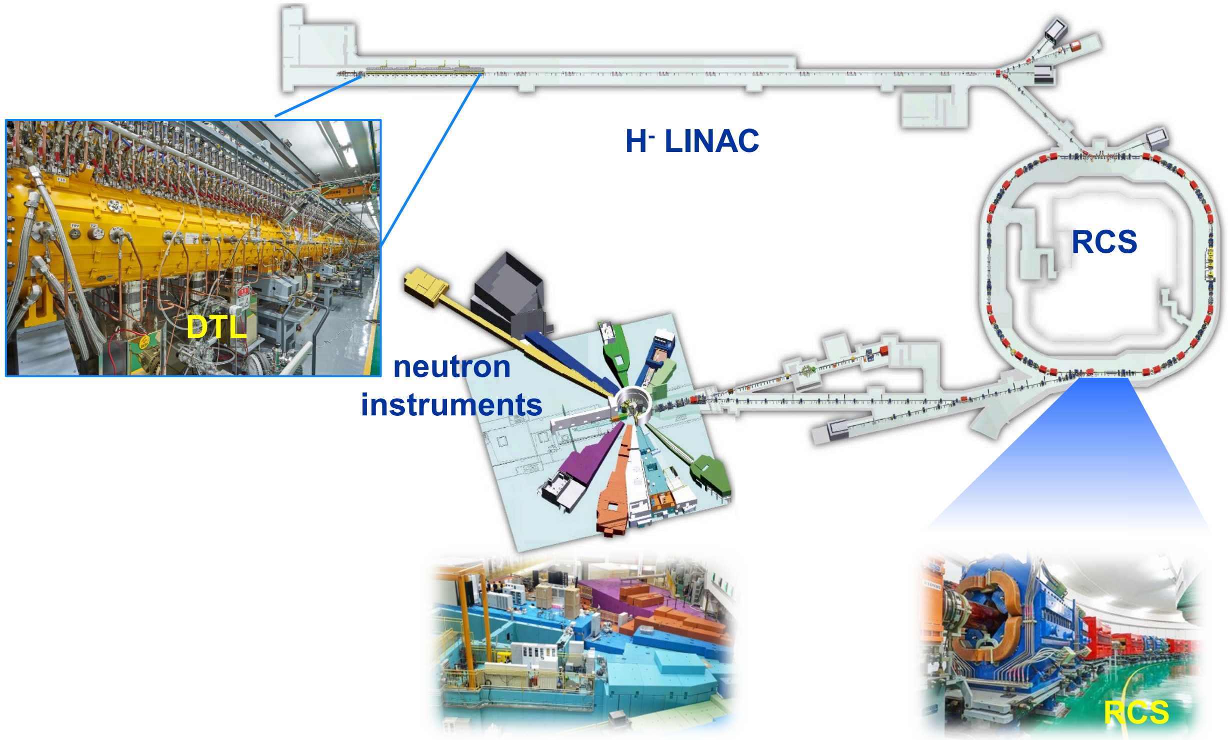
The newly fabricated d100 μm CNTF ropes are adequate as next-generate SEM material !

China spallation neutron source

- The 4th pulsed neutron source in the world; user program started since October 2018
- CSNS-II (2024-2030): beam power ramp up to 500 kW
- Beam parameters upgrade in Linac: 300MeV, 575us, 50mA

Major machine parameters

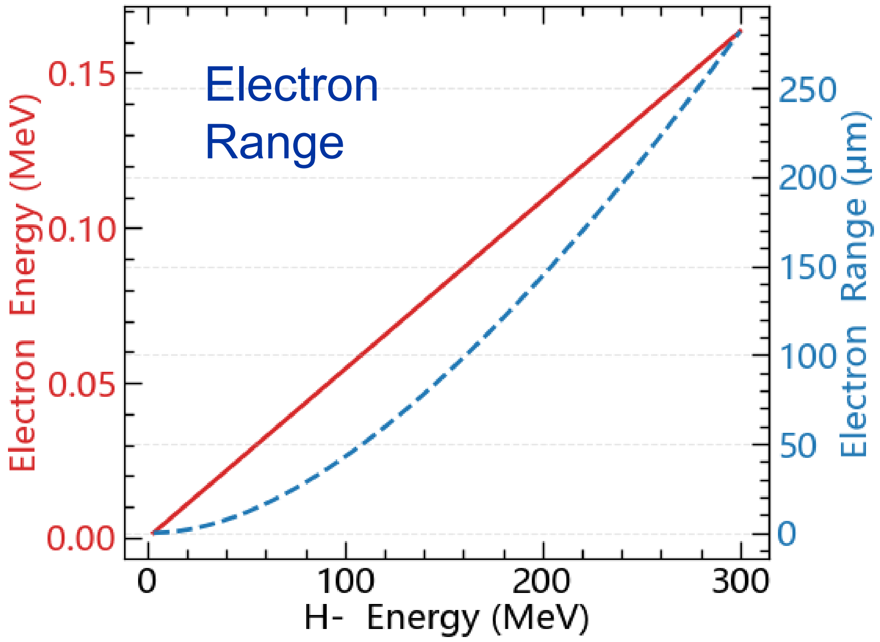
	CSNS	CSNS-II
Beam Power on target [kW]	185	500
Proton energy [GeV]	1.6	1.6
Average beam current [μA]	62.5	312.5
Pulse repetition rate [Hz]	25	25
Linac energy [MeV]	80	300
Macropulse. ave current [mA]	15	50
Linac bunch frequency [MHz]	324	324

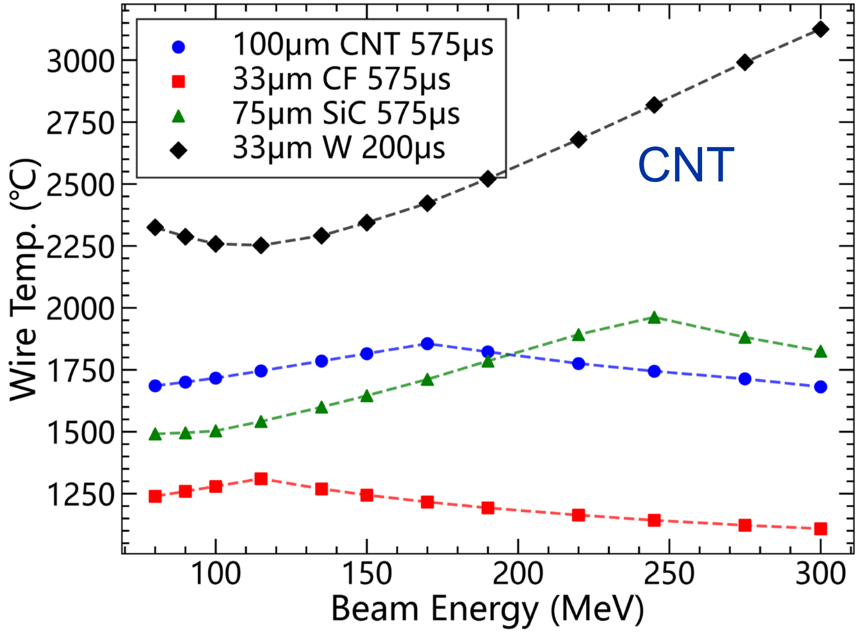


[1] H. Chen et al., NIMA 2025

Application 1#: CSNS RCS SEM-Grid

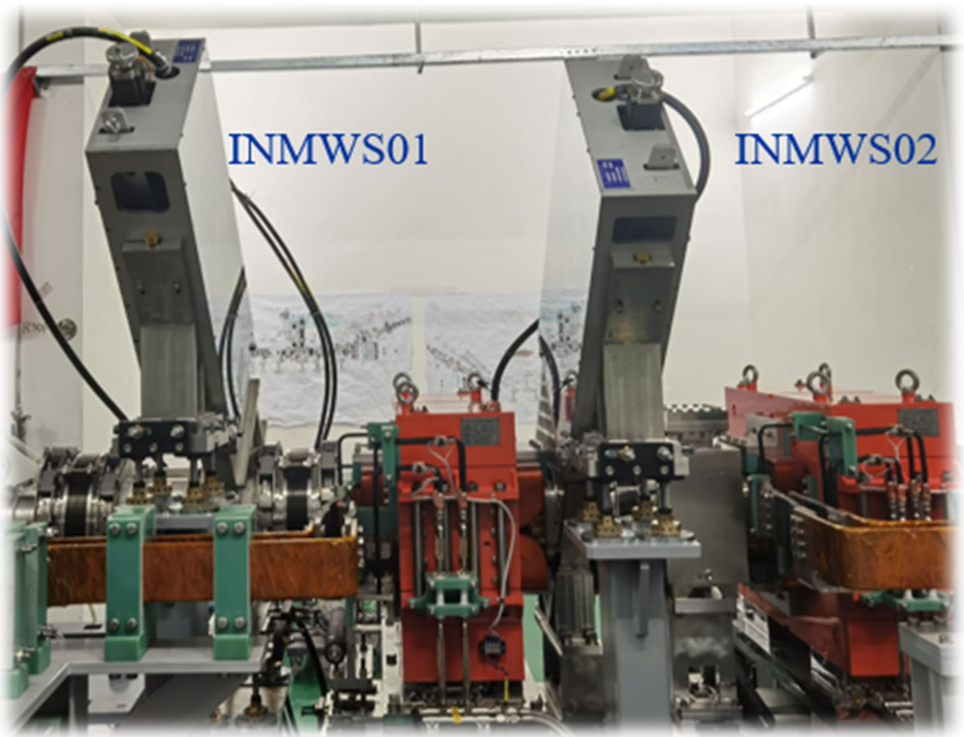
- Based on beam deposition energy analysis of wire temperature: at pulse width 80-300 MeV, 30 mA, 575 μs, CNTF temperature is 1652°C for the SEM grid next to the injection point
- While W wire approaches melting temperature of 3200°C at 200 μs pulse width; therefore CNTF wire is selected

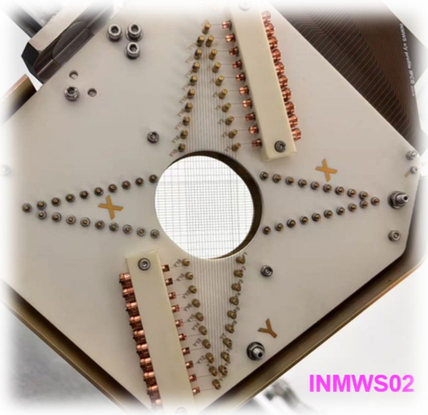


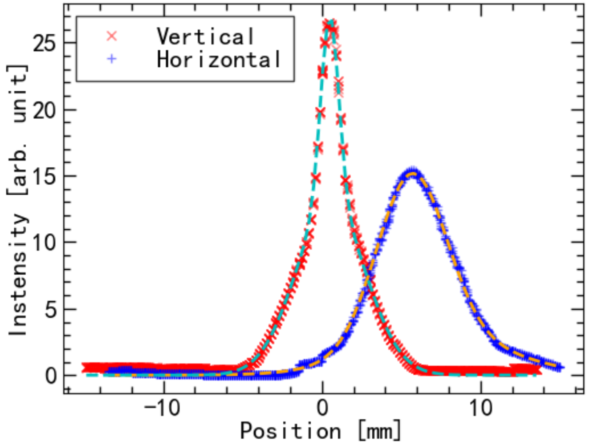


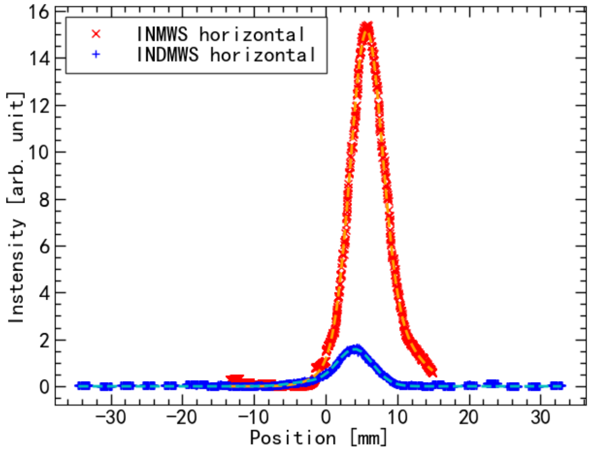
Application 1#: CSNS RCS SEM-Grid

- RCS SEM-Grid uses 100 μm carbon nanotube (CNTF) material, total of 136 wires, minimum wire spacing 1.55 mm
- Injection region H^- beam horizontal/vertical fitting rms values 2.96/1.96 mm, same as expect



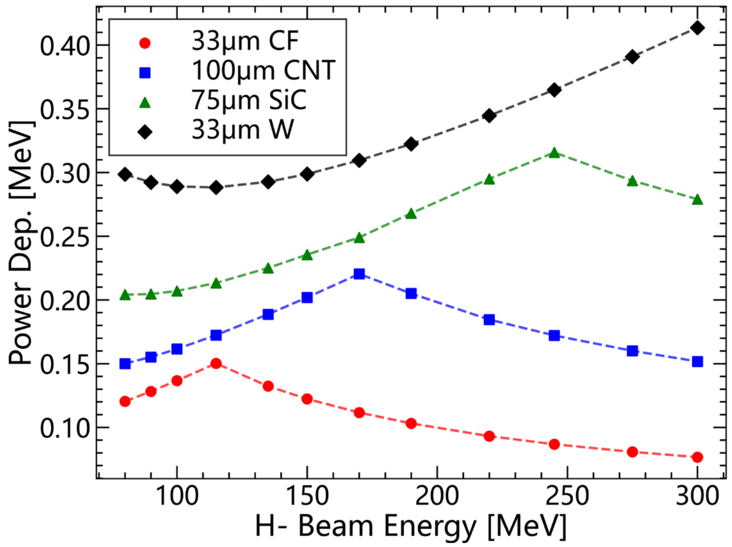






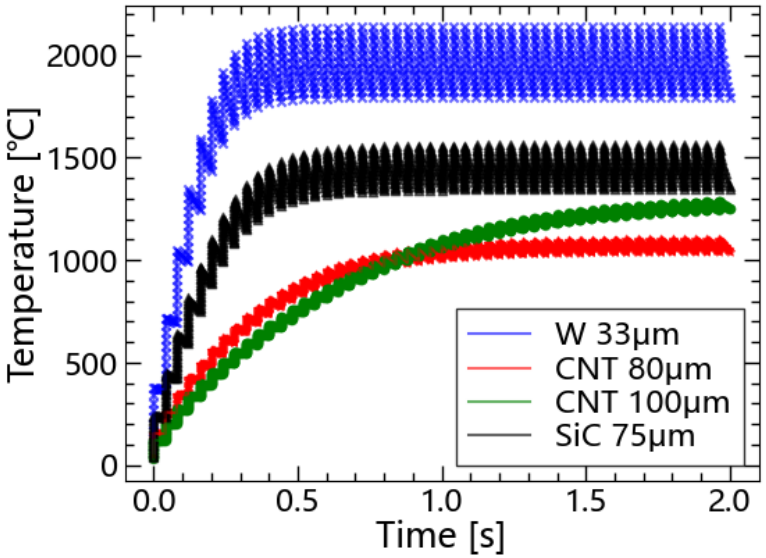
Application 2#: Isotope factory target monitor

- For 300 MeV, 40 mA, 625 μs, 25 Hz, 25 mm spot size at the target monitor of the new isotope project at CSNS, W and SiC suffer from serious thermal emission (>100 μA) and melting
- The temperature of the 80 μm CNTF wire is approximately 300 °C lower than that of the 100-μm wire (about 1000 °C vs. 1300 °C) => under thermal/beam test!



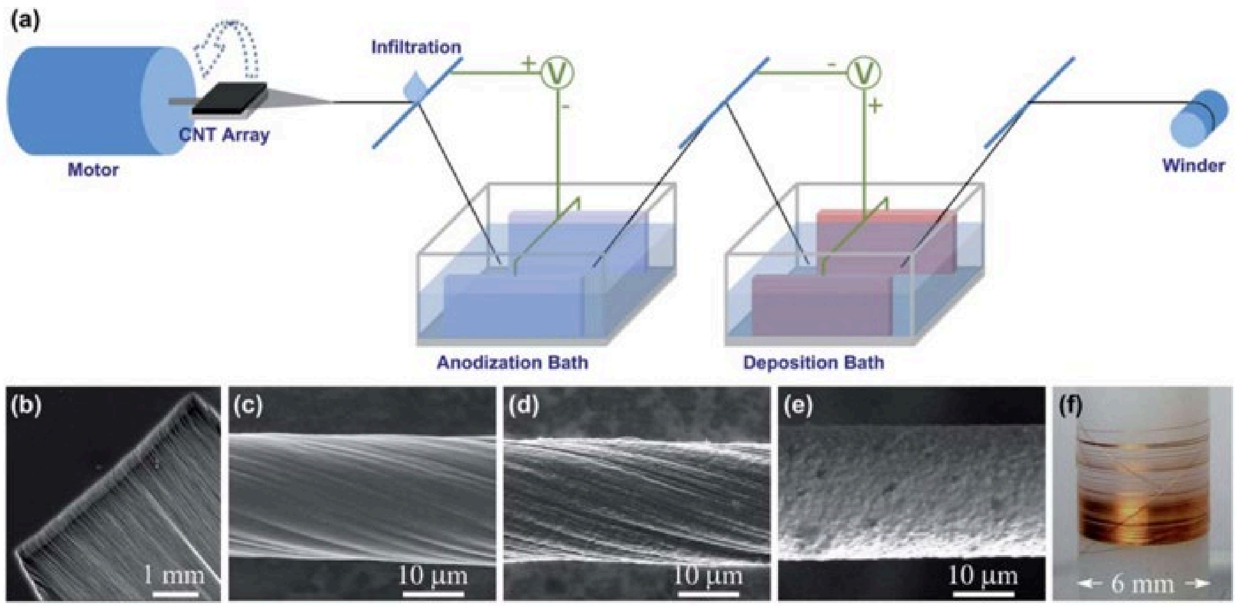
Parameters of the candidate material

Material	W	SiC	CNTF-I	CNTF-II
Diameter [μm]	33	75	100	80
Density [g/cm^3]	19.35	2.89	1.07	0.97
Thermal conductivity [W/m·K]	173	340	350/24	350/24
Tensile Strength [Gpa]	1	5.9	1.79	1.9~2.0
Conductivity [MS/m]	18	<0.01	0.58	0.57
Work Temperature [K]	<2000	<1500	<2000	<2000

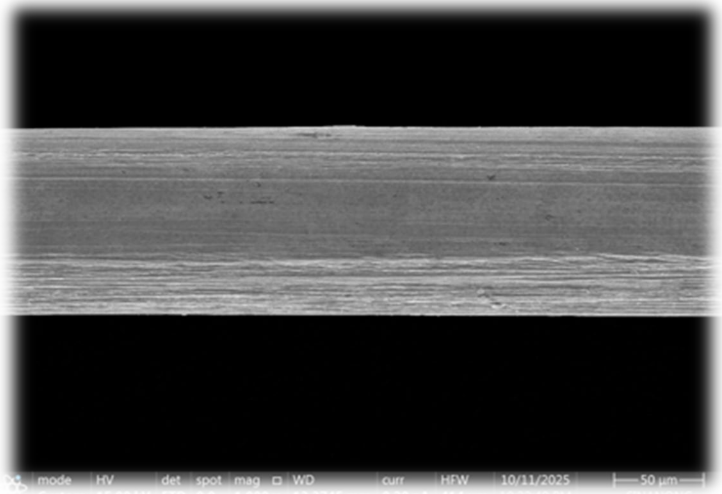


Outlook: metal coating on CNTF side wall

- To enhance the signal of CNTF wire in high-energy proton beams (>1GeV), a metal coating experiment on CNT wires is conducted
- CNTF electroplating deposits metal ions onto the fiber surface via electrochemical reduction, with surface pretreatment critical for ensuring coating uniformity and adhesion



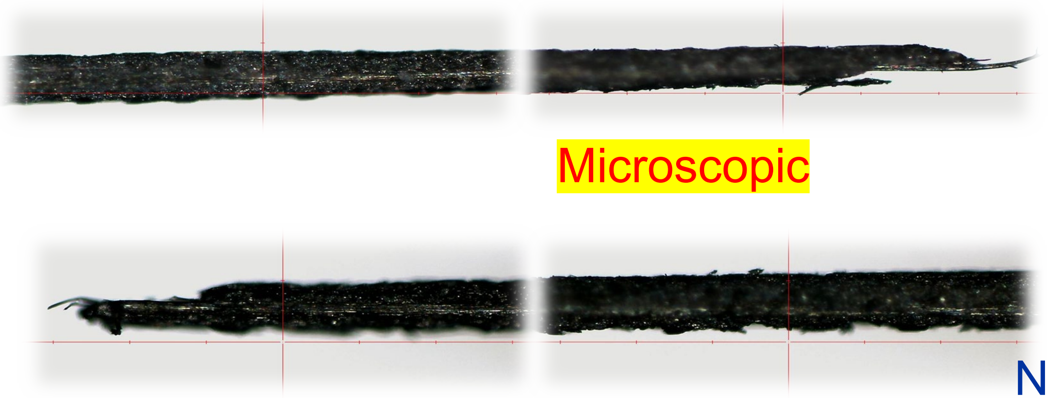
Process of Metal coating on CNTF

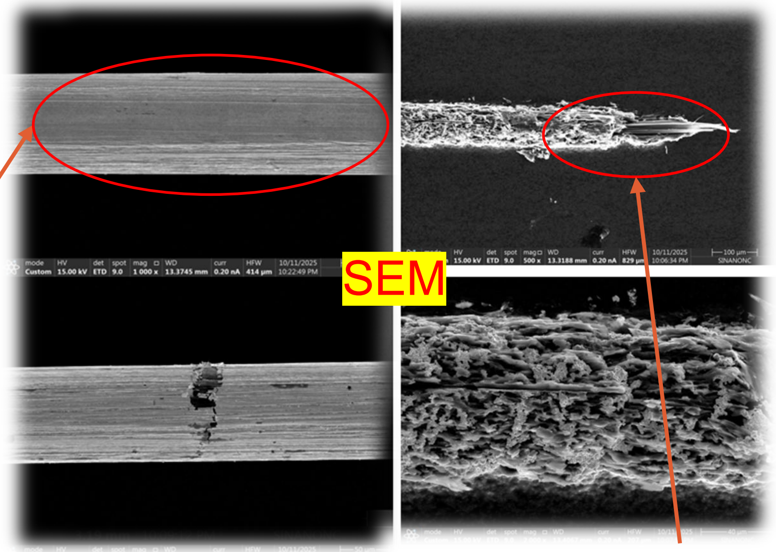


Tungsten-coated CNTF

Outlook: Tungsten-coated CNTF rope (preliminary)

- Thermal heating of the coated CNTF at 2270 K@140 h (CW)
  => the wire fracture in the end
- Surface melting observation with microscopic & SEM
  - Microscopic: Carburization-like surface features, tungsten-coating damage, and pronounced surface ablation
  - SEM: Matching fracture surfaces indicate tensile failure; rapid coating sublimation is expected near 2000 °C





Summary

- Fabrication: Purified multi-walled CNTFs with tunable diameters of 20–300 μm have been successfully developed
- Performance: Thermal, secondary-emission, and beam-damage studies demonstrate the suitability of 100-μm CNTFs for high-power beam diagnostics
- Application: 136 CNTF wires have been successfully deployed in the CSNS RCS injection SEM-grid system, with stable operation for over one year
- Collaboration: Extensive cooperation with SINANO, Peking University, CERN, KEK, GSI, and other partners


CSNS/IHEP, Dongguan, China