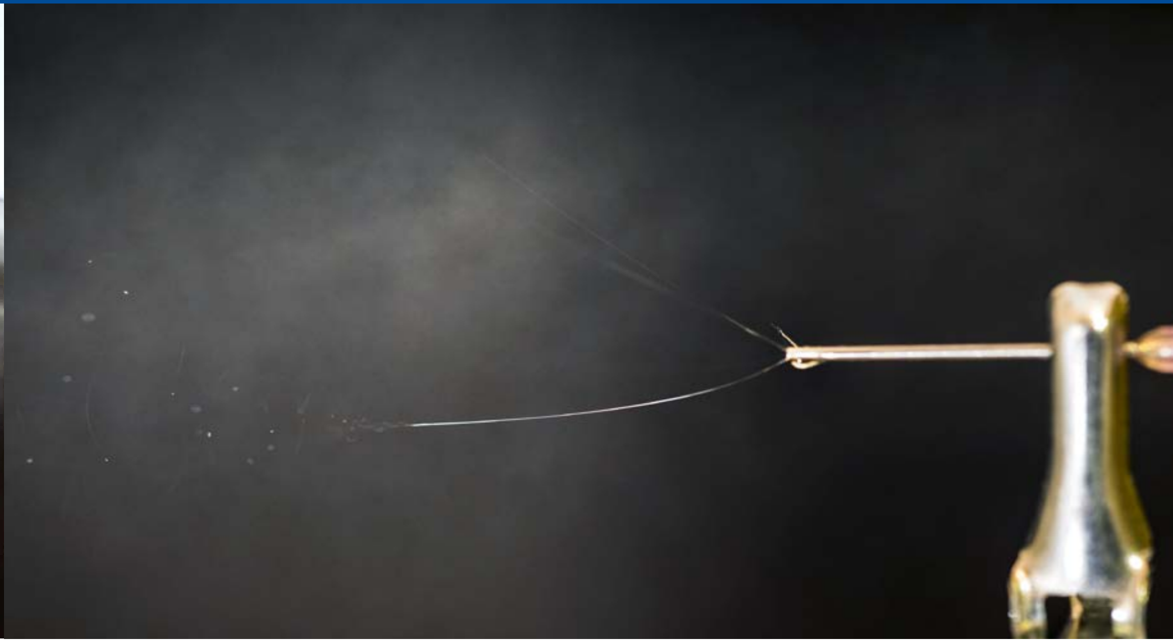
The Oak & the Reed

AN OAK TREE that grew by the side of a river was blown down in a violent storm. It fell into the river and as it was floating along, its branches happened to get caught against a thin little Reed that stood near the shore. It occurred to the Oak that it was rather odd that he who was so strong had been blown over, and this thin Reed had been left standing.

"Reed," said the Oak, "I admire you; how did you ever stand up secure and unhurt in that terrible wind that blew me over and into this river?"

"I am really sorry to see you blown down, Oak," said the Reed, "but I was afraid that would happen to you. You see, I do just the opposite from you when the wind blows very hard. I know that it is stronger than I am, so instead of being stiff and stubborn about it and trying to stand up and throw my strength against it, I just bend a little and let it blow over me because I know there is no use resisting it."

The Point It is better to bend than to break.

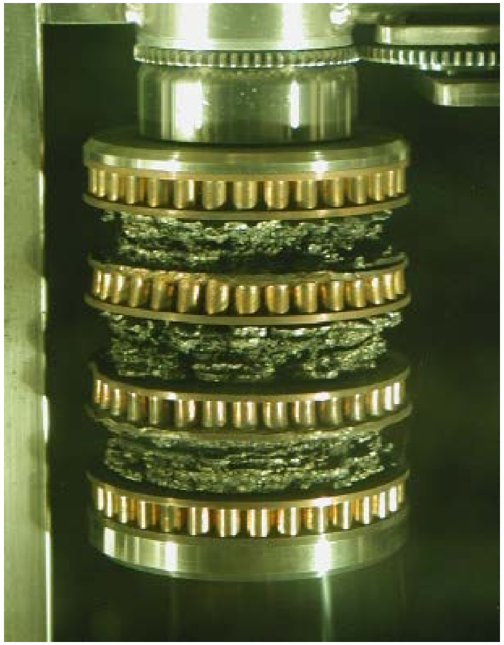



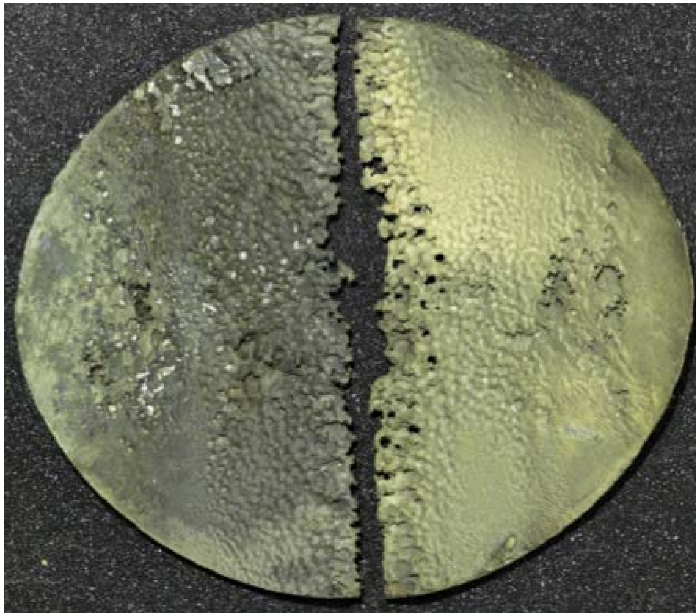
The Sinuous Target

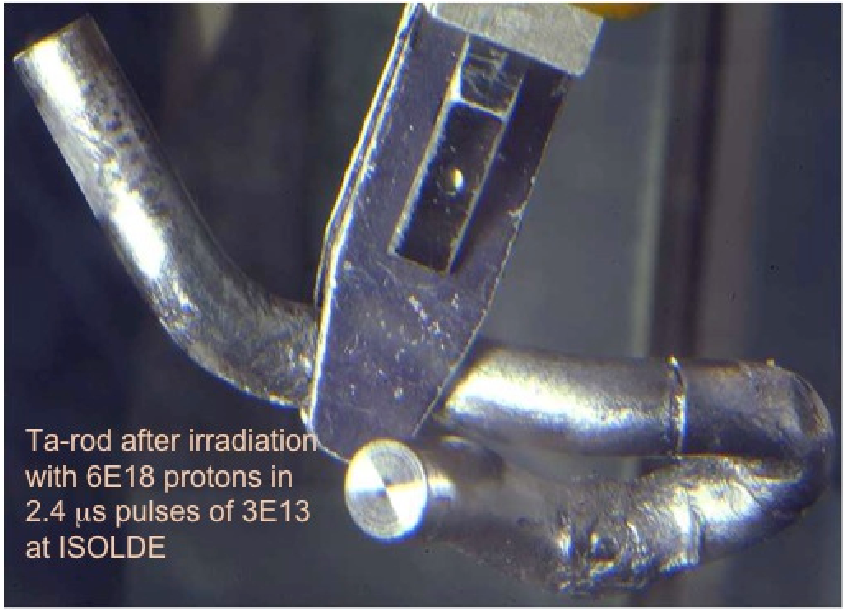
Robert Zwaska
LDRD-Fest
31 March 2017

New Approaches for High-Power Targets

- Many accelerator facilities world-wide are limited by the capabilities of their targets
  - Compromised in physics performance are sometimes made
- Future facilities will use higher powers and have higher demands for performance







Breaking a Target - Fundamentally

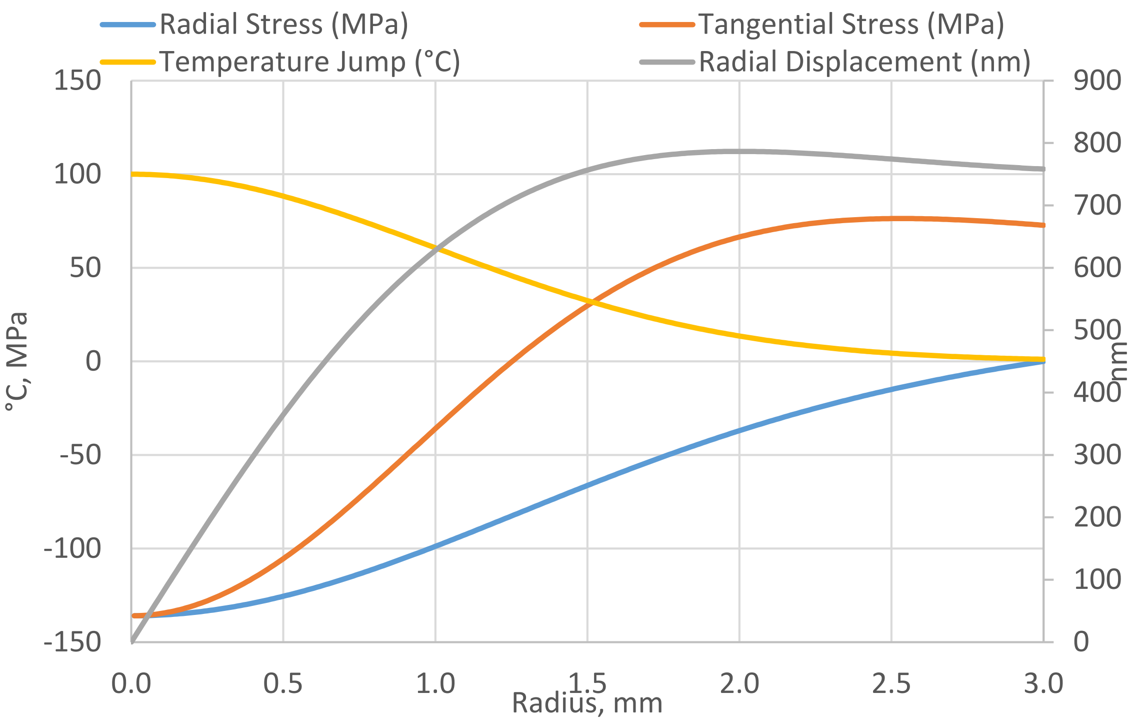
- Non-uniform heating leads to stress in target
- Axisymmetric case:
  - Max compressive stress at center
  - Max tensile stress near edge

$$\Delta T(r) = \frac{Q}{C\sigma^2}\exp\left[\frac{-r^2}{2\sigma^2}\right]$$

$$\sigma_r = \frac{\lambda}{1-\upsilon^2}\left[(\varepsilon_r + \nu\varepsilon_\theta) - (1+\nu)\alpha T\right]$$

$$\sigma_\theta = \frac{\lambda}{1-\upsilon^2}\left[(\varepsilon_\theta + \nu\varepsilon_r) - (1+\nu)\alpha T\right]$$

$$\frac{d^2\delta}{dr^2} + \frac{1}{r}\frac{d\delta}{dr} - \frac{\delta}{r^2} = (1+\nu)\alpha\frac{dT}{dr}$$



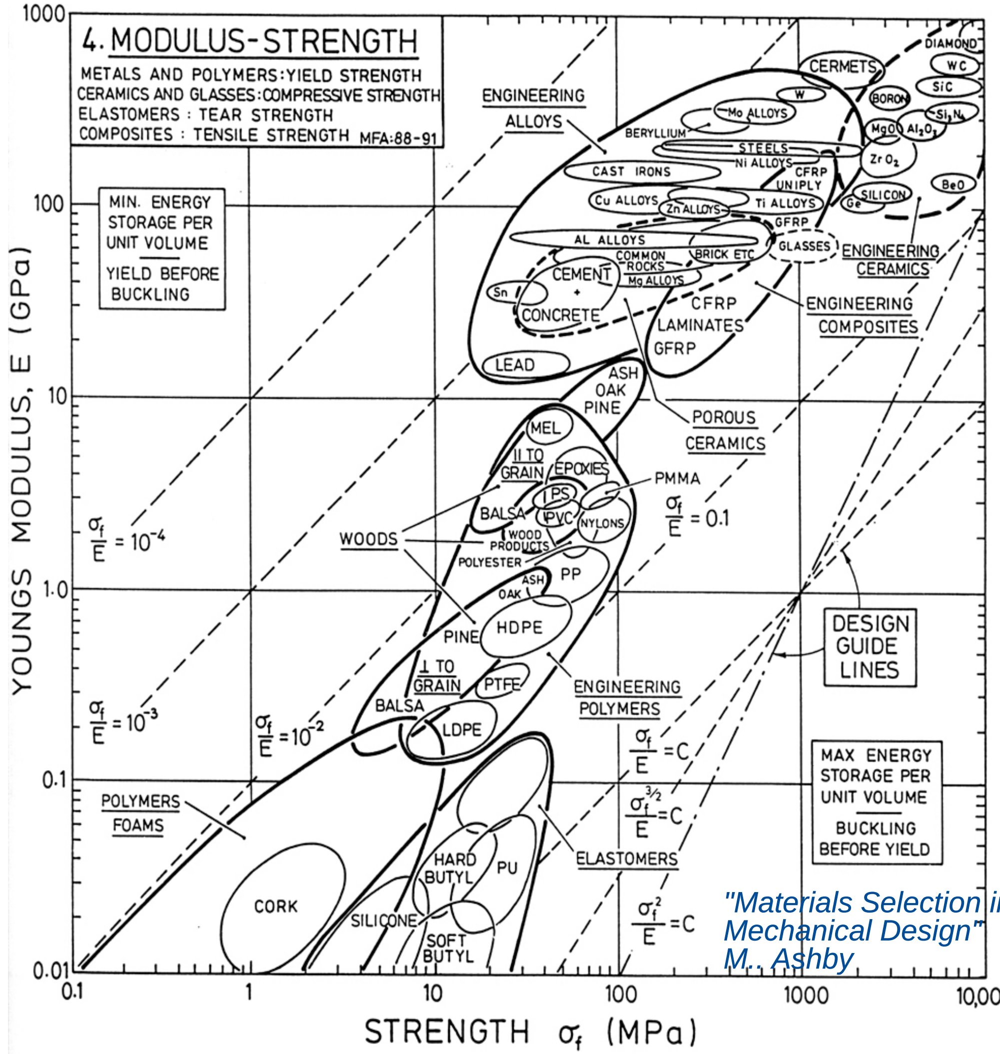
$$\sigma_{\theta,\max} \propto \frac{\alpha\lambda Q}{C\sigma^2}$$

- Proportional to:
  - Energy deposition
  - Coefficient of thermal expansion
  - Modulus of elasticity
- Inversely proportional to:
  - Specific heat
  - Beam spot area

Strong Materials have High Elastic Modulus

- We already use the best of available materials
  - Stronger materials are stiffer, so there is little to be gained.

- Can we engineer a material to have low elastic modulus, but have high strength?
  - At least strong on the micro-scale? Overall strength is not generally important.



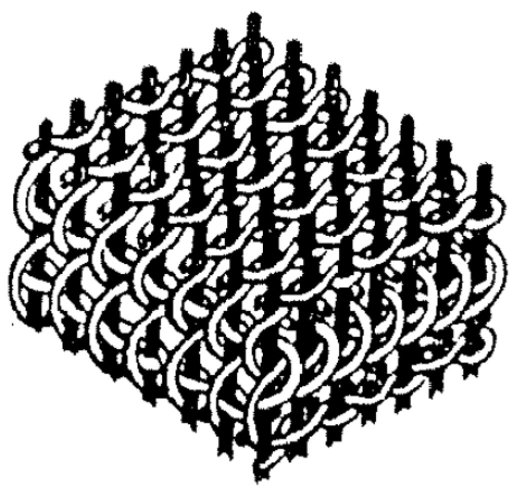
"Materials Selection in Mechanical Design"
M.. Ashby

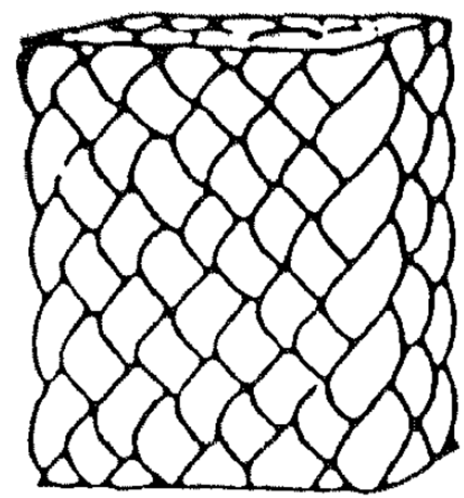
Fermilab

The Sinuous Target

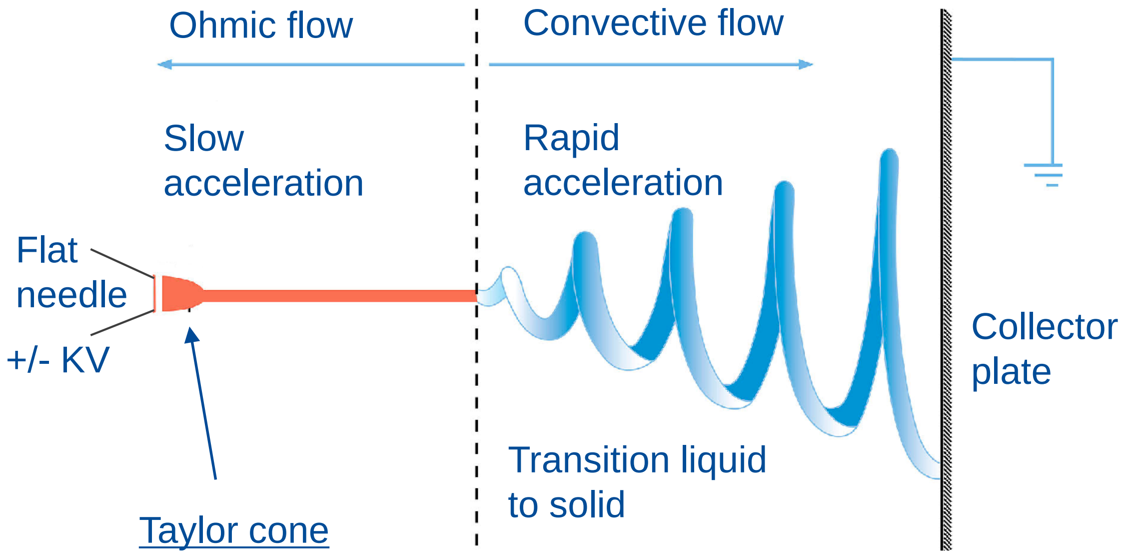
- Engineer a target material that can sustain the high-beam powers we anticipate in the future
- Conceptual material is composed of an interlaced matrix of wires or strings of a high-strength material

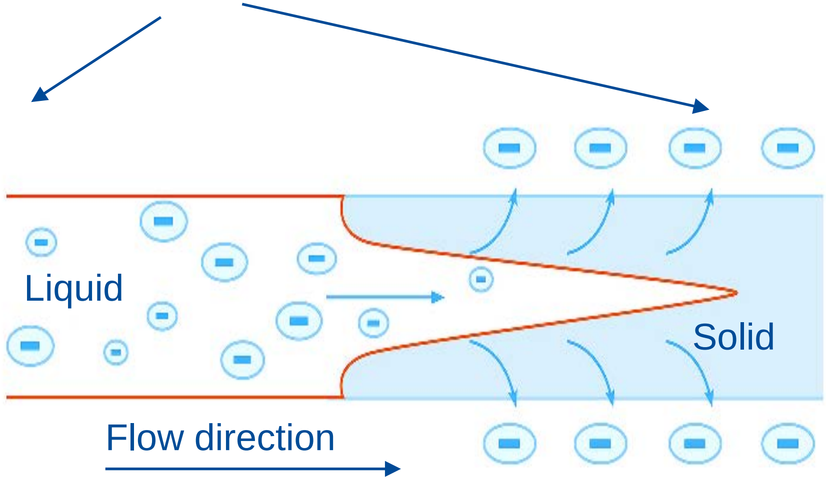
- Project Scope:
  - Produce a microstructure scheme
  - Model thermo-mechanical response
  - Fabricate scaled prototypes
  - Test and compare to analogues
  - Develop fabrication techniques





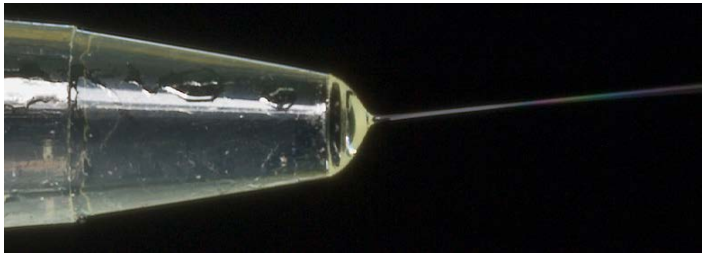
Electrospinning Fabrication Technique





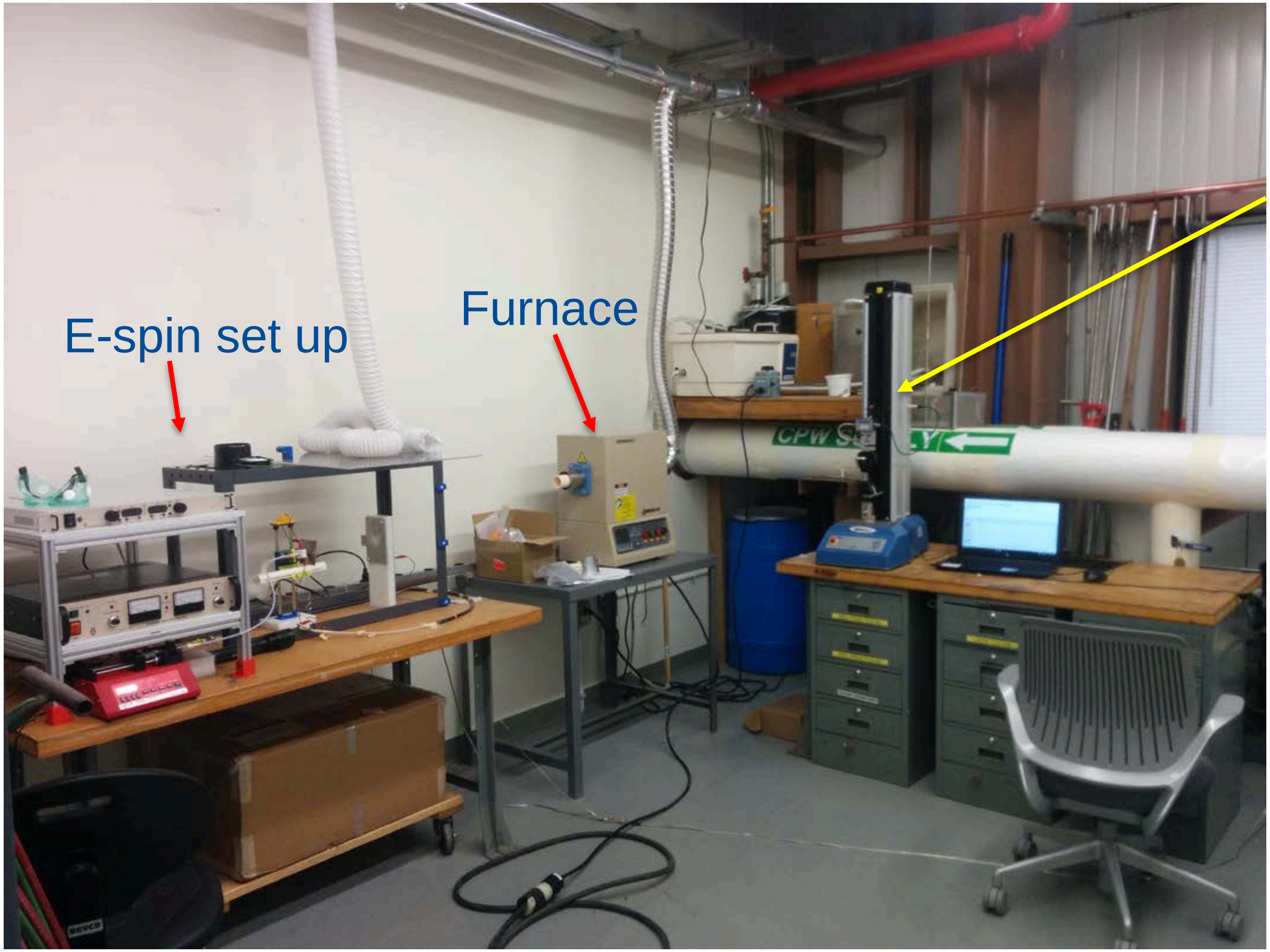
Electrostatic repulsion > surface tension

- Droplet is stretched
- Jet elongated by whipping action
  - (hosing instability)



Fermilab

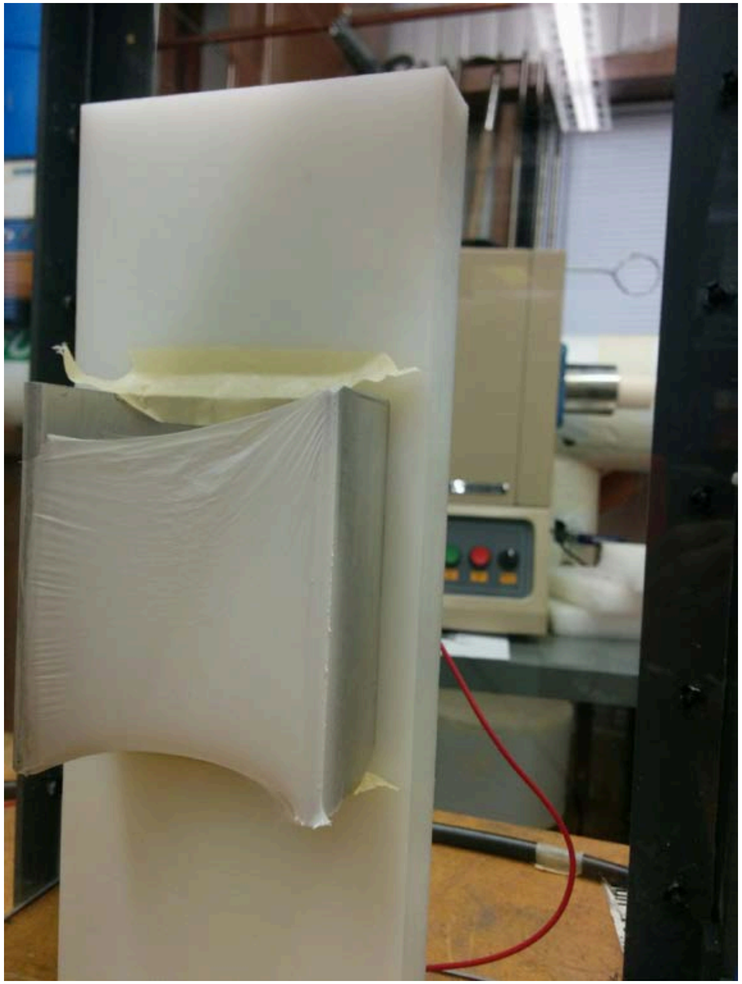
Electrospin Lab – MI-8 Cage area

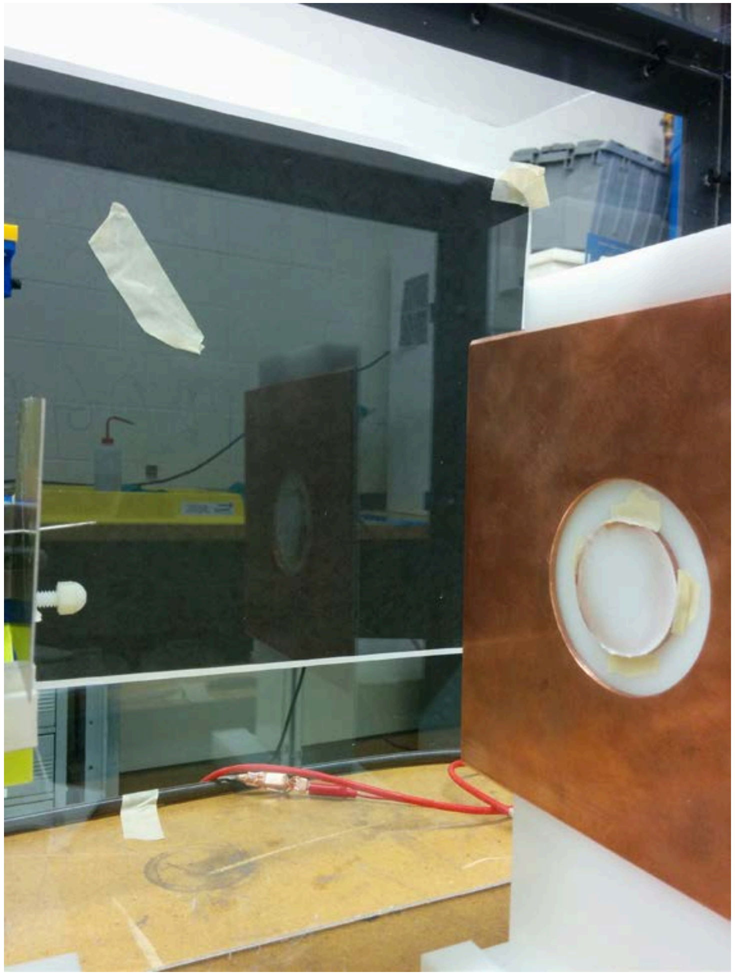


Fermilab

Electrospinning in Action

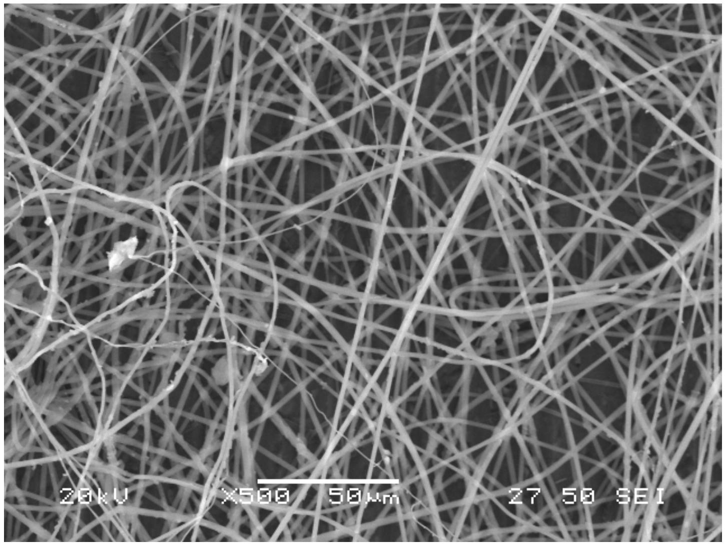
Electrospinning Accumulation



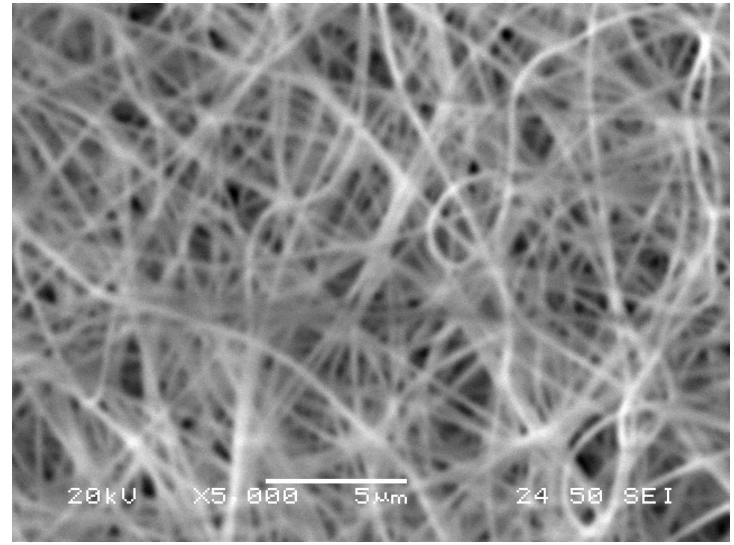


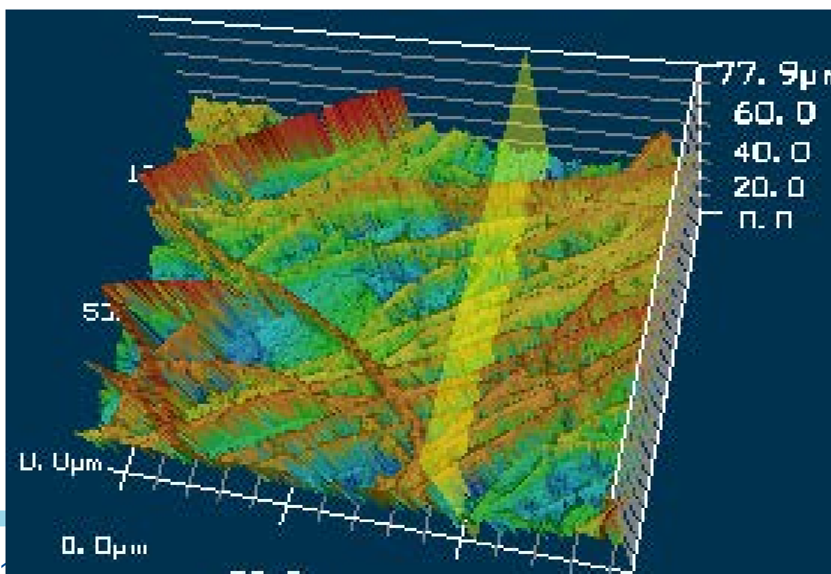
As spun nanofiber- Microanalysis

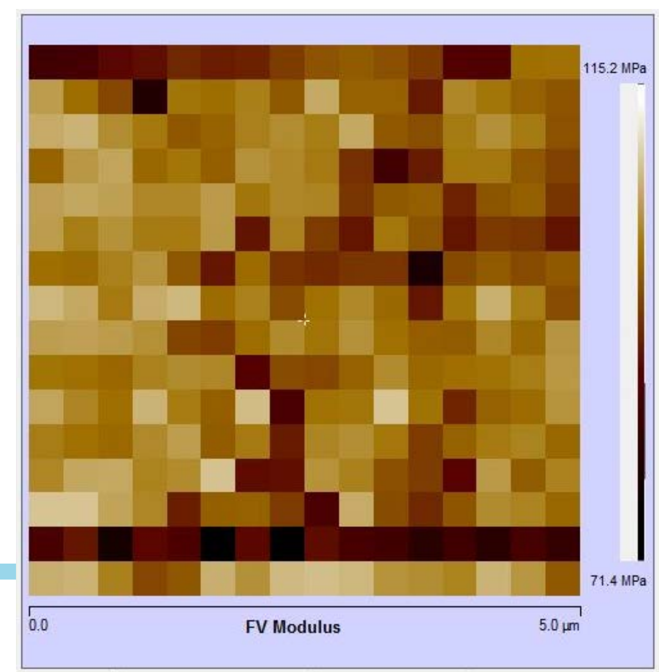
Alumina+PVP



Tungsten+PVP







Potential Benefits of Nanofibrous Target

- Improved Thermal Shock Resistance
  - Fundamental limit for solid materials
  - Suppress stress wave generation and interference
  - Elongated crystal grains may have superior performance
- Alternate cooling approaches
  - Very high surface area -to- volume ratio
  - Nanfibrous material provides relatively low resistance to gaseous coolant flow
- Improved radiation damage
  - Material defects and gaseous transmutation products can diffuse to the surface
  - For isotope production targets, rapid diffusion is also an advantage

Future Work

- Produce a variety of thicker materials
- Produce pure ceramics and metals
  - Incorporate carbon nanotubes
- Perform macro- and micro-mechanical testing
  - Compare to bulk and analogue materials
- Perform thermal testing
- Compare with mechanical simulations

⇨ **Establish Sinuous Materials as a serious avenue**

Later research (beyond this LDRD) may include radiation and beam testing

Acknowledgements

- Sujit Bidhar
- Josh Kubicek
- MI-8 Technical Crew
  - Henry Schram, Paul Schild, Hiep Le, Chris Kelly, …
- ESH&Q
- Marty Murphy & Denton Morris
- Technical Division Material Science Laboratory
- Valerie Goss (Chicago State University)
- LDRD Program & Committee

Conclusion

- Some future accelerator facilities and HEP experiments will be limited by the capabilities of targets (and their materials)

- We are investigating an exotic, engineered material as a replacement for bulk target materials
  - Electrospun, sinuous materials
  - Material properties of electrospun materials is a sparsely-researched topic

- Goal is to overcome the strength-stiffness limit
  - Other potential benefits of cooling, radiation hardness

- Other “engineered” approaches may prove beneficial as well

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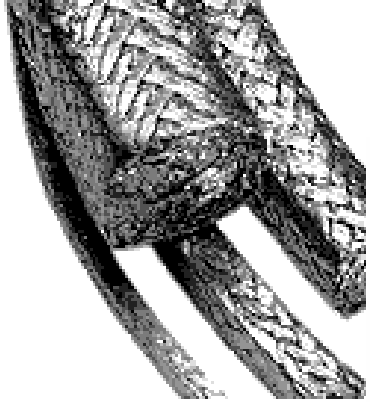
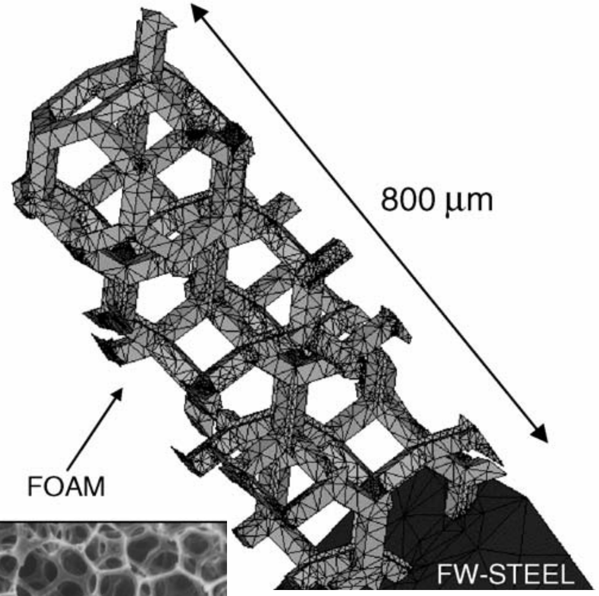
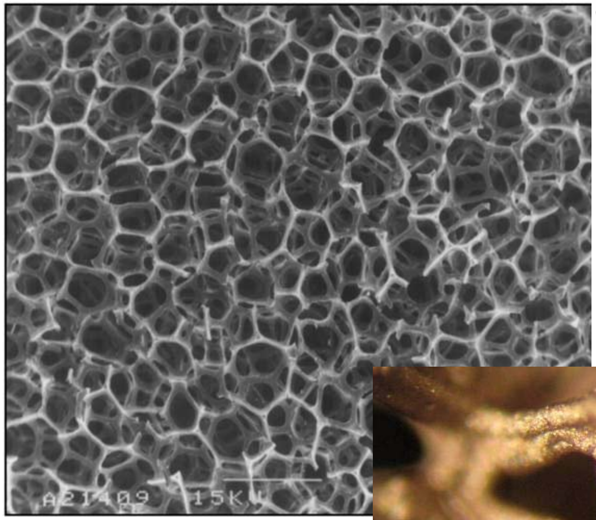
Array of analogue materials

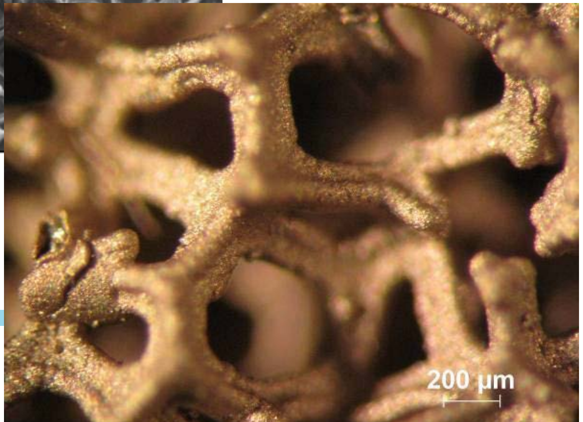
- Exfoliated materials
  - Exfoliated graphite
  - Vermiculite
- Reticulated Vitreous carbon
  - “Glassy” carbon, in 3-D foam-like shape
- Silicon Carbide
  - Material of interest for defense and aerospace applications
  - Solid and foam
- HfC and HfN foams







(d) 1 mm



Raw material for electrospinning solution

Polymer

Asphaltene
Nylon
Polyacrylonitrile (PAN)
Polyvinylepyrrolidone (PVP)

Solvent

Toluene
Formic acid
N-N,dimethyle-formamide
Ethanol

Salt additives (surfactants)

- Fiber diameter
- Stable jet length
- Morphology

Inorganic precursor

Ceramics

TiO_2
WO_3
Zirconia

Precursors

Titanium(IV) propoxide
Ammonium Metatungstate Hydrate
Zirconium Carbonate

Ceramics nanofiber fabrication

Inorganic precursor(ceramic+precursor solution)

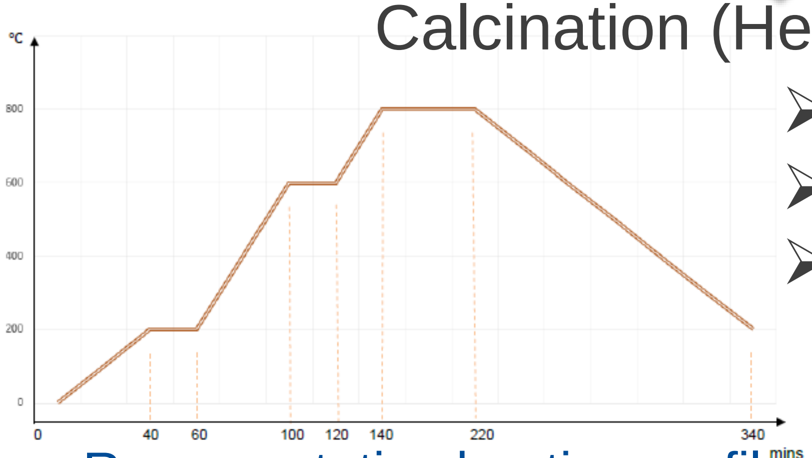
Polymer solution(polymer+solvent)

Salt additives (surfactants)

Solution for electrospinning→polymer-ceramic nanofiber

Calcination (Heat treatment)

- Vaporize polymer
- Promotes crystal growth
- Bonding



Representative heating profile

Candidate electrospin nanofiber

<u>Polymer (for Starter)</u>

- Nylon 6

<u>Metal/Ceramic</u>

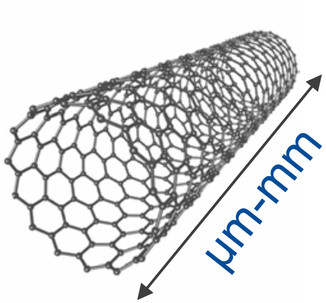
- Alumina
- Zirconia
- WO_3
- Titania
- Graphite

<u>Carbon-nanotube Composite(Ultimate)</u>

- CNT-Alumina
- CNT-Zirconium

CNT-ceramics nanofiber composites-advantage

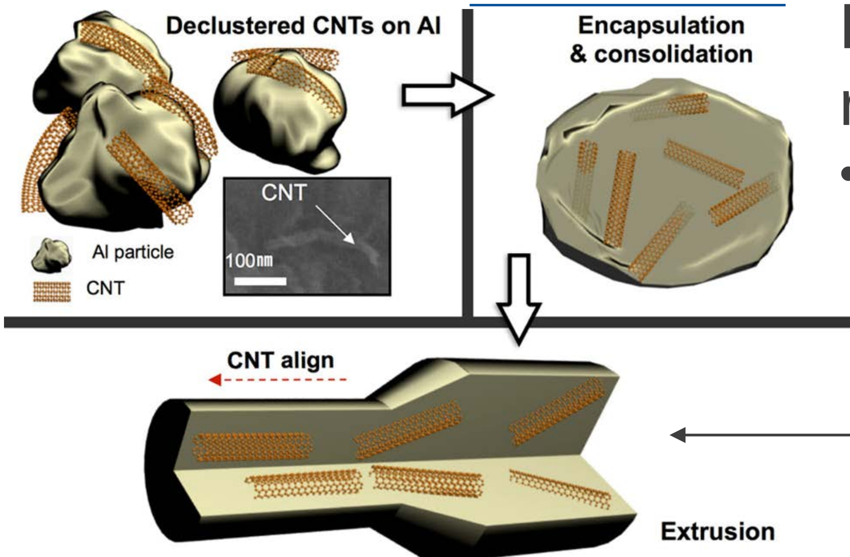
1-3 nm



SWNT

Excellent mechanical properties
E : 1~5 Tpa
Tensile strength : 15-50 Gpa
Elongation % : 16%
High thermal conductivity (axial), insulator lateral

1~2 Vol% CNT



MIT-research

Protects Aluminum metal against radiation damage

- 1-D transport network for He to escape

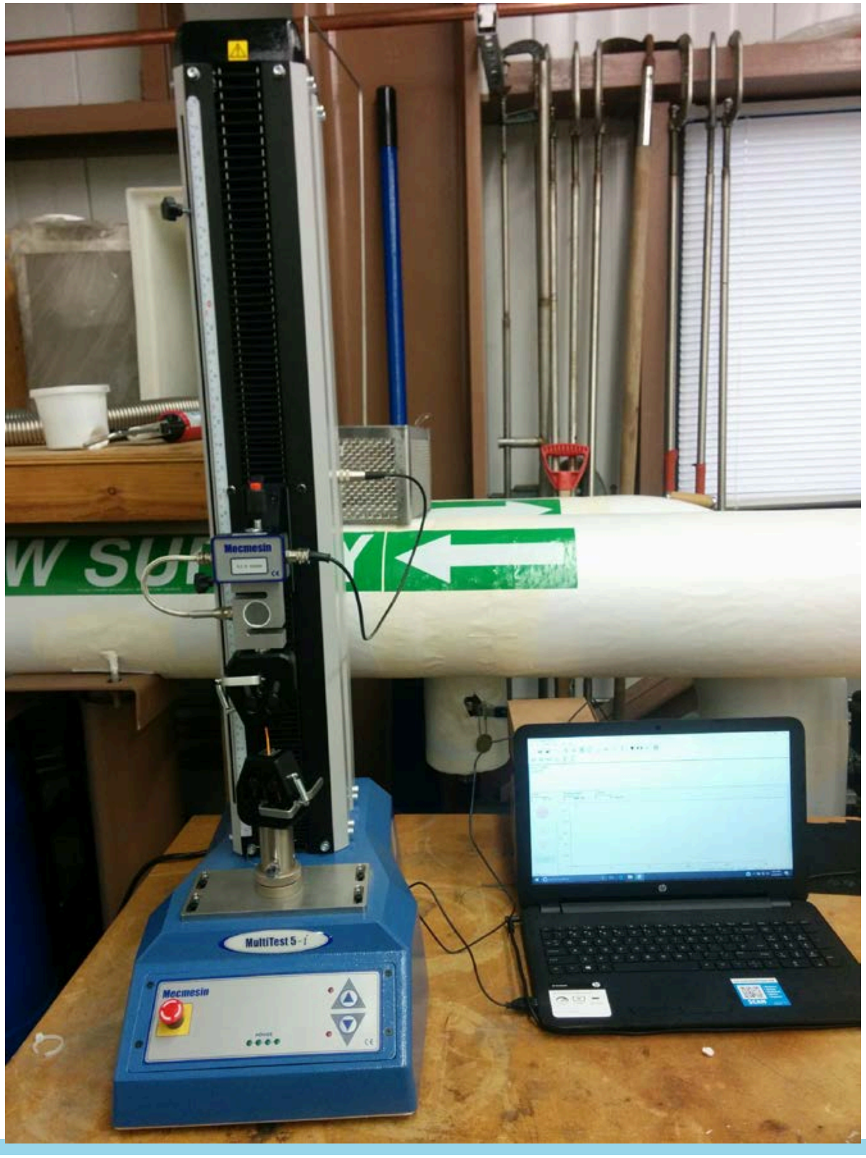
Bulk not nanofiber!!

Fermilab

Heat treatment – High temperature furnace

- Programmable temperature control up to 1500C
- To vaporize polymer part and to allow recrystallization, grain growth of metallic ceramic part in as-spun nanofiber

Mechanical testing of nanofiber mat



- Universal force tester to evaluate mechanical strength
- High precision testing using 2N load cell.
- Wide range of test piece testing with 5kN load cell.