Aligned Boron Nitride Nanotube Reinforced Polyethylene Nanocomposite for Space Radiation Shielding

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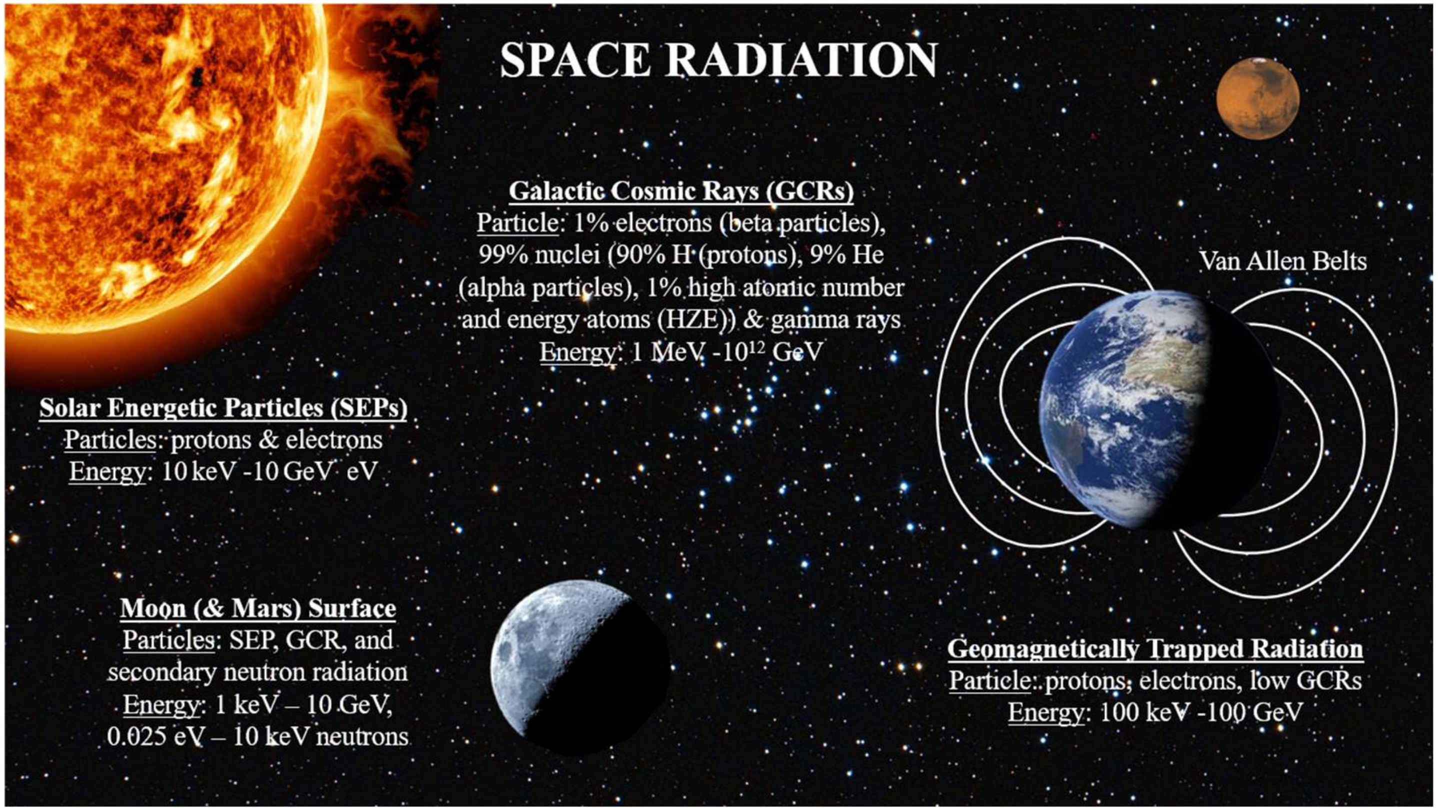
Radiation in the Space Environment

Satellites in low Earth orbit (LEO) and geosynchronous orbit (GEO)

Radiation damages electronics in satellites



Radiation Damage Mechanisms for Space Electronics

Three common radiation damage mechanisms for space electronics:

- Total ionizing dose (TID)
- Displacement damage dose (DDD, non-ionizing dose)
- Single event effects (SEEs)

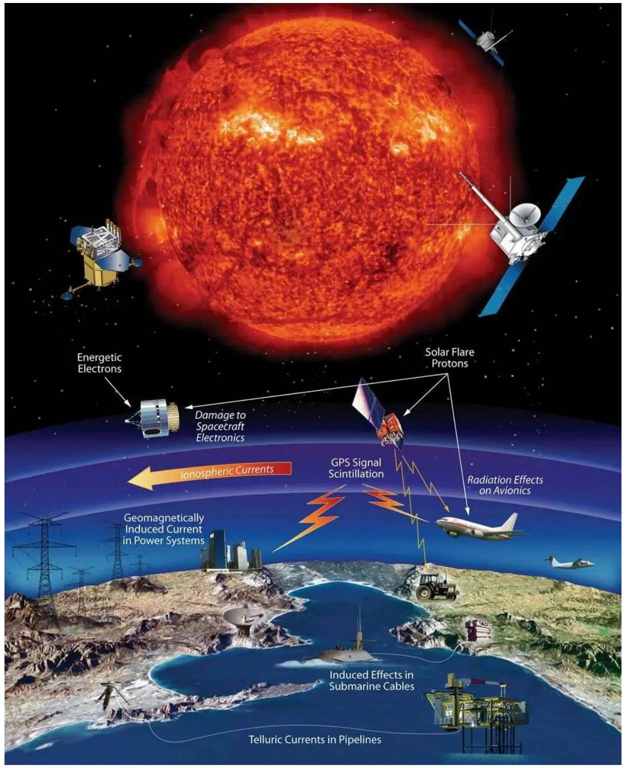
TID and DDD accumulate overtime while SEEs are associated with single particle strikes, usually in critical areas.

Relevant particle-matter interactions:

- Elastic scattering: include gamma rays + electron radiation

  Causes TID, DDD **attenuation $\propto Z^2/A$ -> high Z material**
- Inelastic scattering: include heavy ion + high energy proton + electron radiation

  Causes SEEs, TID, DDD **attenuation $\propto Z/A$ -> low Z material**



NASA – Technological Effects of Space Radiation Events

Z: atomic number

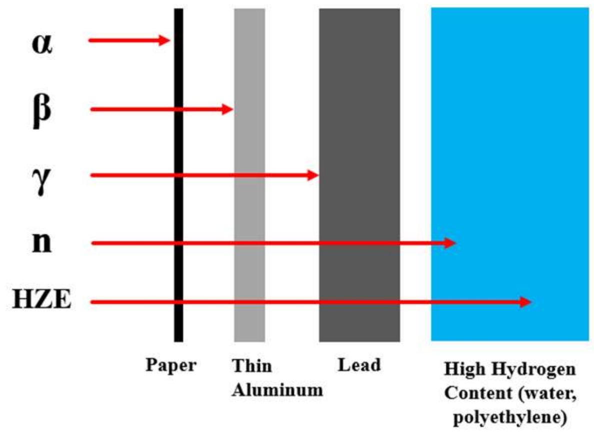
A: atomic mass

Comparing Materials for Radiation Shielding for Satellites in Earth Orbit

Z: atomic number
A: atomic mass

State of the Art (SOTA): 6.25 mm (¼”) thick Aluminum

Material	Liquid Hydrogen	High-Density Polyethylene (HDPE)	Boron Nitride	Aluminum	Titanium	Copper	Tungsten
Z/A	1	0.83	0.483	0.48	0.46	0.45	0.4
Z^2/A	1	1.67	2.91	6.26	10.11	13.23	29.79

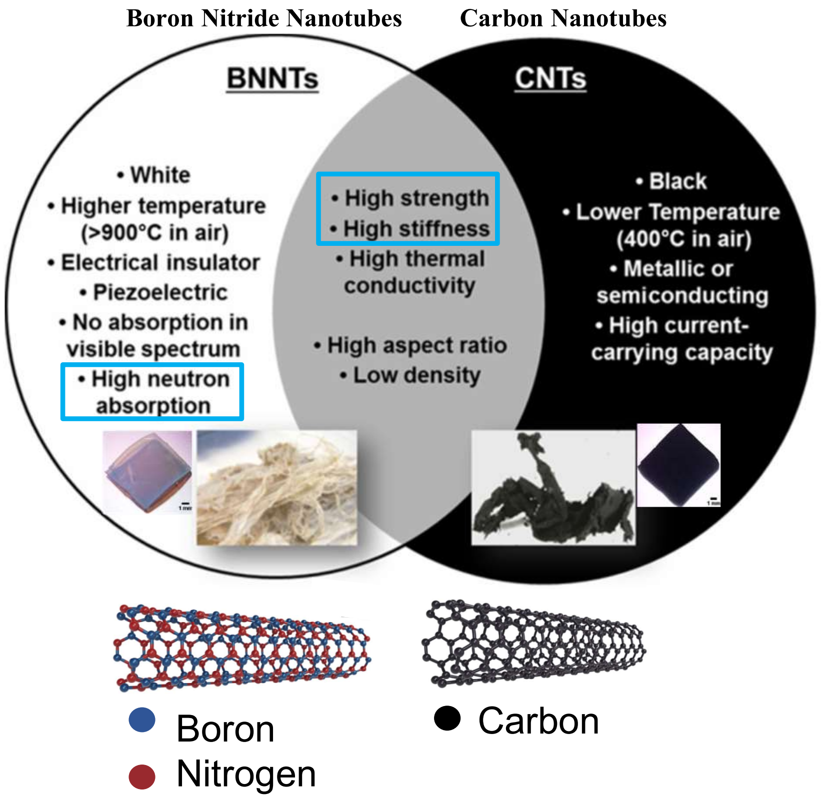


Lower density
Better at attenuating inelastic scattering
e.g., proton and heavy ion radiation

Higher density
Better at attenuating elastic scattering
e.g., gamma radiation

A layered structure consisting of low Z materials such as **Boron Nitride Nanotube (BNNT) – HDPE nanocomposites** and high Z materials including metals like aluminum, copper, and titanium can offer shielding for a wide range of radiation types while saving on mass (areal density).

Boron Nitride Nanotubes for Radiation Shielding



Venn modified from: Michael Jakubinek et al, Polymer Nanocomposites Incorporating BNNTs, *Nanotech 2015 Conf.*

- BNNTs shield from secondary neutrons better than hydrogen-rich materials
- Boron-10 has a cross-section much higher than hydrogen
- BNNTs can improve mechanical properties

Absorption cross section for 2200 m/s neutrons[c] for selected elements with the cross-section highlighted for hydrogen and Boron-10. [Sears et al. 1992]

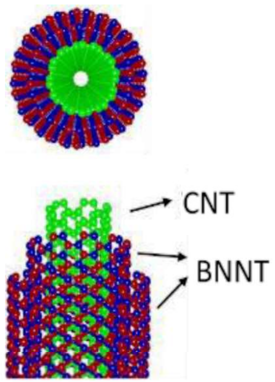
Element	Atomic number	Atomic mass	[b] σ Cross Section
Hydrogen	1	[a] N	0.3326
		1	0.3326
		2	0.000519
		3	0
Boron	5	N	767.8
		10	3835.9
		11	0.0055
Carbon	6	N	0.0035
		12	0.00353
		13	0.00137
Nitrogen	7	N	1.9
		14	1.91
		15	0.000024
Oxygen	8	N	0.00019
		16	0.0001
		17	0.236
Aluminum	13	N	0.231

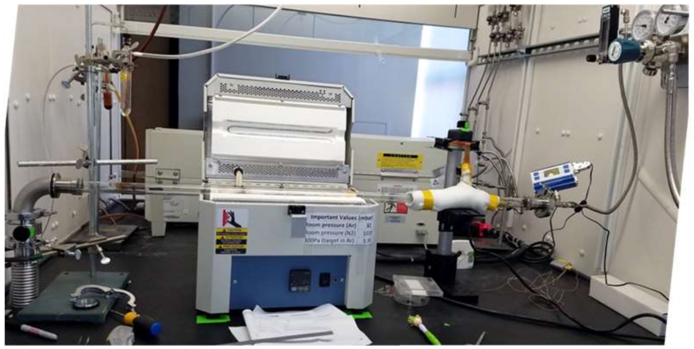
[a] N = natural abundance

[b] σ = cross-section, measured in barns, 1 barn = 100 fm^2,

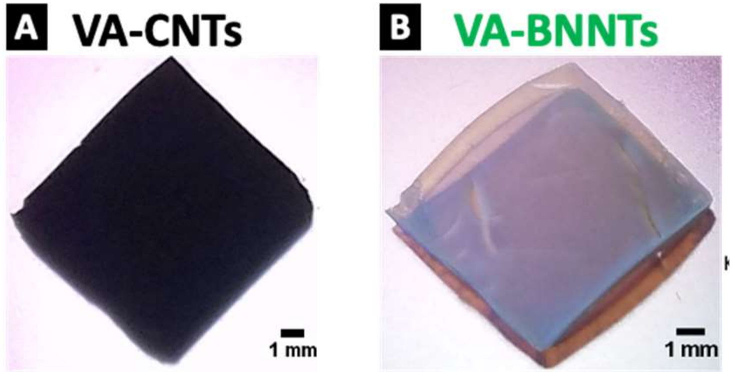
[c] E = 25.30 MeV, k = 3.494 $\dot{A}^{-1}$, I = 7:798 $\dot{A}$

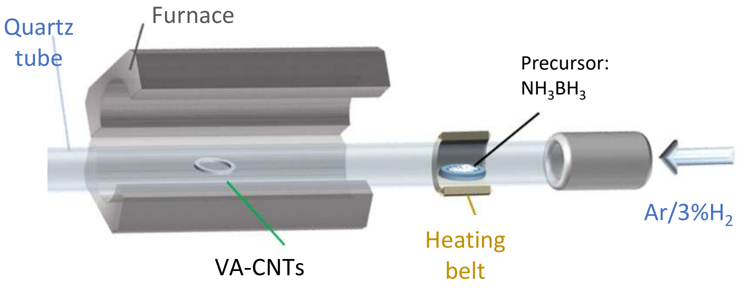
1-mm tall Vertically Aligned (VA) BNNT Synthesis at MIT necstlab



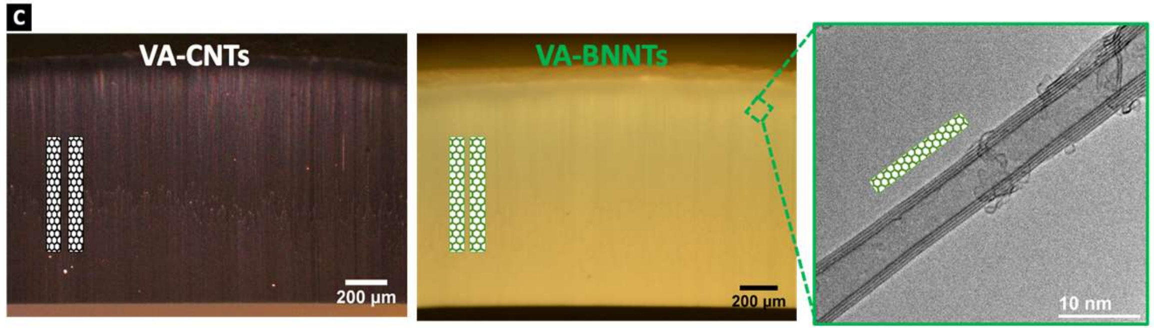


BNNT Furnace @ MIT necstlab





Modified from: R. Xiang *et al*, One-dimensional van der Waals heterostructures, *Science*, 2020, 537-542

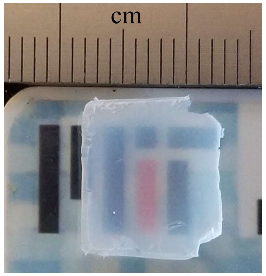


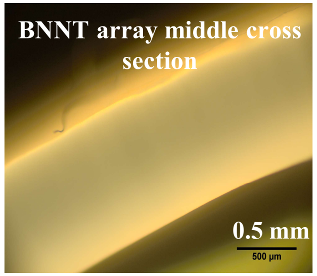
Acauan, (Wardle) et al., *ACSNano, 2023*.

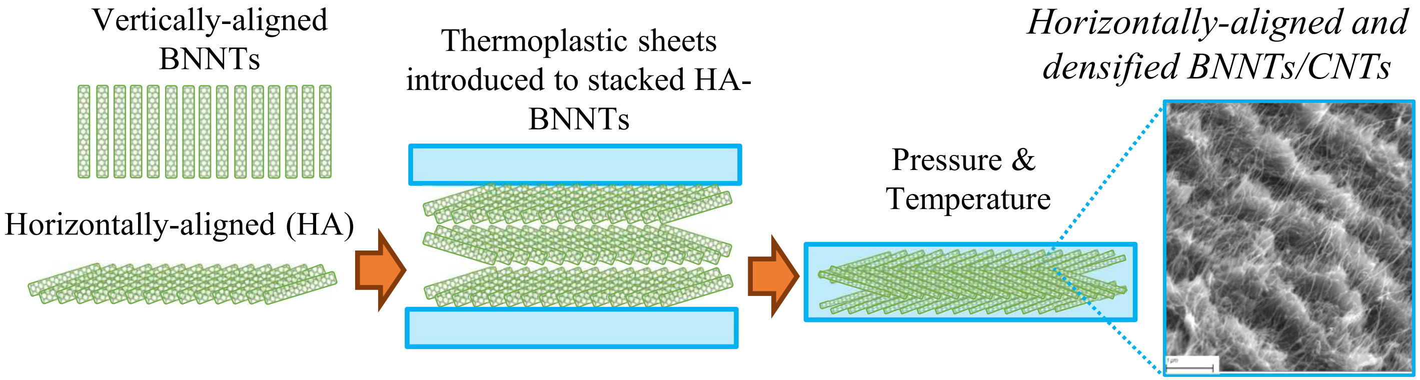
Bulk Nanocomposite Laminating Process Eliminates vol% Limitations in Manufacturing Nanocomposites

- Limitations in nanocomposite manufacturing keep the SOTA to 1-10 vol% nanotubes hence limiting mechanical properties
- BNL process demonstrates up to 50 vol% of CNTs or BNNTs
- Multifunctionality (e.g. thermal conductivity and radiation protection)

Boron nitride nanotube (BNNT) arrays

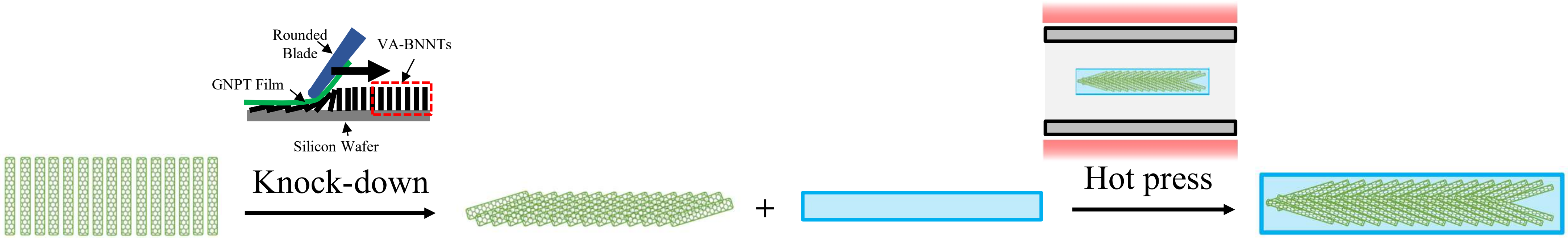






Bulk Nanocomposite Laminating (BNL) process for thermoplastics

Manufacturing of BNNT-HDPE Samples

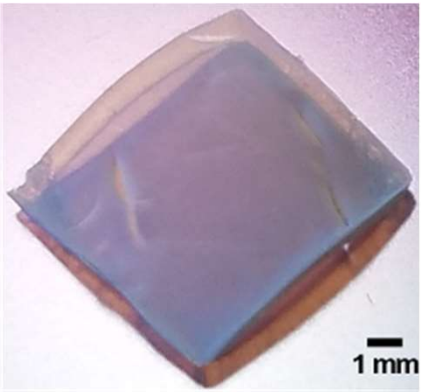


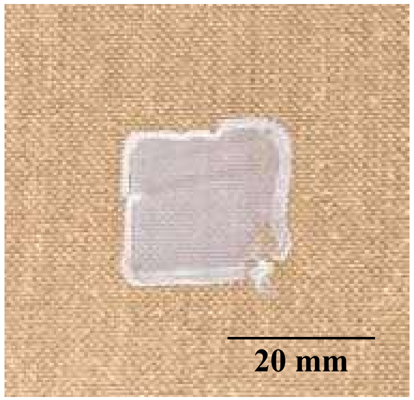
Vertically aligned BNNTs
Height ~1 mm

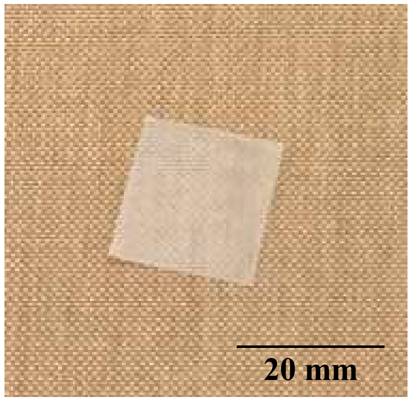
Horizontally aligned BNNTs

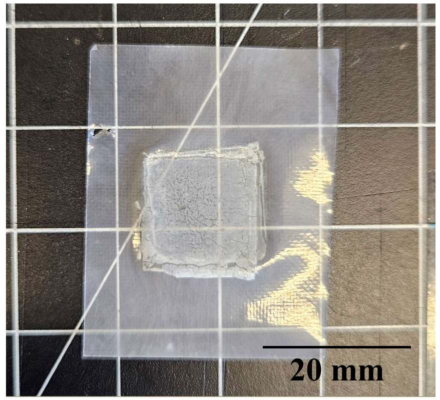
HDPE sheets

2 ply 40 vol% BNNT-HDPE
thickness ~60 µm

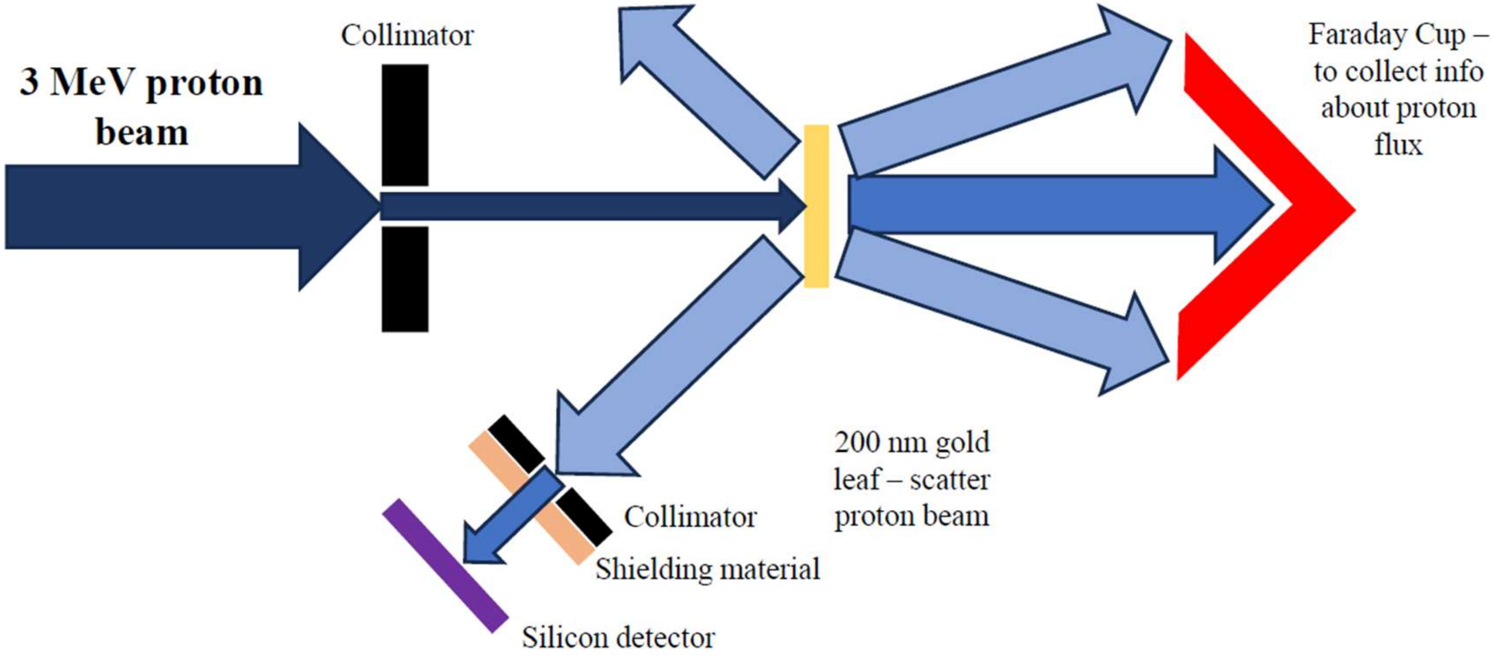


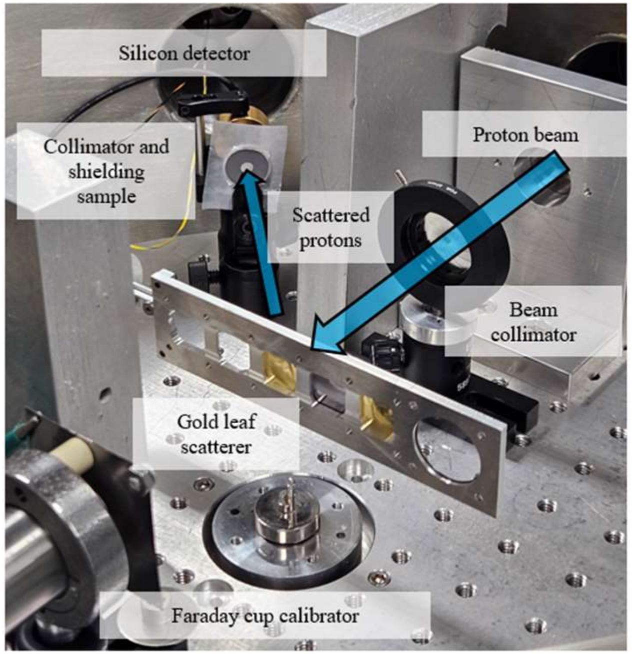




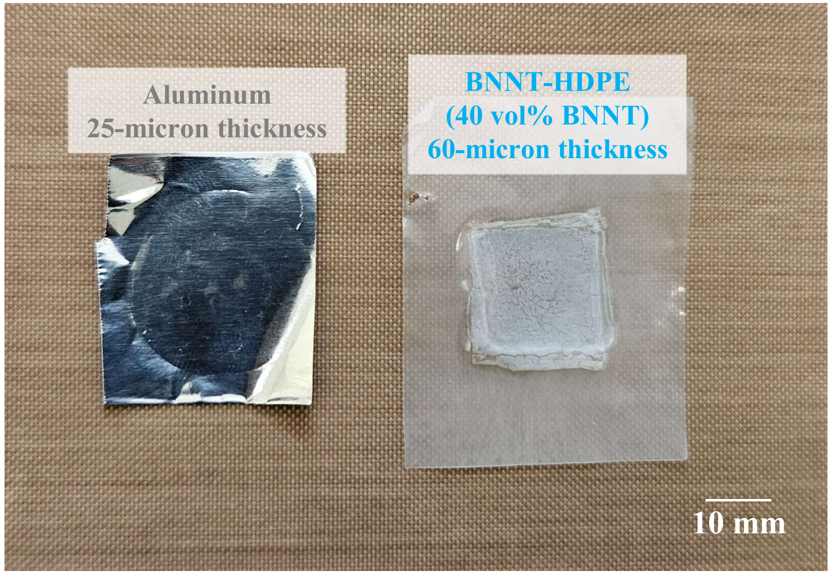


Experimental Testing at the Proton Radiation Beamline Setup at UMass Lowell



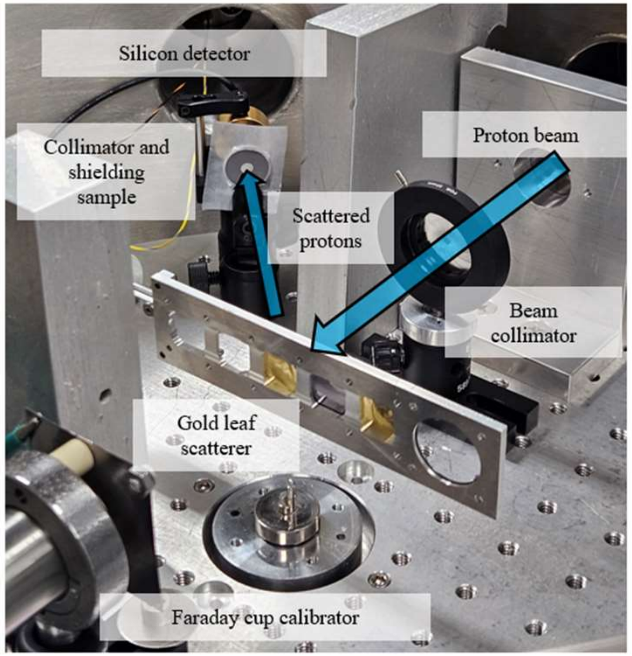


BNNT-HDPE and Aluminum Comparison Under Radiation



Samples with the same areal density ~6 mg/cm^2

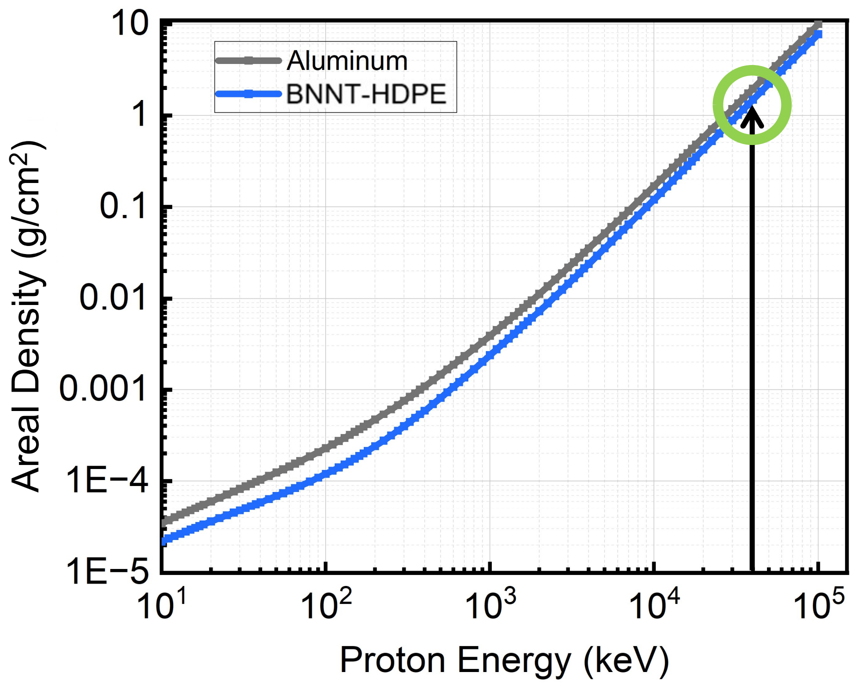
Tantalum collimated sample to keep the area of proton radiation the same



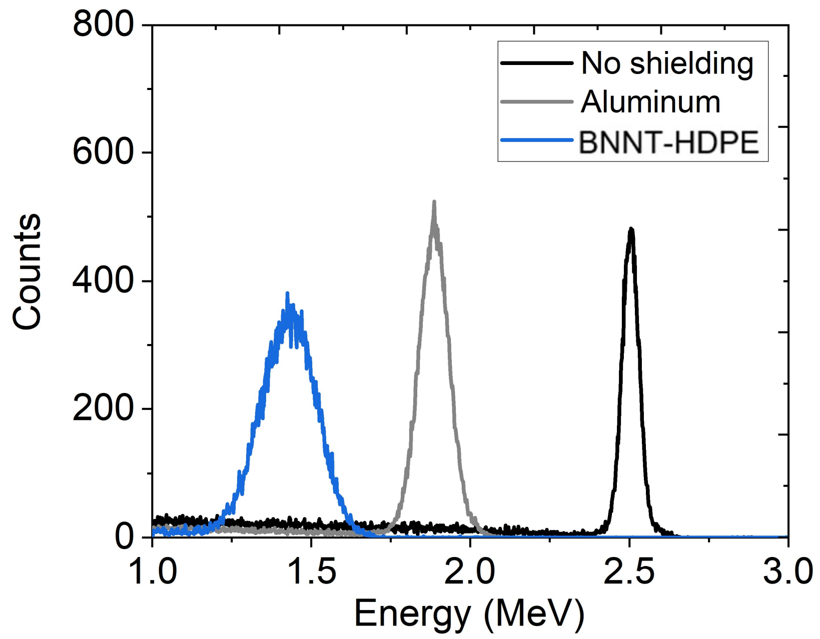
Proton Beam Simulation Results Compares BNNT-HDPE with SOTA Aluminum

Simulations run on Stopping and Range of Ions in Matter (SRIM)

- Simulations show that lower areal density of HDPE-BNNT is required to stop the same energy of protons
- SOTA is 6.25 mm (¼”) thick Aluminum
- Calculations show ~ **25% mass savings with using BNNT-HDPE** to shield the same proton radiation as SOTA Aluminum

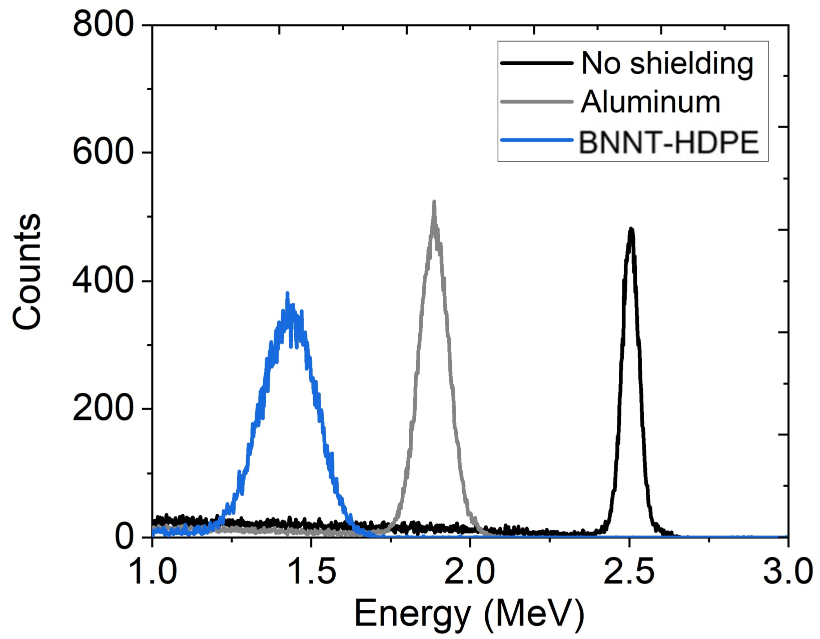


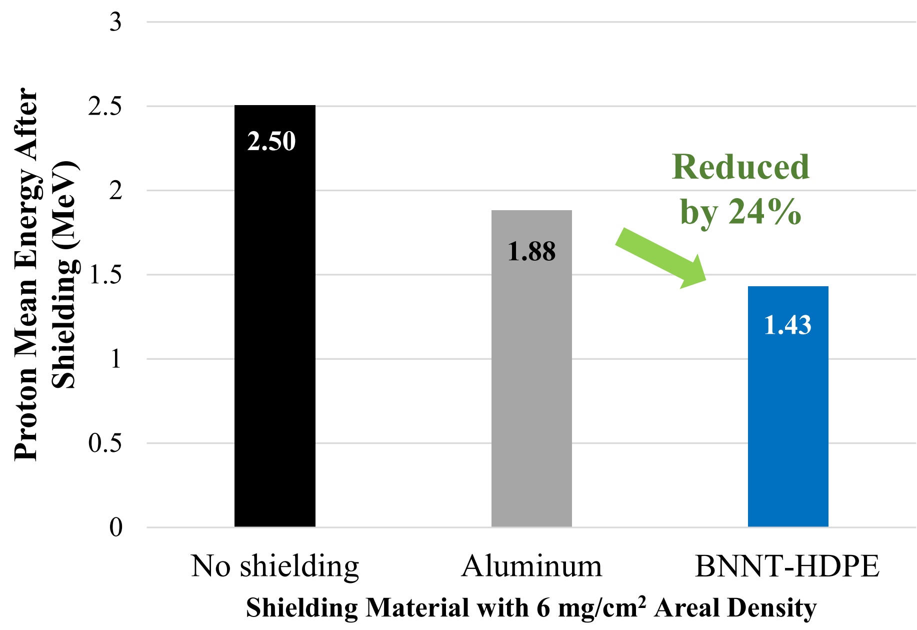
Experimental: Proton Energy and Number of Protons Detected After Shielding



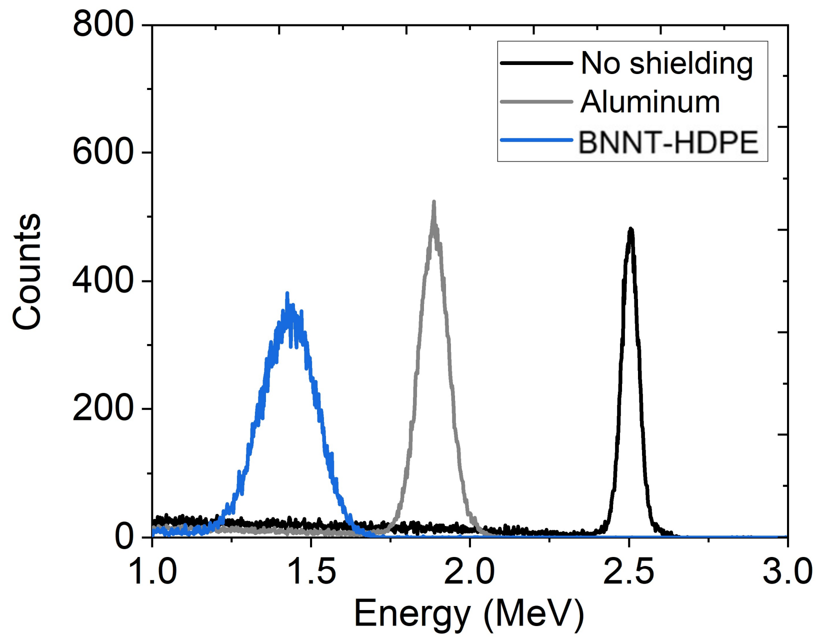
- Reduction in the energy of protons that pass through shielding material
- Widening of the histogram curve that counts the number of protons at different energies – indicates energy straggling and potential for more protons to be stopped at lower areal densities

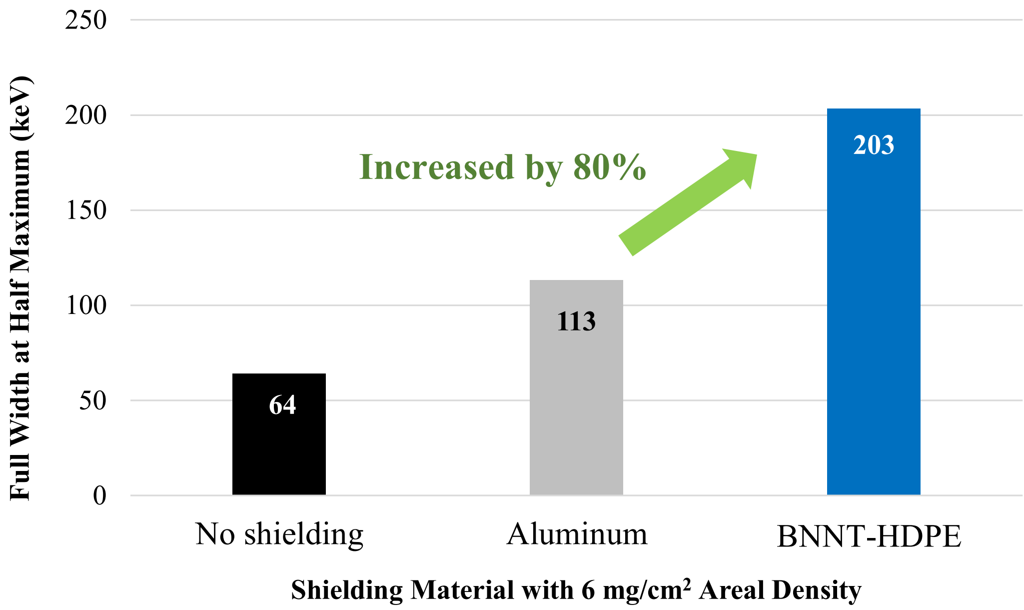
Experimental: Proton Energy Reduces Due to Shielding





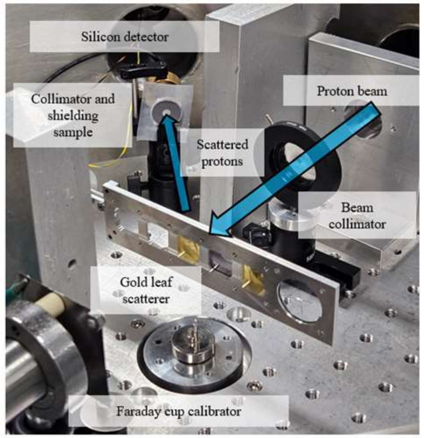
Experimental: Histogram Width Shows Energy Straggling

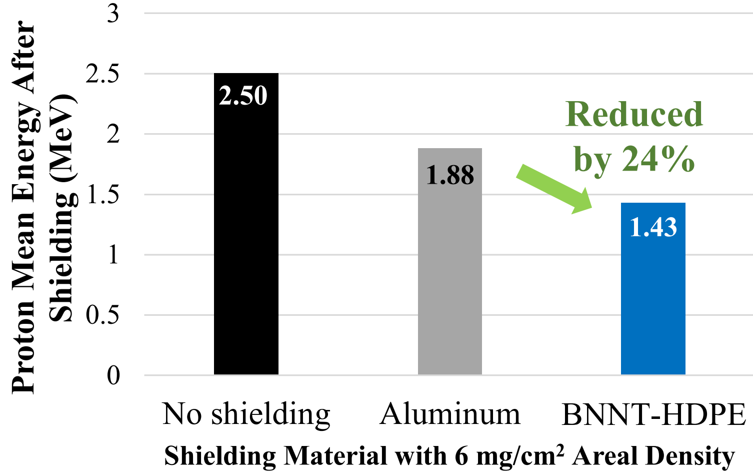




Conclusion and Future Work

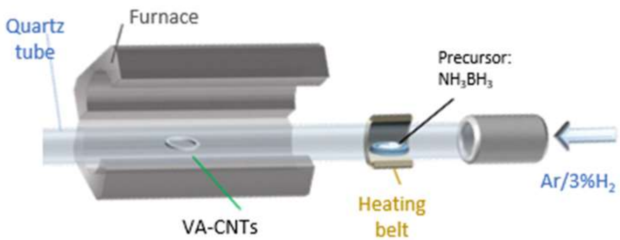
- BNNT-HDPE nanocomposite manufactured with ~40 vol% aligned BNNTs
- At low proton energies (2.5 MeV), a significant mass savings of ~ 25% is shown by using BNNT-HDPE
- For space representative proton energies (10 keV-100 MeV), thicker nanocomposites, including layered materials (Al, Ti, Cu, etc.) need to be explored

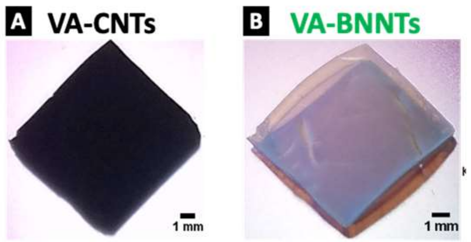




Future Work: BNNT BNL for Radiation Shielding

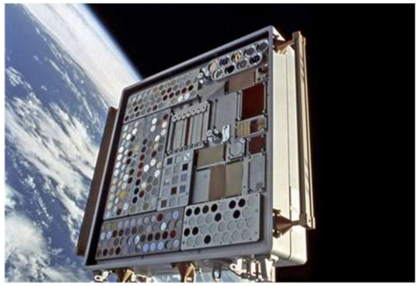
Synthesizing 50 vol% ^{10}BNNT Nanocomposite



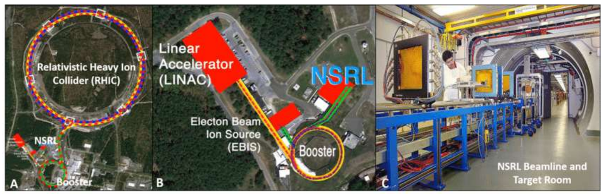


Radiation Testing (Protons, Thermalized Neutrons, Galactic Cosmic Rays, Low Earth Orbit)

NASA Langley Research Center

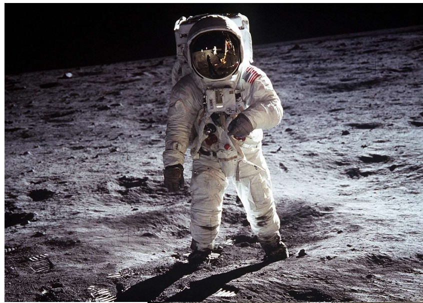


Materials International Space Station Experiments



Brookhaven National Lab – NASA Space Radiation Lab

Nanocomposite in Spacesuits and Habitats



NASA Lunar Spacesuit

Sierra Space Lunar Habitat

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Thank you! Questions?

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