MULTIPHYSICS SIMULATION OF THE THERMAL RESPONSE OF A NANOFIBROUS TARGET IN A HIGH-INTENSITY BEAM

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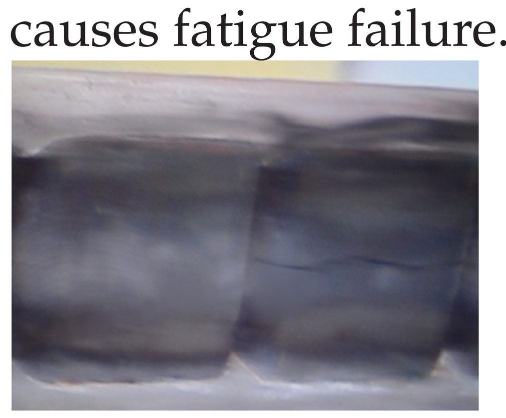
The Intensity Barrier

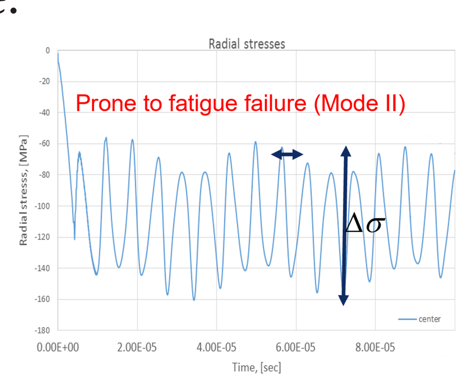
The Intensity Barrier: upper bound on primary beam power reachable with current technology in neutrino beamlines. Must advance this frontier to meet demands of future facilities. Accelerators have enough power—need advanced targets.

Record: 893 **kW (NuMI, June 2022)**
LBNF w/ PIP-II: 1.2 **MW (2025)**
LBNF w/ PIP-III: 2.4 **MW (2035)**

Conventional Targets

Current convention—solid graphite targets (e.g., NuMI), with water cooling. Have been successful so far ~ 1 MW, but unknown if they will do well at higher intensities due to sensitivity to thermal stress waves caused by pulsed beams. Their uniform solid lattice lets stress waves propagate easily and causes fatigue failure.



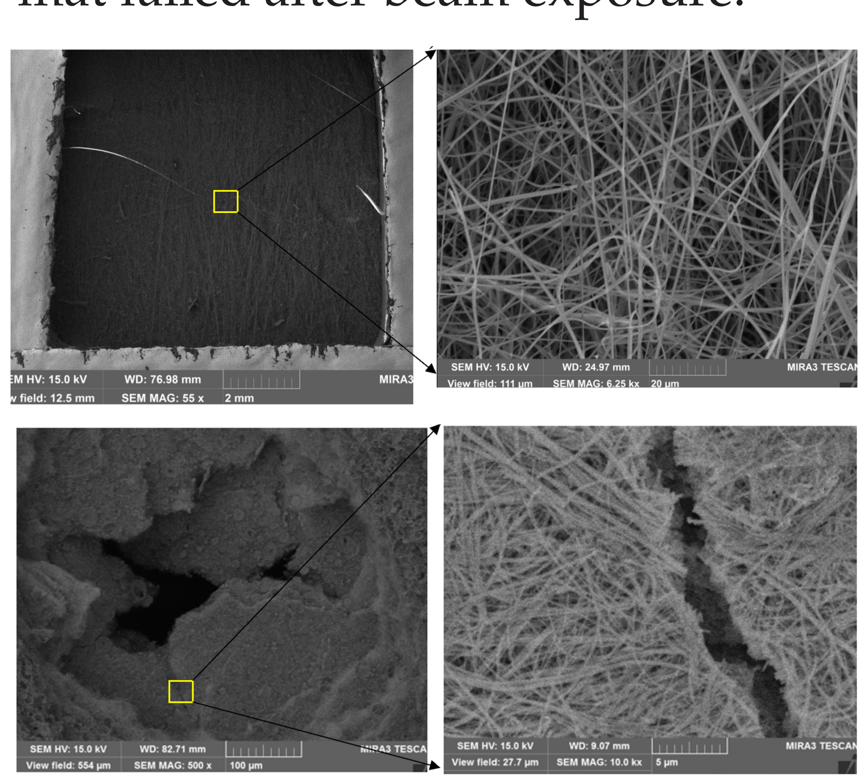


Nanofiber Targets

The High Power Targetry Research and Development Group at Fermilab is studying a nanofibrous target material—electrospun mats of Yttria-Stabilized Zirconia nanofibers. Several advantages over conventional targets:

1. Empty space dissipates thermal stress waves
2. Porosity allows cooling with helium flow
3. Intrinsic radiation hardening

Study at HiRADMat revealed lifetime is sensitive to construction parameters. Top row: less dense nanofiber mat remained undamaged. Bottom row: denser mat failed after beam exposure.

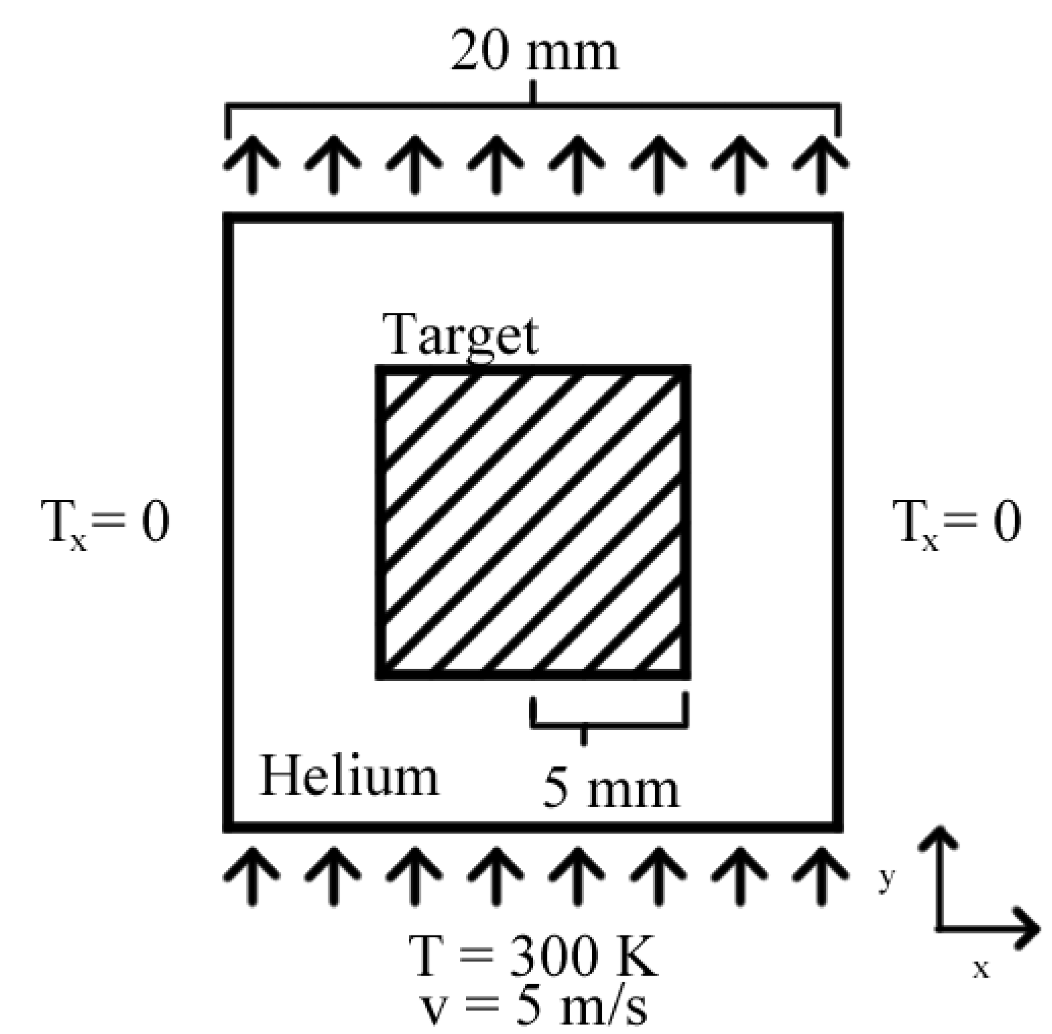


Simulations: ANSYS Fluent

Used ANSYS Fluent as multiphysics solver because Darcy's Law, effective material parameters, and beam heating implemented easily. Problem: 10 mm × 10 mm target in 20mm × 20mm helium medium. Nanofiber mats ≈ stacked 2D planes of fibers, thickness is 1mm, so beam heating is uniform in each layer. Thus, used a "thin target approximation" to reduce to 2D. Other parameters:

- Structured mesh of squares w length 0.2mm
- Time-dependent source term to energy eq'n to imitate beam cycle of NuMI:
  - Single timestep of 10μs with source on
  - 18 timesteps of 0.1s with source off
- 2nd order SIMPLE solver used to calculate transient solution over 4 cycles (≈ 7s)

Domain & BC's

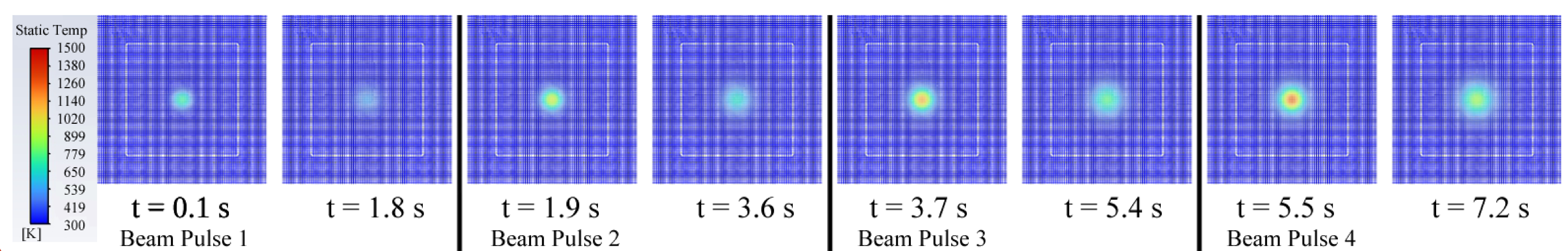


Models & Theory

To better understand thermal properties of the nanofiber targets and predict their response to beam heating, need theoretical description to be used in multiphysics simulations. Nanoscale structure of the mats has significant effects on the properties of the target, so cannot ignore fine structure. However, it's impossible to model the nanoscale behavior explicitly since there are *millions* of nanofibers in even a small part of the mat. Instead, we use *Porous Media Models* (PMMs):

1. PMMs translate nanoscale properties to macroscopic effects
2. Nanoscale geometry is then "forgotten": fibrous mat is replaced by bulk material with effective physical parameters

Results: Temperature Contours For Each Beam Pulse



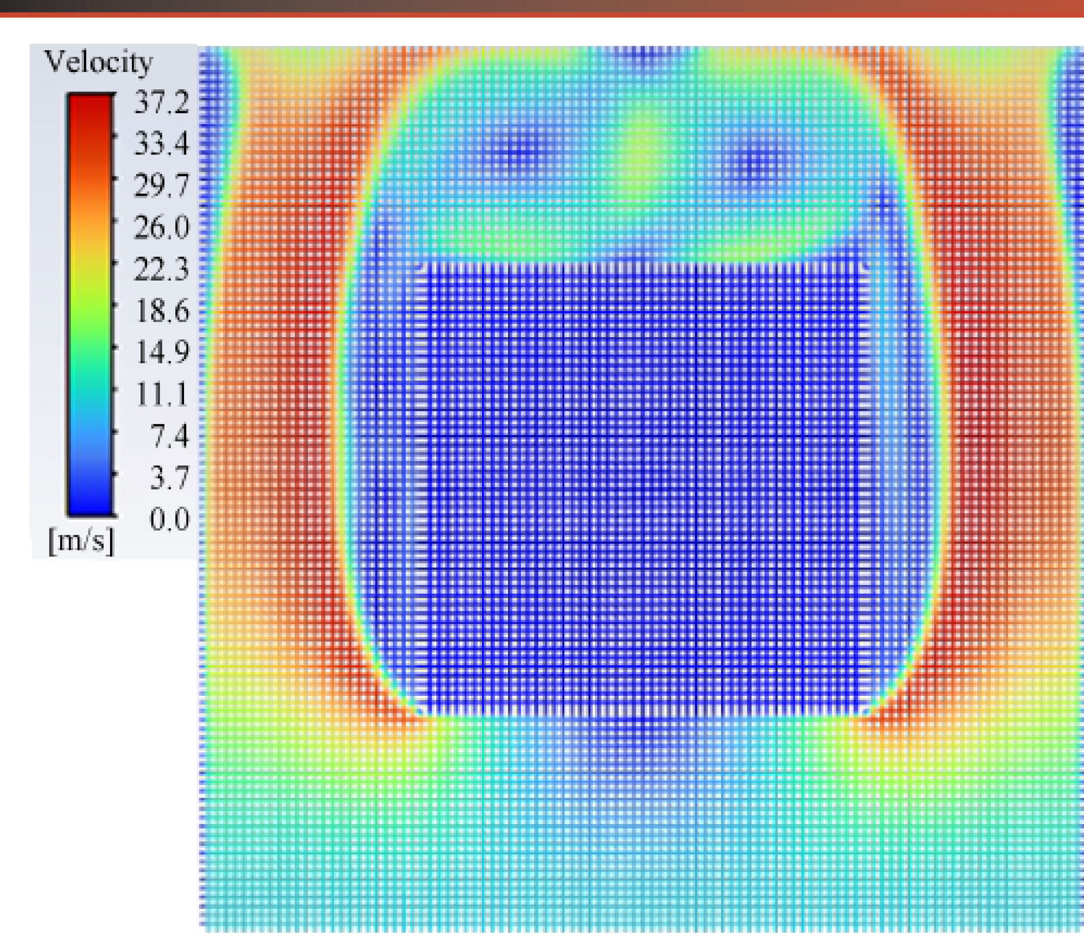
Helium Cooling Flow

For helium cooling flow, used Darcy's Law, which models fluid flow thru a porous medium by adding a momentum source term to the governing eq'ns for the *macroscopic* flow-field of the form:

$$\vec{S} = -\frac{\mu}{\alpha}\vec{u}$$

where μ is dynamic viscosity, and α is the permeability to fluid flow. We estimated $\alpha \approx 2.524 \cdot 10^{-15} m^2$ using Johnson et al.'s Λ-methods.

Results: Helium Flow Field



Conclusions

Temperature contours show target center getting slowly hotter and hotter with each cycle. This temperature "creep" could lead to target failure.

Potential explanation: helium velocity contours reveal that cooling gas does *not* penetrate target at all—velocity drops to zero inside target. So, cooling system is not working as intended.

Further studies include monitoring long term behavior of temperature "creep", and studying effects of adjusting parameters to increase permeability which could fix helium cooling and even eliminate temp "creep". Permeability improved by increasing fiber radii *or* lowering packing density. Latter approach is delicate, however, since it lowers the neutrino yield. Creating a neutrino beam is the target's main purpose, after all.

Energy Deposition by Beam

To determine the heat generated by the beam, used MARS to calculate the volumetric energy deposition. Beam parameters were based off NuMI: pencil beam with $\sigma \approx 0.50$mm, 10μs pulse of 120GeV protons, $N = 10^{13}$ per pulse. Implemented as time-dependent source term to energy eq'n.

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Conductive Heat Transfer

Nanofibers are ≈ 1D, so heat can only move between fibers at crossings or into surrounding He gas. We used Bhattacharyya's model for effective thermal conductivity of a fibrous object:

$$k_{eff}(T) = k_0 + \frac{k_g - k_0}{1 + \frac{f}{1-f}\left[1 + \frac{5}{6}\frac{k_g - k_0}{k_g + k_0}\right]}$$

where k_g is gas conductivity (calculated with a model by Daryabeigi) and k_0 is fiber conductivity.