MULTIPHYSICS SIMULATIONS OF THERMAL SHOCK TESTING OF NANOFIBROUS HIGH POWER TARGETS

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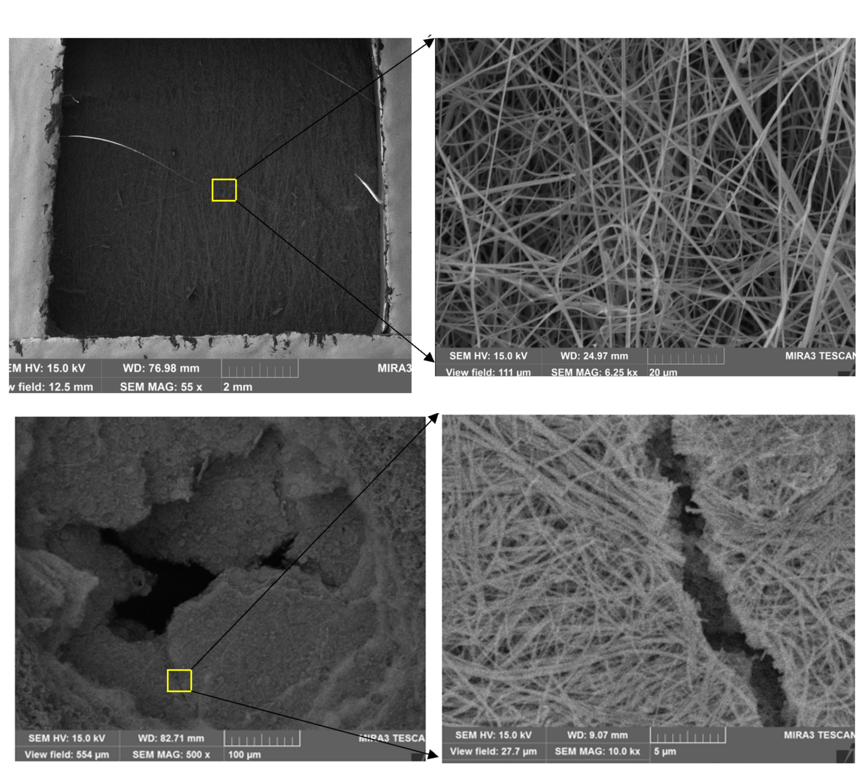
BACKGROUND

Neutrinos are one of the biggest research areas to look for Beyond the Standard Model physics, and studying rare processes requires high intensity neutrino beams. For next generation facilities, robust targets need to be designed which can sustain the increased radiation damage and thermal shock from higher beam intensities (up to 4+ MW)

Record: 959 **kW (NuMI, May 2023)**
LBNF w/ PIP-II: 1.2 **MW**
LBNF w/ PIP-III: 2.4 **MW**

NANOFIBER TARGETS

- High Power Targetry R&D Group at Fermilab studying nanofibrous target material—electrospun mats of Yttria-Stabilized Zirconia nanofibers [1,2].
- Several potential advantages:
  1. Empty space dissipates thermal stress waves
  2. Porosity allows cooling with gas flow
  3. Intrinsic radiation hardening
- Thermal shock test with single beam pulse at HiRadMat revealed survival depends on construction parameters.
- Top row: less dense nanofiber mat (Solid Volume Fraction (SVF) $f = 0.05$) appears undamaged. Bottom row: denser mat (SVF $f = 0.20$) failed after beampulse.



Objective of this work: replicate HiRadMat test with multiphysics solver, and identify failure mode, and how it depends on density of mat.

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CONTACT INFORMATION

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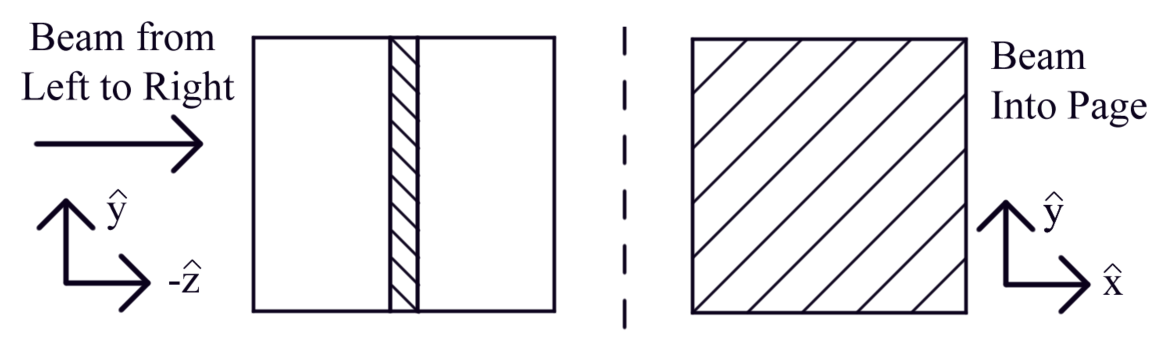
DOMAIN & BC'S

- 10 mm × 10 mm × 0.1 mm rectangular porous zone
- Two 10 mm × 10 mm × 5 mm columns of air as outflows

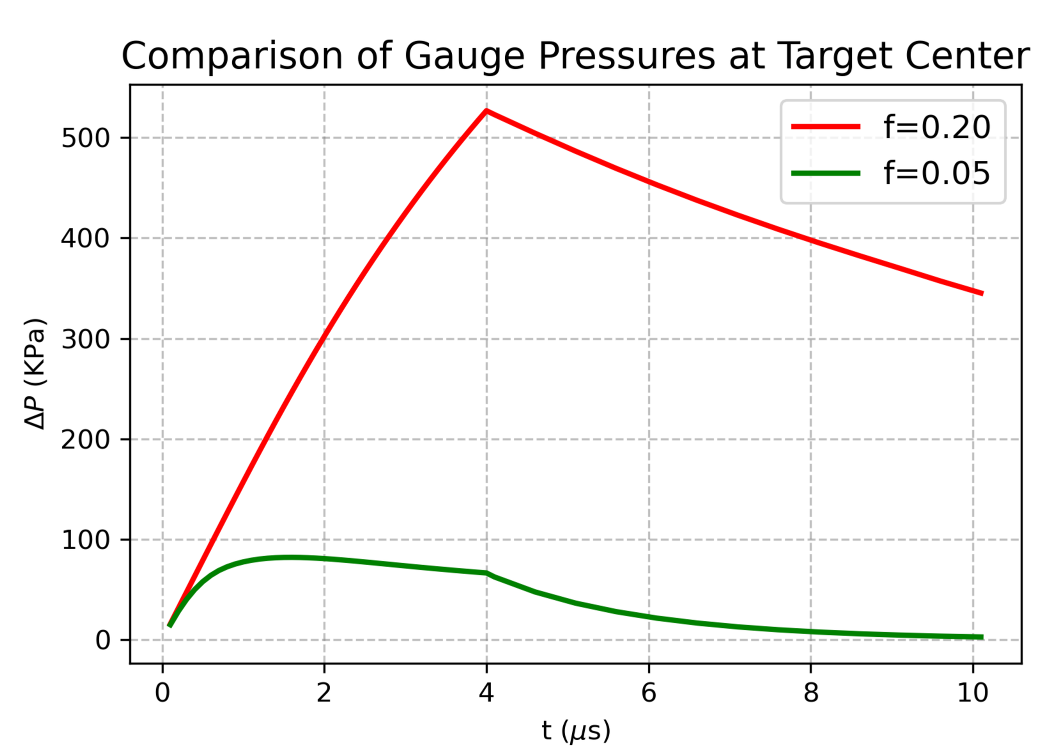


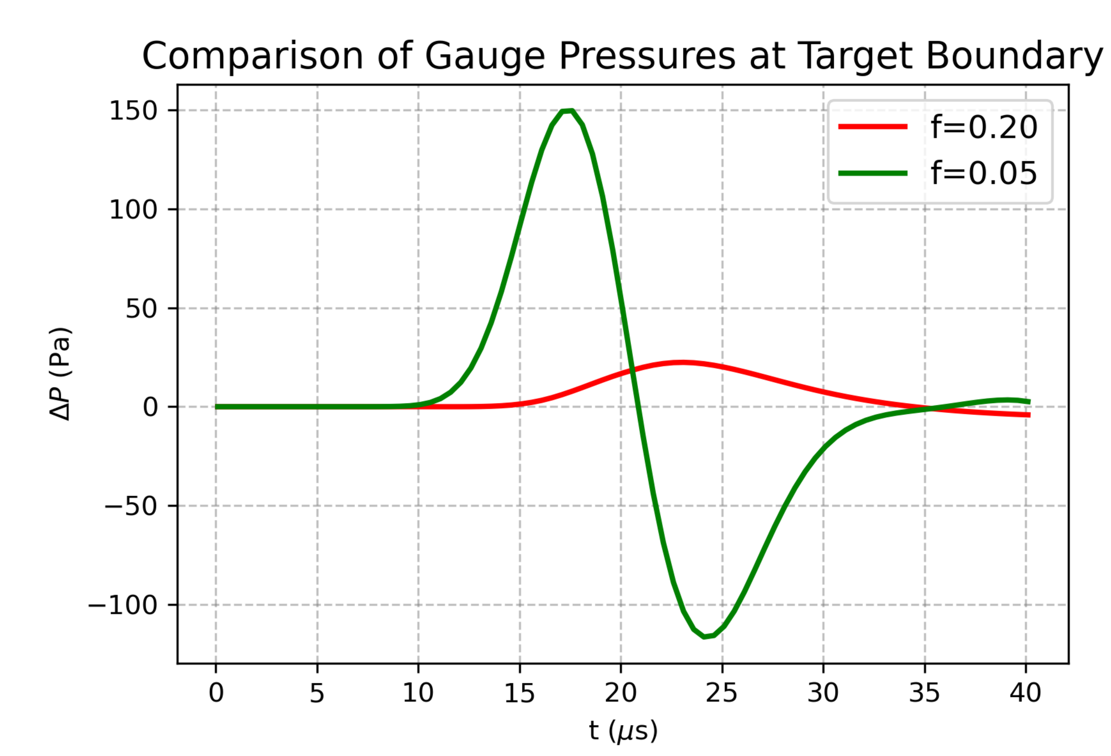
- $\pm\hat{z}$: homogeneous Dirichlet pressure BC, and fixed temperature of 300 K
- $\pm\hat{x}, \pm\hat{y}$ directions, homogeneous dirichlet velocity BCs, zero heat flux.

SIMULATIONS

- Solver: ANSYS Fluent
- Two simulations, low density mat ($f = 0.05$) and high density mat ($f = 0.20$).
- Uniform mesh, $\Delta x = 0.02$ mm in porous zone, $\Delta x = 0.1$ mm in air
- Beam: time-dependent volumetric source term to energy eq'n in porous zone from MARS [6,7,8]
  - 4 μs with source on, $\Delta t = 0.1\mu$s
  - 36 μs with source off, $\Delta t = 0.5\mu$s
- SIMPLE algorithm, transient laminar flow

RESULTS: COMPARING AIR PRESSURE CHANGE FROM BEAM PULSE





LOWERING AMBIENT PRESSURE

Table of air pressure rise in target center at $t = 4\mu$s with decreasing operating pressures

Operating Pressure	f = 0.20	f = 0.05
1 atm	527 KPa	66.6 KPa
0.1 atm	63.6 KPa	42.1 KPa
0.01 atm	6.33 KPa	6.42 KPa
0.001 atm	0.629 KPa	0.639 KPa

Notice that $f = 0.20$ has the higher pressure rise until operating pressure falls below 0.01 atm, and that pressure rises are similar at that point.

MODEL

- Gas phase thermal conductivity [3] incorporates size effects and non-equilibrium
- Porous zone effective thermal conductivity [4], nonlinear combination of solid and gas
- Permeability to fluid flow (in Darcy's Law), α, given below [5]

$$\alpha = \frac{\epsilon\, r^2}{8\,(\ln \epsilon)^2}\ \frac{(\epsilon - \epsilon_p)^{x+2}}{(1-\epsilon_p)^x\ \left[(x+1)\,\epsilon - \epsilon_p\right]^2}$$

- Beam-target interaction: MARS [6-8], 440 GeV protons, 4μs beampulse, $\sigma = 0.25$mm, 1.21×10^{13} protons on target

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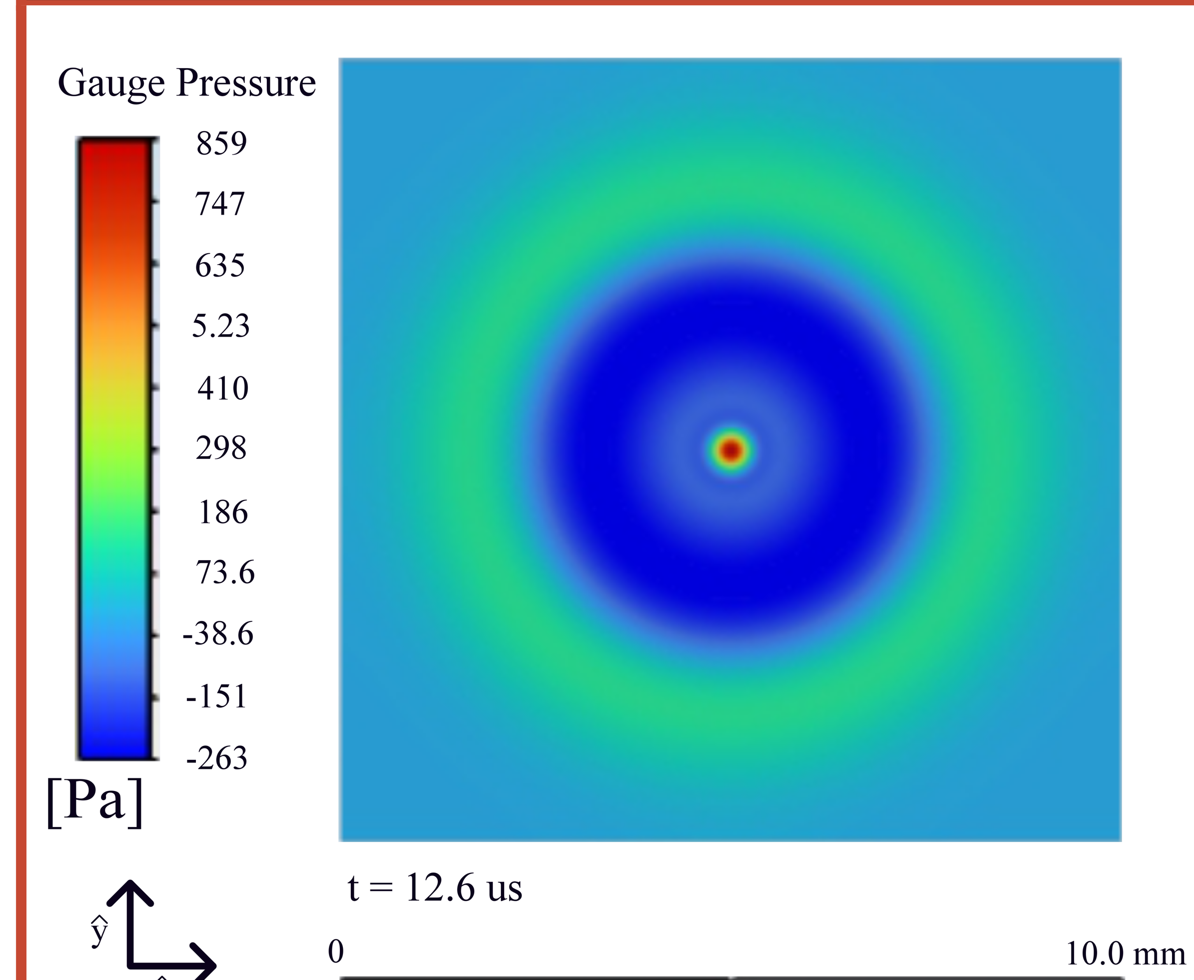
$f = 0.05$ PRESSURE CONTOURS



Contours of air pressure rise inside a $f = 0.05$ target after 12.6μs as seen from the perspective of the beam (into the page). Shows that a wave of air radiates from the center outward after beam pulse.

CONCLUSIONS

Results support hypothesis that the high density ($f = 0.20$) nanofiber target failed because of air in the pores exerting higher pressure after being heated by the beam as compared to the low density ($f = 0.05$) sample, because:

- Pressure rise at target center is about 5 times larger in $f = 0.20$ case
- Pressure wave at target center induced by beam arrives at boundary slower and more attenuated for $f = 0.20$ case
- Lowering operating pressure (simulates vacuum) causes difference in pressure rise between two cases to vanish