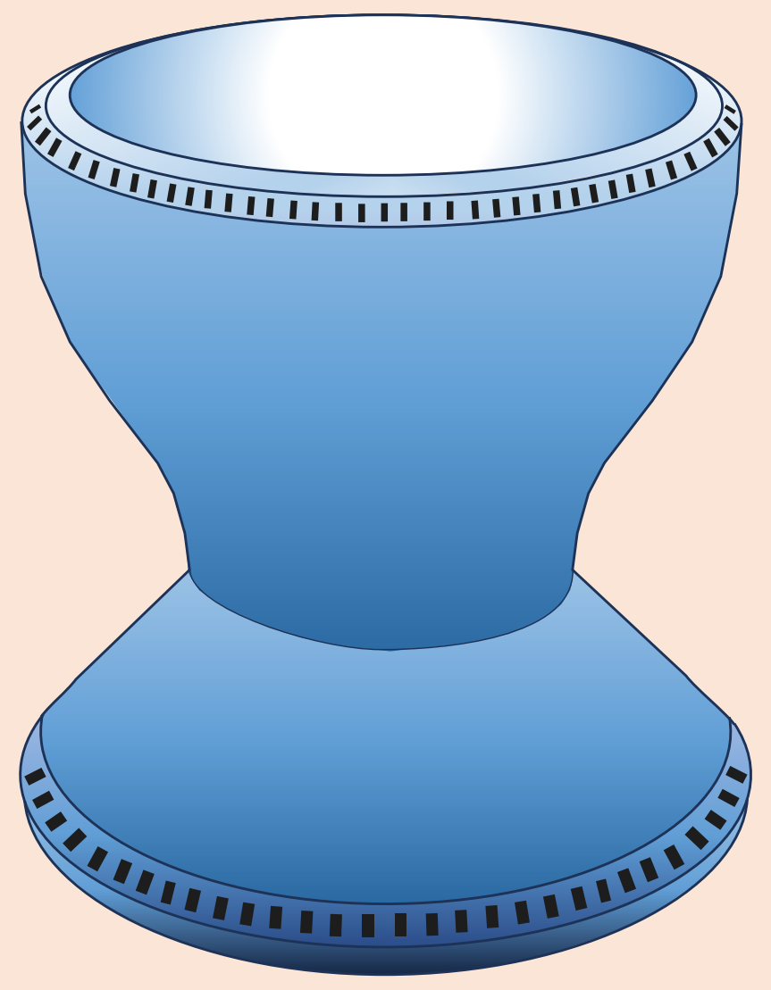
Residual Stress Mapping of GRCop-84 Fabricated by SLM

R. Minneci[1], J. Bunn[2], T. Tramel[3], C. Rawn[1]

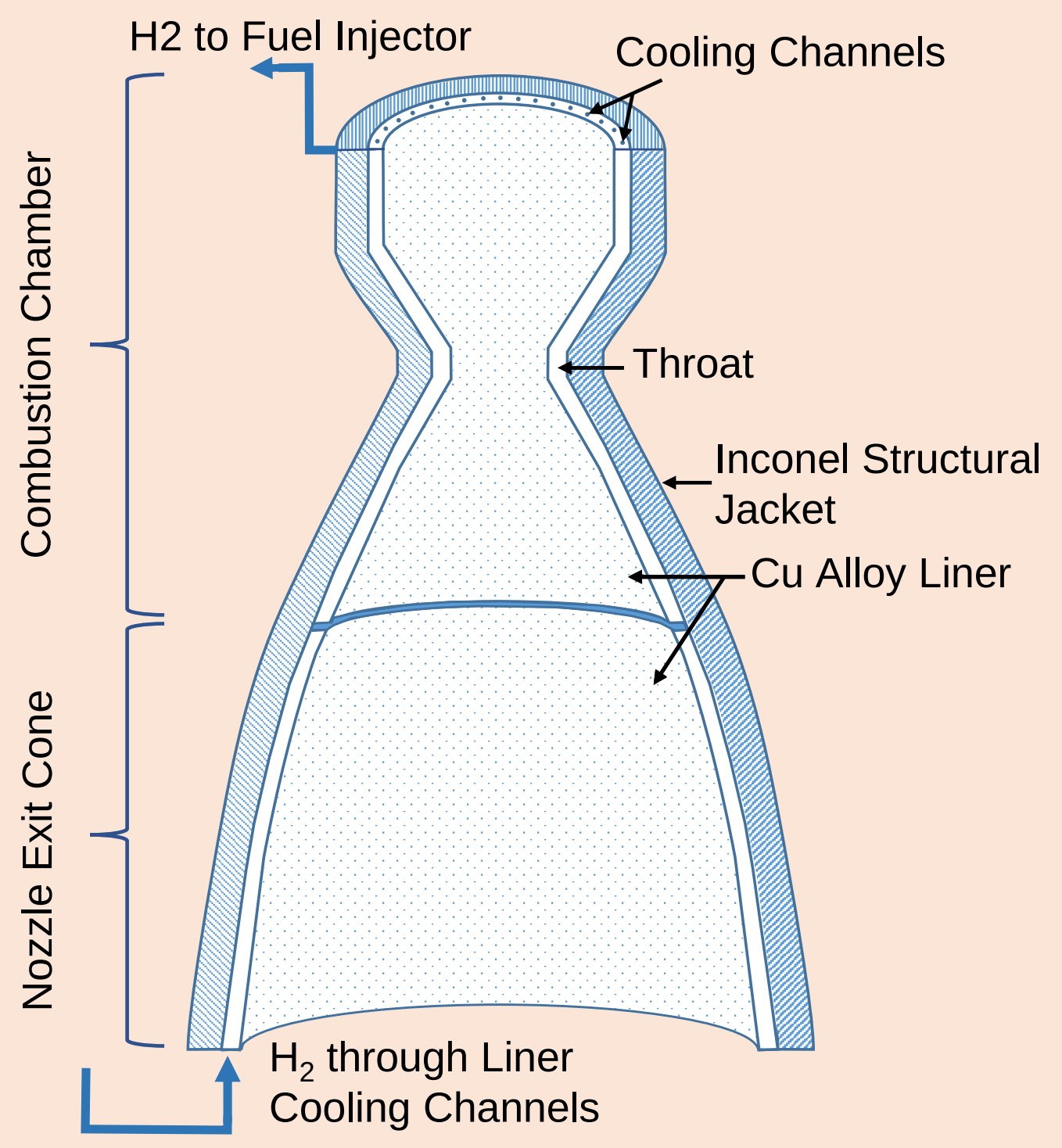
HFIR
Oak Ridge National Laboratory[2]
THE UNIVERSITY OF TENNESSEE KNOXVILLE
CENTER FOR MATERIALS PROCESSING[1]
Marshall Space Flight Center[3]

Background

GRCop-84 is a precipitation strengthened alloy composed of Cu-8 Cr-4 Nb at% with Cr_2Nb precipitates that provide dispersion and precipitation strengthening characteristics and limited solubility in the Cu matrix. The particle role of Cr_2Nb is unusual only contributing 1/3 of strengthening at high temperatures while the matrix provides the remainder. The particles mechanically and thermally stabilize the matrix retaining purity, preventing coarsening, and loss of strength. At high temperatures (50-85% Tm_{Cu}), GRCop-84 provides the best thermal and mechanical properties of available alloys.



Combustion chamber liner profile



Cross-section of relevant rocket hardware

GRCop-84 is currently developed for reusable launch vehicles, including the Space Launch System (SLS), with a focus on fabrication via additive manufacturing (AM) techniques. GRCop-84 is an optimal material for consolidating with AM. The base material is costly, the production times are long, and geometry control can considerably improve cooling efficiency. Development of AM GRCop-84 with selective laser melting (SLM) has rapidly progressed due to ease of printing and limited operator adjustment between builds, but the necessary knowledge-base of thermal history and stress state during consolidation is still under development. During typical SLM, high thermal energy transferred by the laser develops into thermal strain between volumes cooling at different rates. If the stress exceeds yield, the part plastically deforms. The success of a build is often limited by the final cooling phase of the system after a part has been fully formed and before annealing. Residual thermal strain after heat treatments can interfere with additional fabrication or end properties, so a thorough understanding of the development of stress is vital future progress of building functional hardware with GRCop-84.

Motivation

Neutron diffraction provides an accurate non-destructive method of quantifying stresses in the volume of a part through the highly penetrating nature of neutrons. Specialized instruments like ORNL's NRSF-2 or VULCAN can be utilized to characterize and map the stresses generated in the AM process by measuring the interplanar atomic spacing of a single reflection or full diffraction pattern. Stress can be calculated from interplanar strain.

- Type-1 – Macro-stress over several grains
- Type-2 – Micro-stress developed within one grain
- Type-3 – Sub-micro stress over several atomic distances

$$\varepsilon_{hkl} = \frac{d_{hkl} - d^o_{hkl}}{d^o_{hkl}}$$

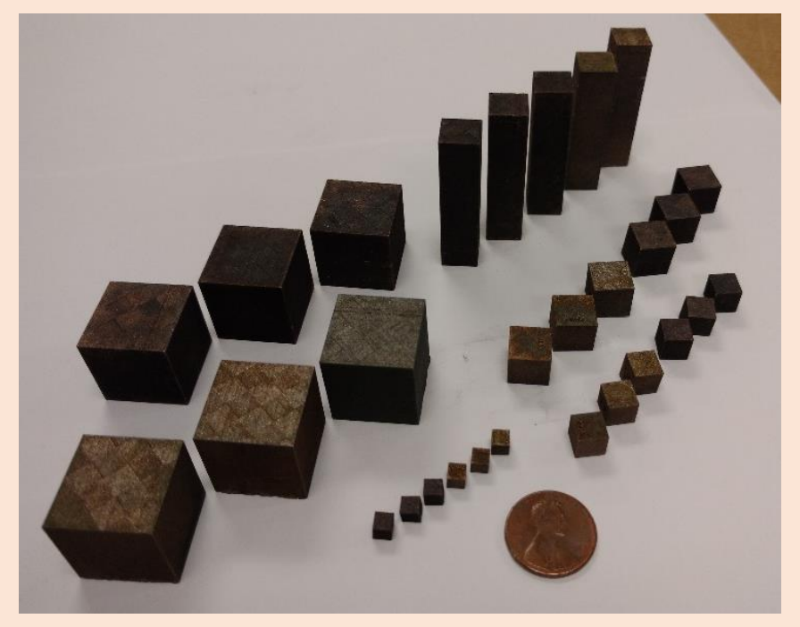
Stress/Strain Estimates

- Young's modulus, E, 111-130 GPa
- Poisson's ratio, v, of 0.29
- d_0 of 1.09152 Å

$$\sigma_{ij} = \frac{E}{1+v}\left(\varepsilon_{ij} + \frac{v}{1-2v}\left(\varepsilon^{hkl}_{11} + \varepsilon^{hkl}_{22} + \varepsilon^{hkl}_{33}\right)\right)$$

Neutron Diffraction

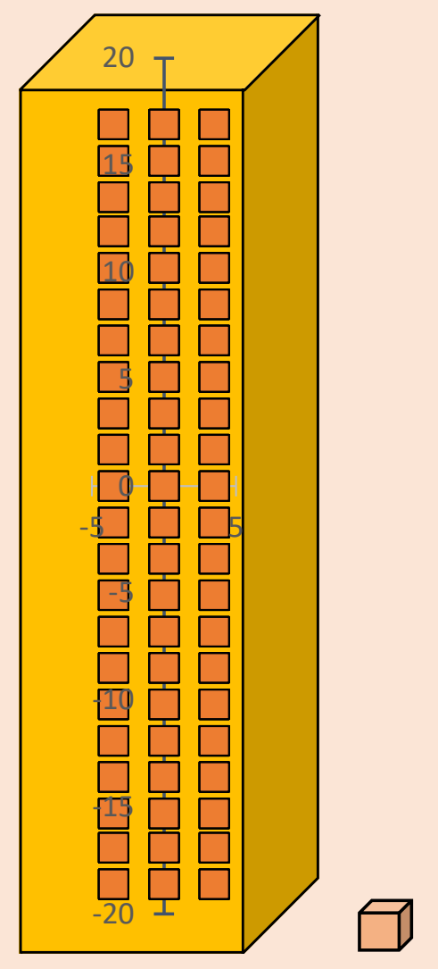
Strain Mapping Data Collected at HFIR's NRSF-2 HB2B beamline

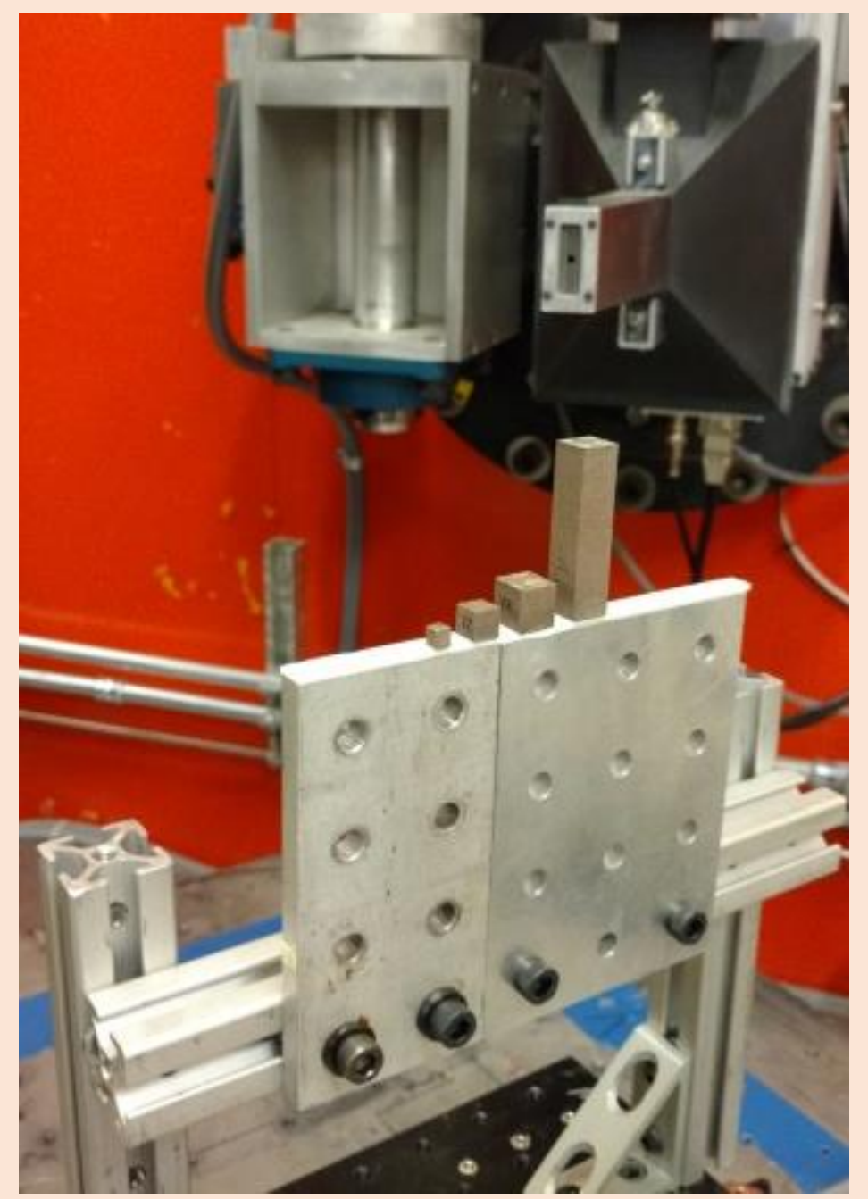


Gauge Volume: 2x2x2 mm^3
Count Time: 5 min/direction

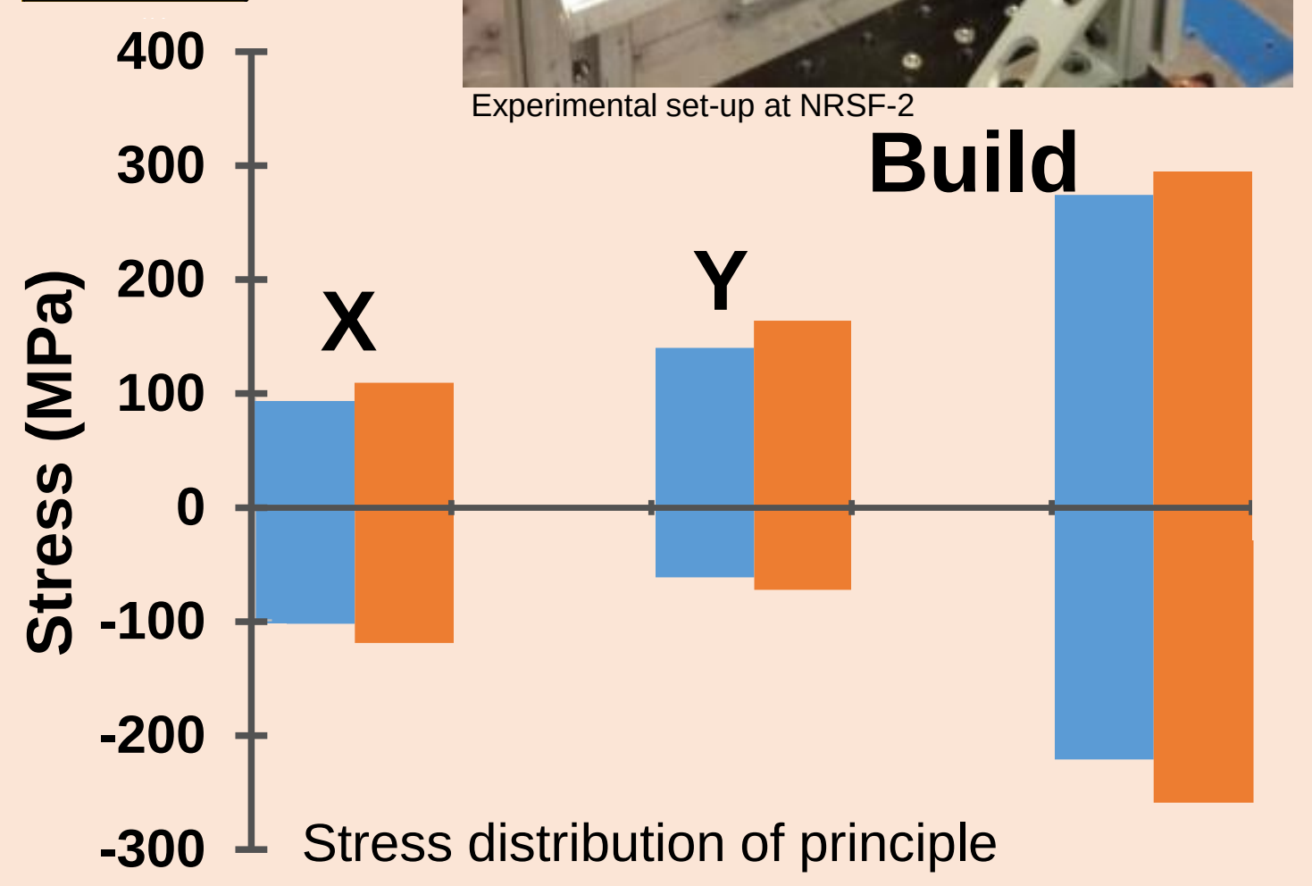
Sample Types

- **Cubes**
  - 4x4x4 mm^3
  - 7x7x7 mm^3
  - 10x10x10 mm^3
- **Pillars**
  - 10x10x40 mm^3

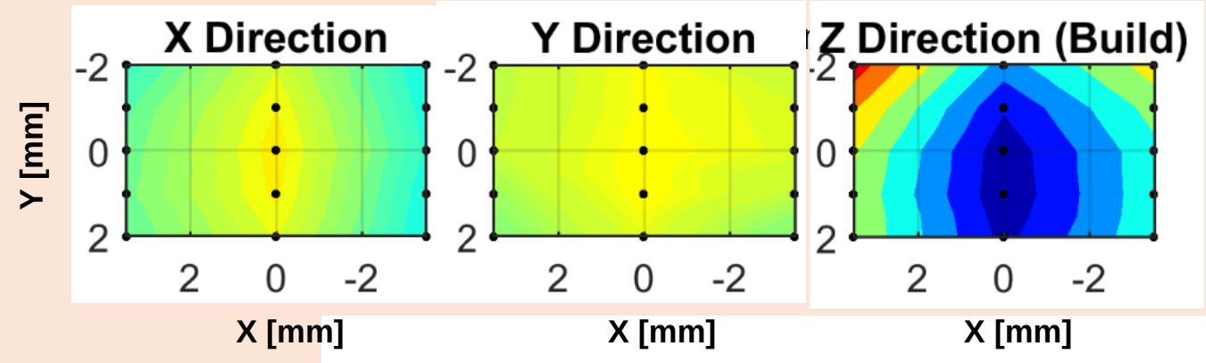




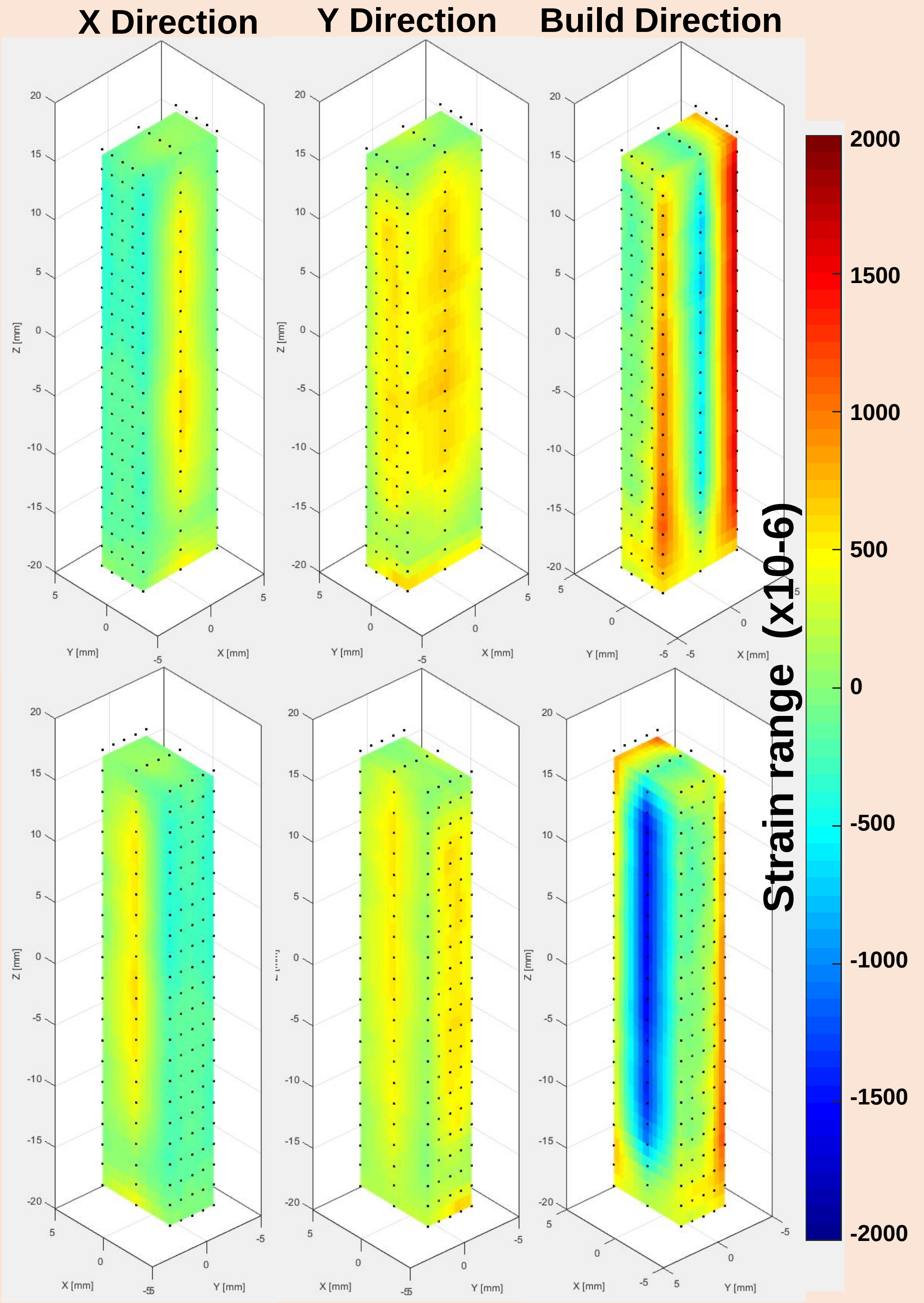
Experimental set-up at NRSF-2



Stress distribution of principle directions with arbitrary x and y



As-Built Pillar Strain (rotated views)



Pillar Strain Maps

Scale around each map represents full sample volume

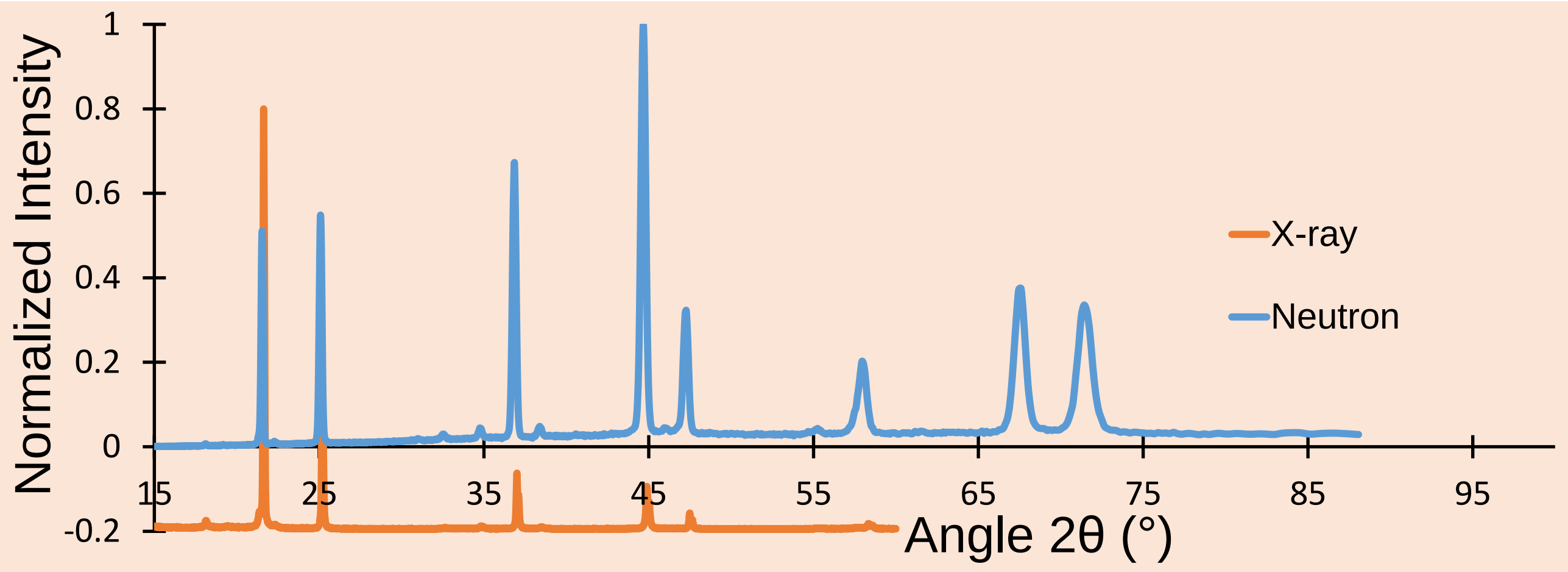
- Significant strain in build direction
- Strong compressive strain visible in center
- Some tensile strain at edges
- Stress relief from removal from build plate is visible

As-built

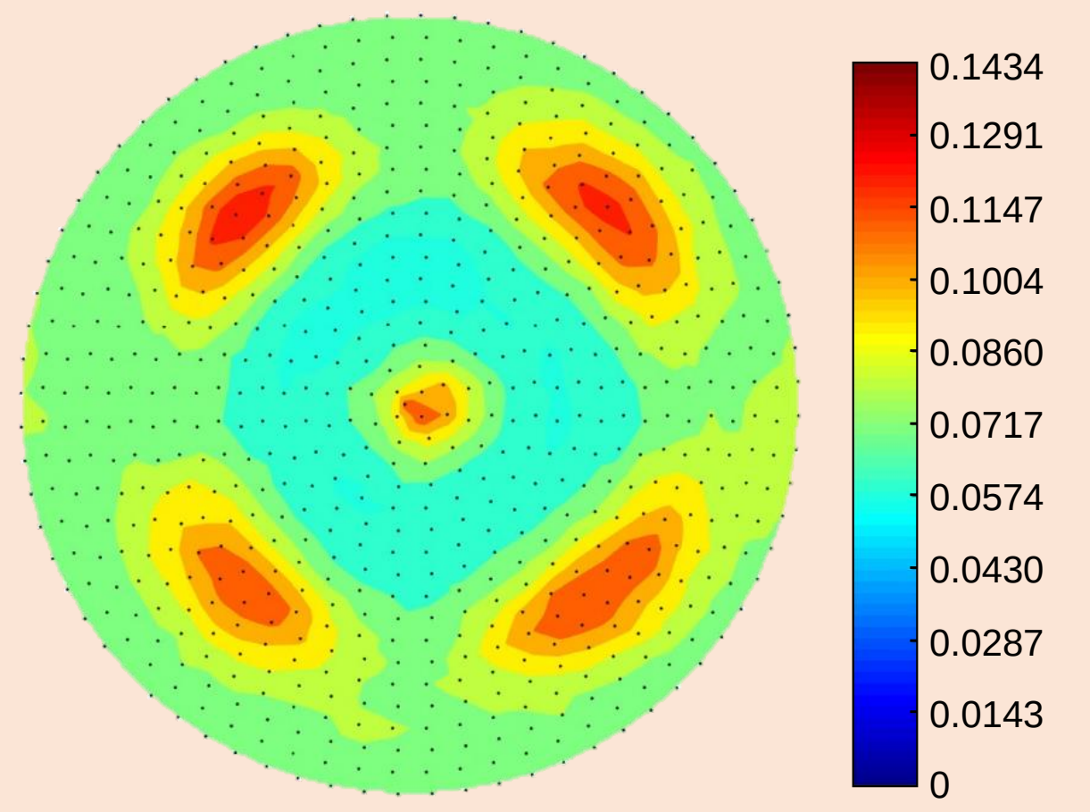
- Maximum strain: 0.002042
- Minimum strain: -0.0018

HIP

- Maximum strain: 0.0007
- Minimum strain: -0.0003



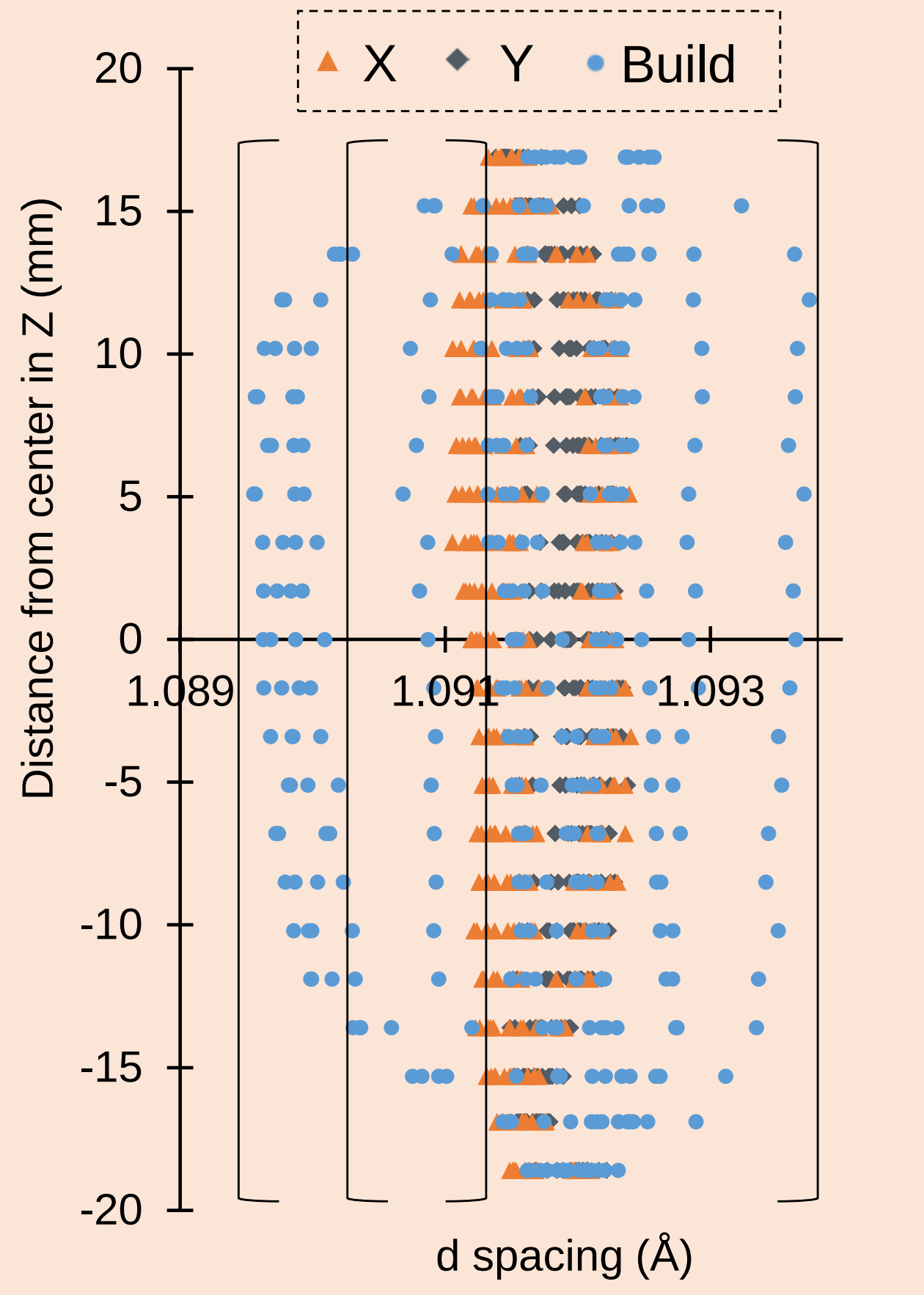
Normalized X-ray and neutron diffraction data of GRCop-84 with XRD offset by for visualization



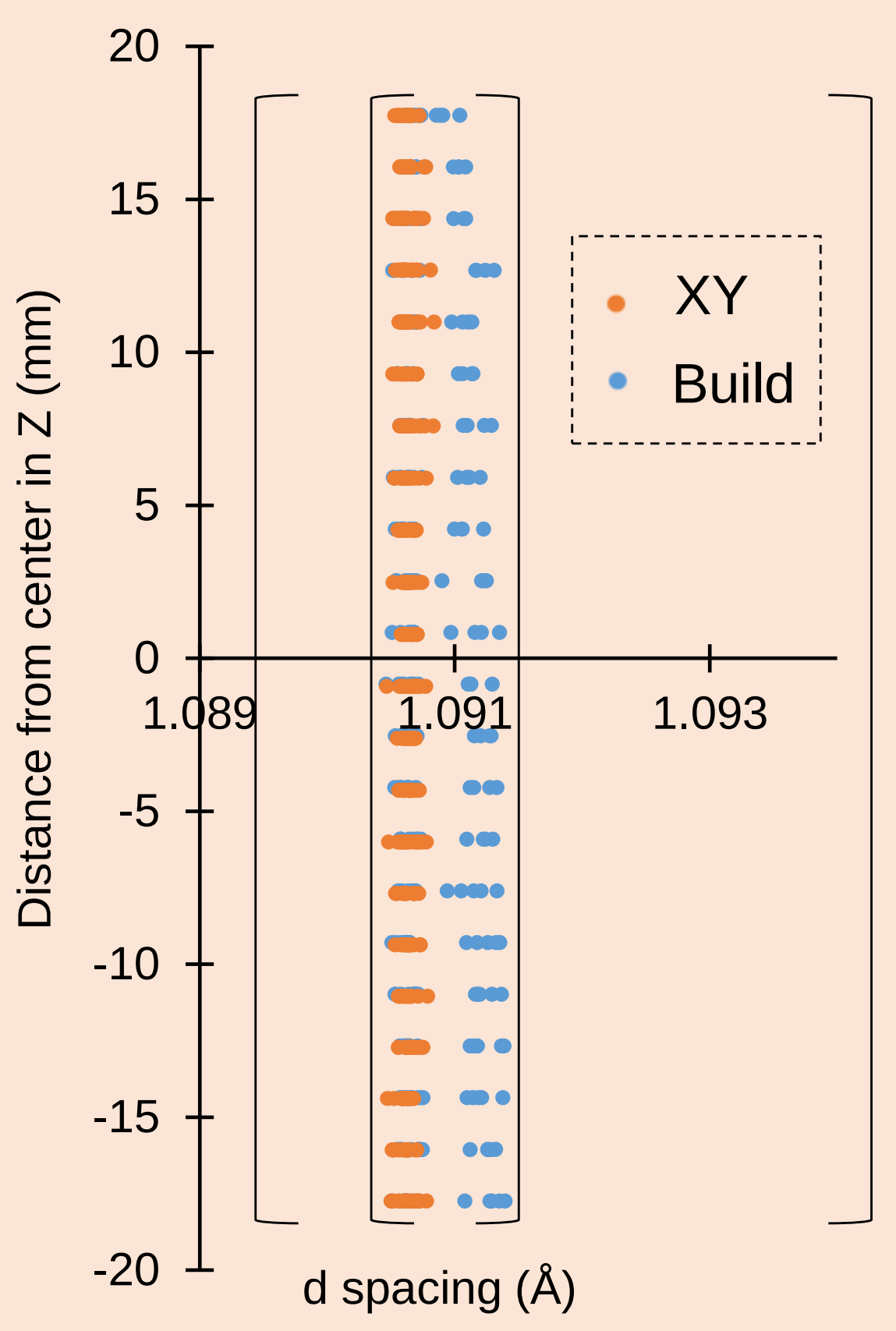
Texture Data (220) as-built GRCop-84

Effects of HIP

- High levels of strain present in as-built parts exceeding nominal yield strength limits
- HIP envelope of strain compared to as-built is greatly reduced
- HIP visibly introduces a reduction to the overall d-spacing

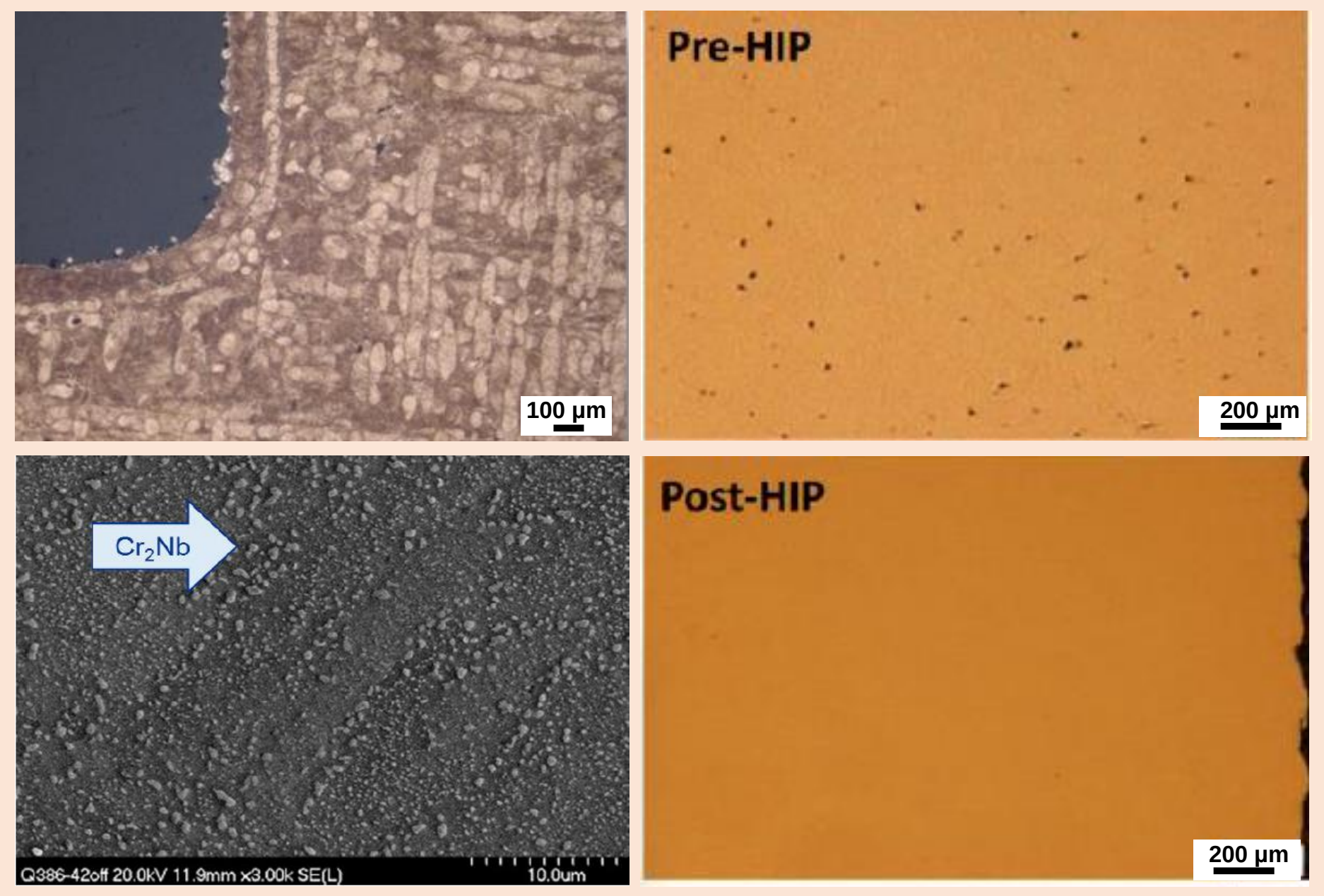


As-built Strain Distribution



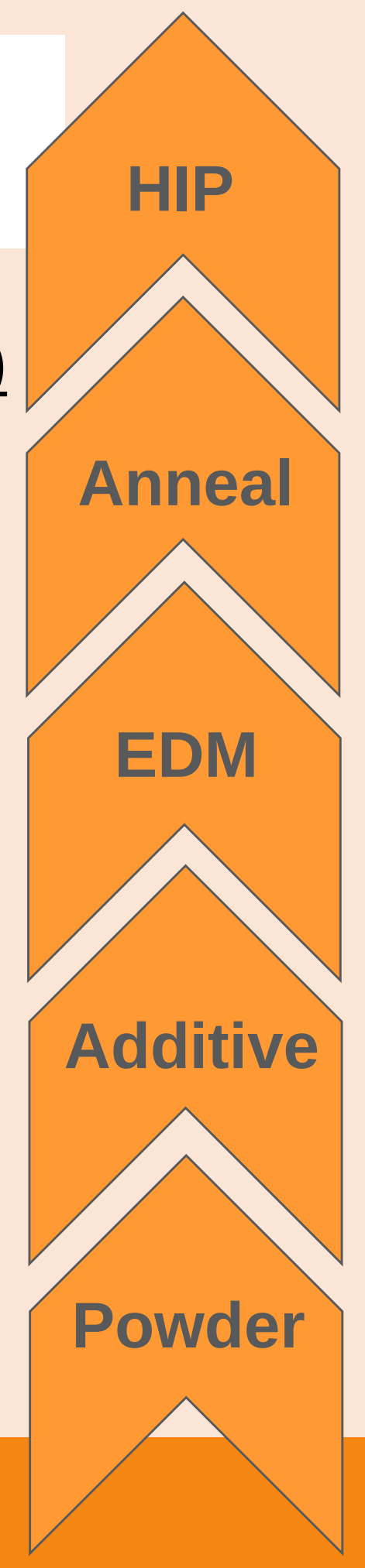
HIP Strain Distribution

Microstructure Evolution



Images reproduced from: Gradl, Paul R., et al. [1]

- Electrical Discharge Machining (EDM)
  - Removes part from build plate
  - Relieves stress at interface
  - Excessive stress can result in deformation
- Hot Isostatic Pressing (HIP)
  - Parts are annealed prior to HIP
  - HIP is conducted well above annealing temperature and high pressure
  - Reduces porosity
  - Homogenizes microstructure
  - Parts are assumed to be fully stress relieved



Conclusions

Strain maps of pillar sample indicate large compressive strain in the center balanced by tensile strains towards the edges in the build direction, which is typical of metal expansion and cooling. Literature values and a recently determined elastic modulus obtained from compression tests are higher than originally anticipated, and using this higher modulus results in pillar stresses that would substantially exceed the yield stress. The material has not yielded despite the strain, suggesting that the microstructure might be responsible for this behavior.

Previously, it was assumed that the HIP process effectively eliminates the residual strain within the parts, but significant, albeit small, stresses remain. Additionally, the HIP process appears to interfere further with the microstructure as the d_0 and even elastic modulus seem to change slightly. While the elastic modulus may be statistical variance, the d_0 has been consistently reduced between samples.

Future work includes obtaining an accurate elastic modulus for principle build directions to further refine stress values and investigate modulus change as a function of processing. Metallography, EBSD, SEM, are planned for samples exposed to the beam to provide direct supplemental microstructure information.

References

1. Carter, Robert, et al. "Evaluation of GRCop-84 Produced Using Selective Laser Melting." White paper (2015).
2. Carter, Robert, et al. "Materials Characterization of Additively Manufactured Components for Rocket Propulsion." (2015).
3. "Neutron Scattering Lengths and Cross Sections." Neutron Scattering Lengths and Cross Sections. NIST, 07 Jan. 2013. Web. 27 Sept. 2016.
4. Ellis, David L. "GRCop-84: A high-temperature copper alloy for high-heat-flux applications." (2005).
5. Gradl, Paul R., et al. "Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications." *53rd AIAA/SAE/ASEE Joint Propulsion Conference*. 2017.
6. Loewenthal, William and Ellis, David. "Fabrication of GRCop-84 Rocket Thrust Chambers." (2005).
7. Thoma, D. J., Chu, F., Peralta, P., Kotula, P. G., Chen, K. C., & Mitchell, T. E. (1997). Elastic and mechanical properties of Nb (Cr, V) 2 C15 Laves phases. *Materials Science and Engineering: A*, *239*, 251-259.
8. McMahan, Tracy. "NASA 3-D Prints First Full-Scale Copper Rocket Engine Part." *NASA Marshall News*. NASA, 30 July 2015. Web. 13 Dec. 2016.
9. Ellis, David L. "GRCop-84: A high-temperature copper alloy for high-heat-flux applications." (2005).

Acknowledgements

RPM would like to acknowledge partial support though the Manufacturing and Materials Joining Innovation Center (Ma2JIC) University of Tennessee, Knoxville site. Ma2JIC is funded by the National Science Foundation (NSF) through the Industry/University Cooperative Research Center (I/UCRC) program award number IIP 1540000.

A portion of this research used resources at the High Flux Isotope Reactor and Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.

THE UNIVERSITY of TENNESSEE
KNOXVILLE