In-situ Mechanical Neutron Diffraction Loading Characteristics of GRCop-84 Fabricated by SLM

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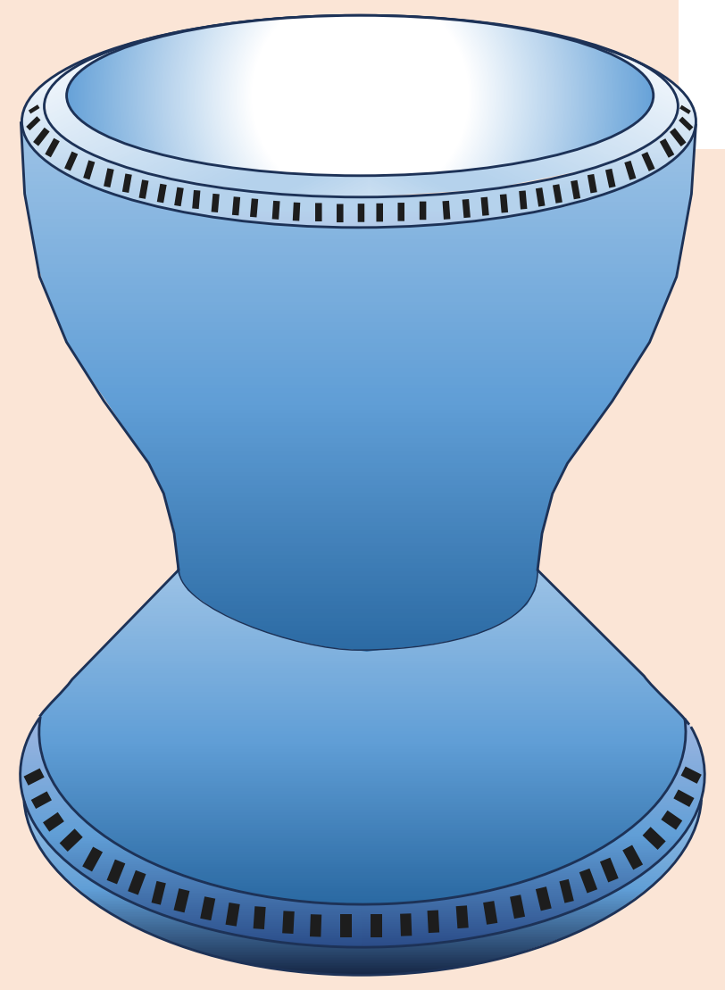
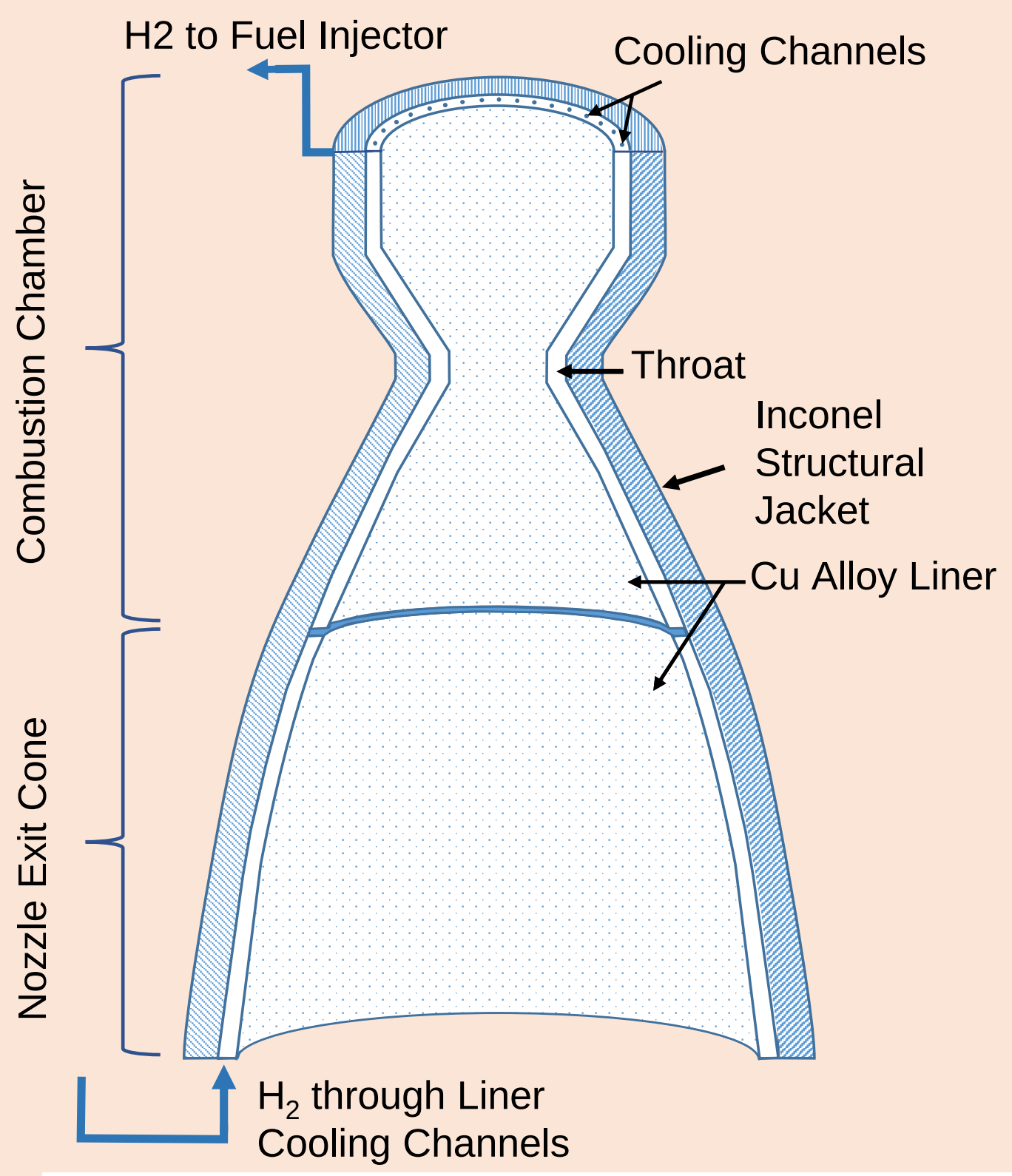
Background

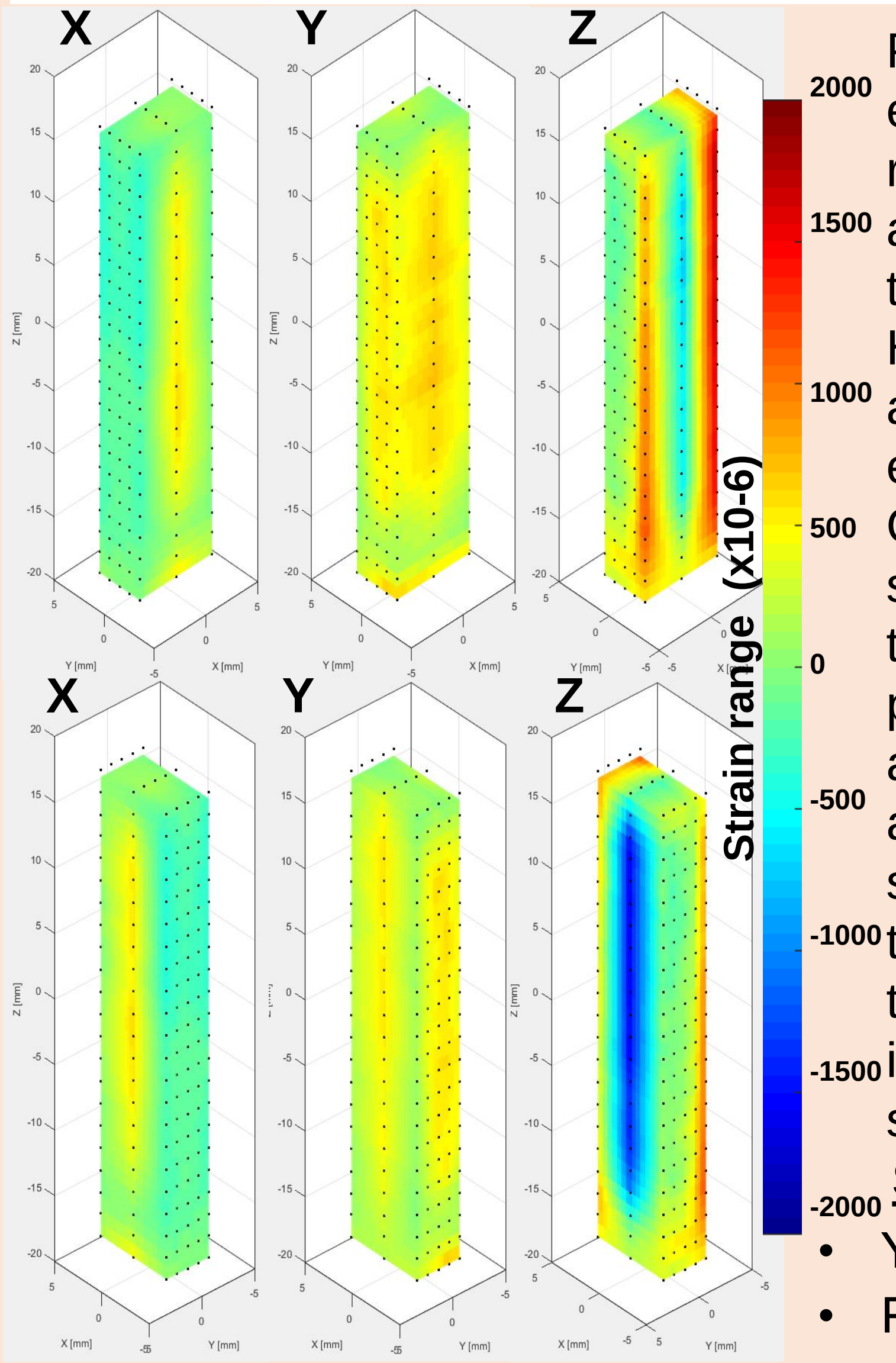


GRCop-84 is a precipitation strengthened alloy composed of Cu-8 Cr-4 Nb at% with Cr_2Nb precipitates that provide dispersion and precipitation strengthening characteristics and limited solubility in the Cu matrix. The particle role of Cr_2Nb (C15 Laves) is unusual only contributing 1/3 of strengthening at high temperatures while the matrix provides the remainder. The particles mechanically and thermally stabilize the matrix retaining purity and 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.



GRCop-84 is currently in development for reusable launch vehicles including the Space Launch System (SLS) with a focus on fabrication with 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 more 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 builds is still under development.

Motivation



Strain mapping of as-built GRCop-84 Cu (311) obtained on HFIR's NRSF-2 showing arbitrary x, y, and z strain in two orientations

Previous neutron diffraction experiments on NRSF-2 revealed high residual stress in the Cu matrix (311) of as-built SLM GRCop-84. Higher even than reported yield strain values. However, GRCop-84 is a two-phase alloy, and almost no literature exists to explain stress evolution in SLM GRCop-84. It is critical to understand stress sharing behavior between the two phases to accurately assess previous and future neutron results on a single peak, and the future of the alloy. Literature suggests 1/3 Orowan strengthening and 2/3 Hall-Petch for traditionally fabricated GRCop-84, but this might not be the case with SLM as its grain structure should be significantly different [1].

Stress/Strain Estimates/Assumptions

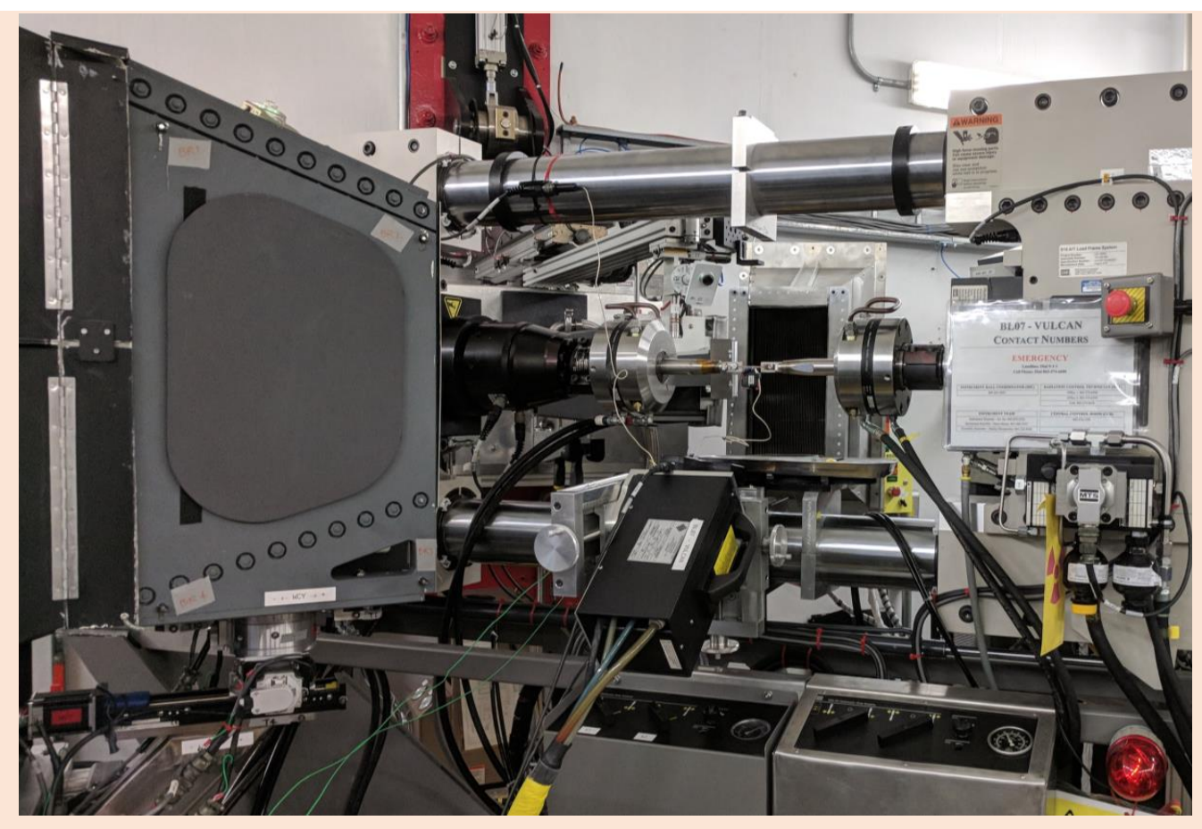
- Young's modulus, E, 111-130 GPa
- Poisson's ratio, υ, of 0.29
- d_0 of 1.09152 Å

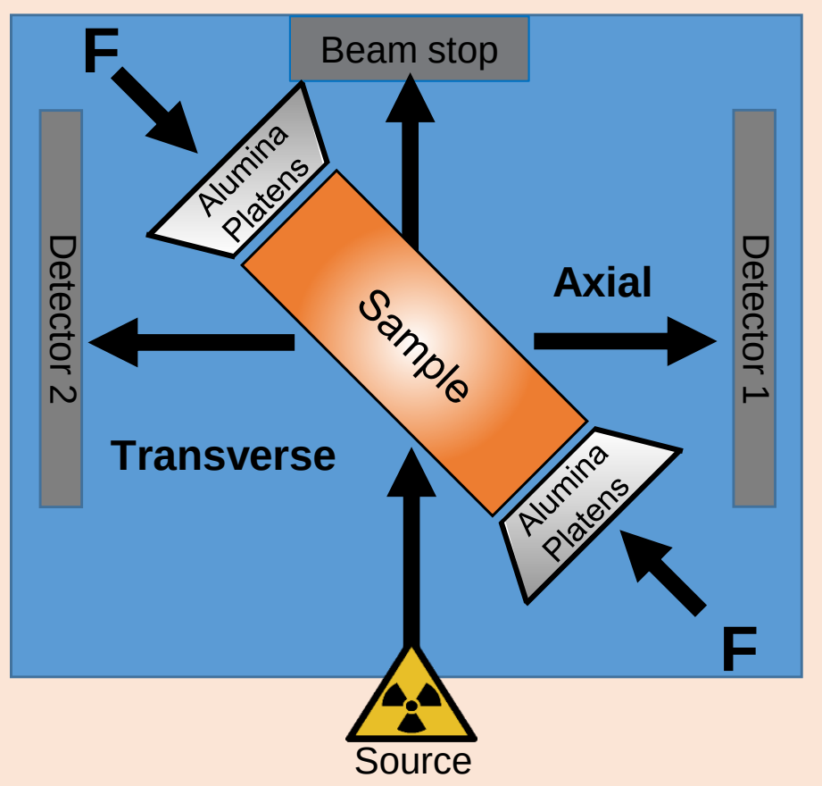
$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{hkl}^{o}}{d_{hkl}^{o}}$$

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

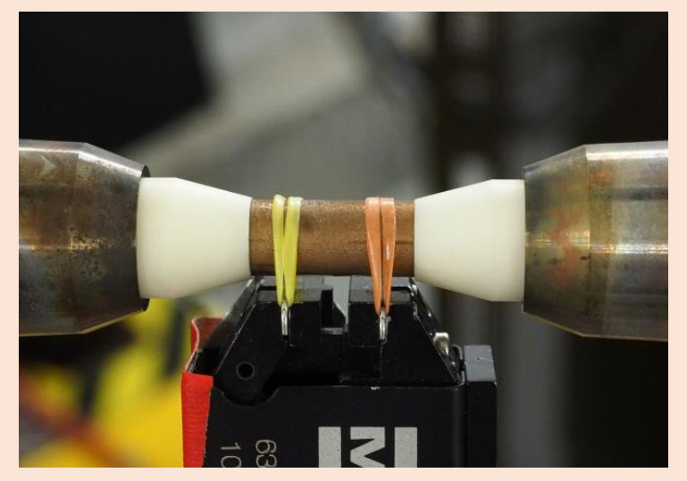
Neutron Diffraction HIP vs As-Built

Sample & VULCAN Environment



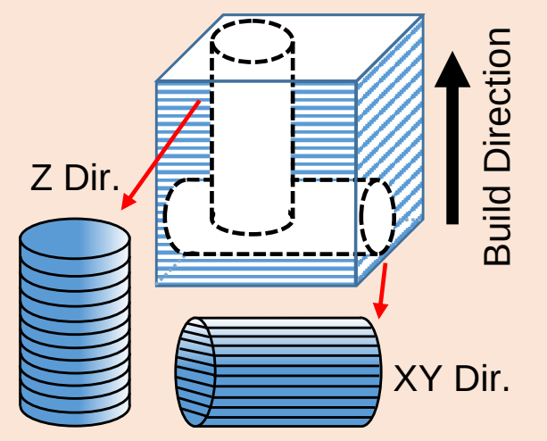


- ❖ **SNS VULCAN beamline**
  - ❖ TOF diffraction
    - ❖ Large d-space range
    - ❖ Can diffract full sample
    - ❖ Axial and transverse
  - ❖ Full scale MTS load-frame



Compression samples EDMed from bulk cubes

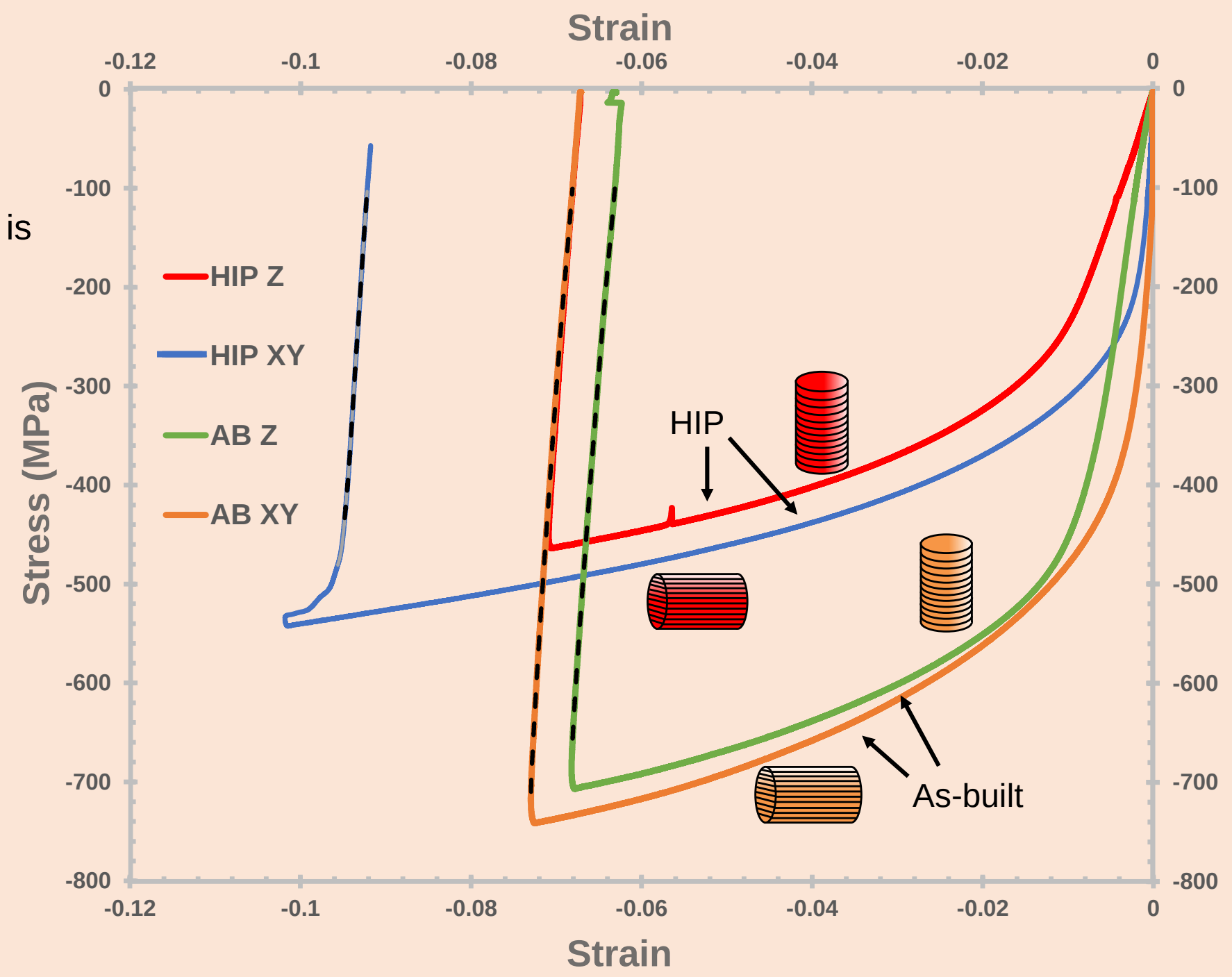
- ❖ XY and Z, but only XY is presented here
- ❖ 8 mm diameter
- ❖ 16 mm length



Elastic Modulus (unloading)

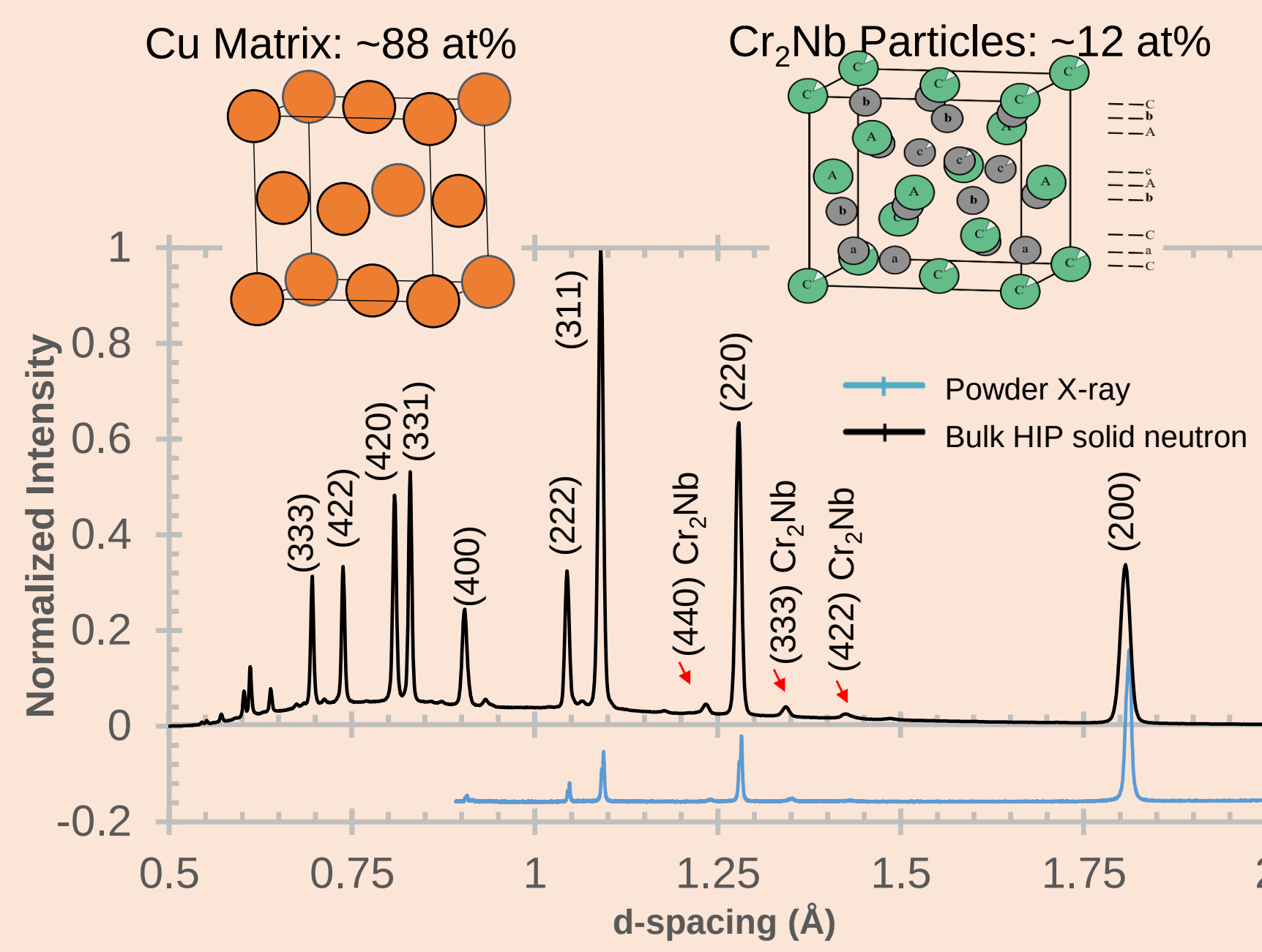
AB XY: 123 GPa HIP XY: 119 GPa
AB Z: 111 GPa HIP Z: 130 GPa

(all R^2 > .99)



Macro stress strain compression curves from MTS load-frame

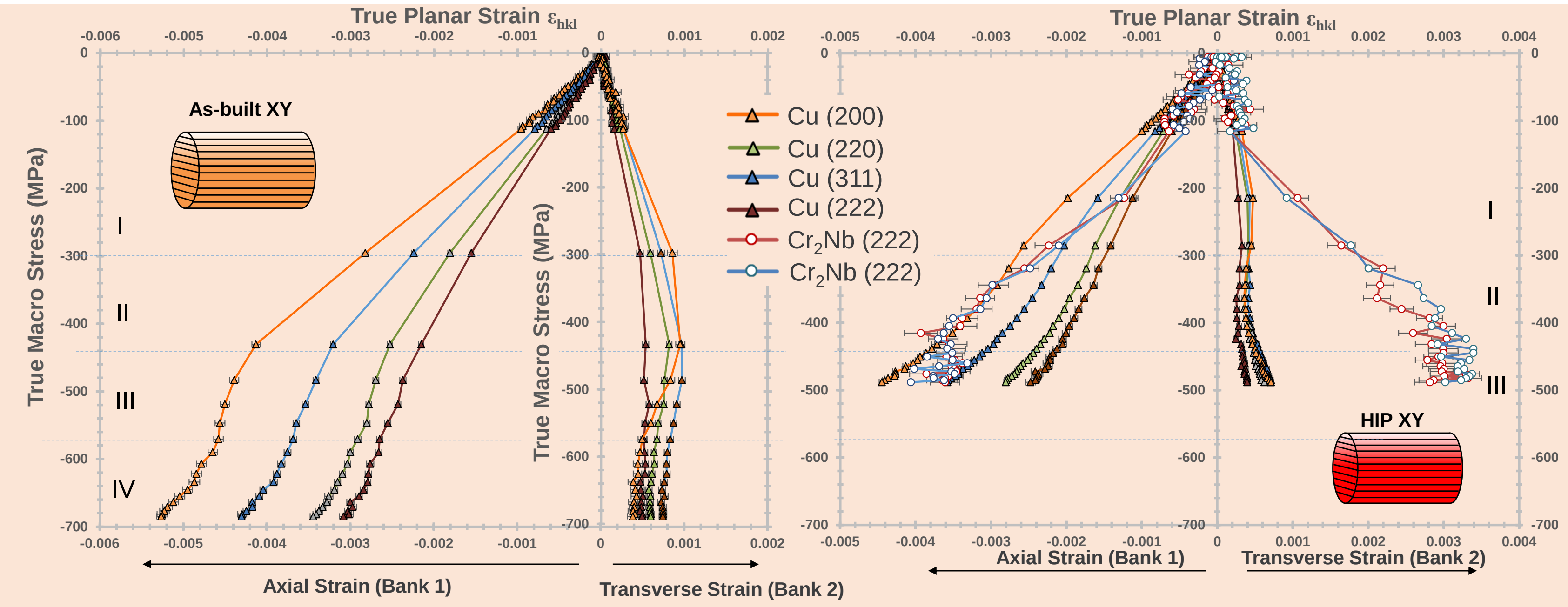
Diffraction Profile



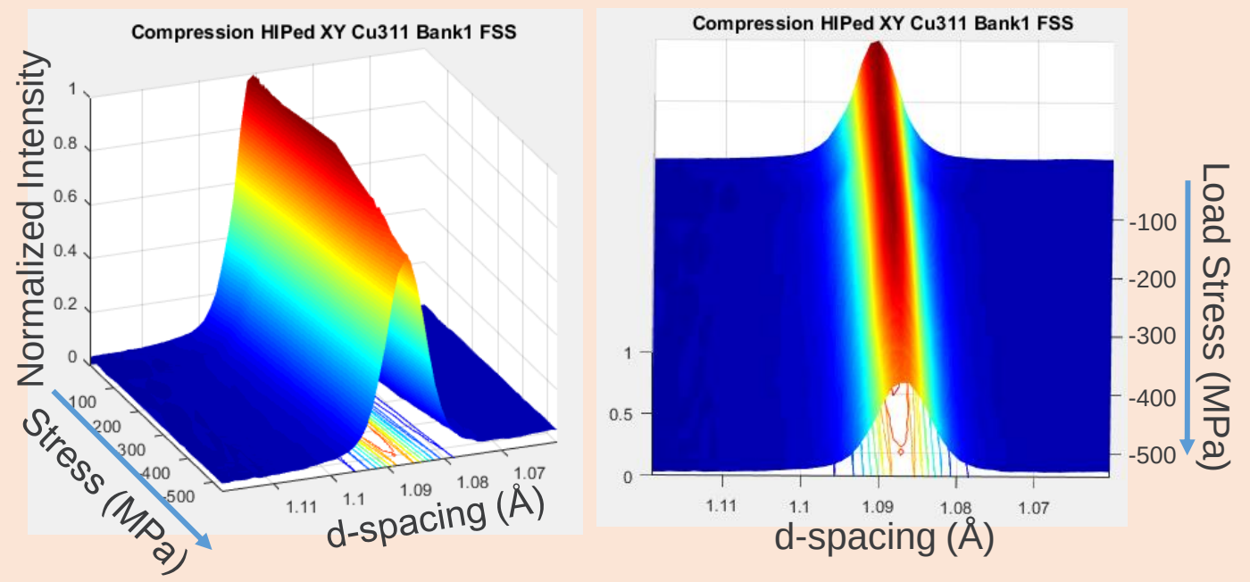
Lattice Parameters
Cu a = 3.615 Å
Cr_2Nb a = 6.991 Å

- ❖ Limited as-built Cr_2Nb diffraction
  - ❖ Effect of strain, crystallite size, & texture
- ❖ 0.1% to 12% phase %
  - ❖ As-built to HIP

Planar strain

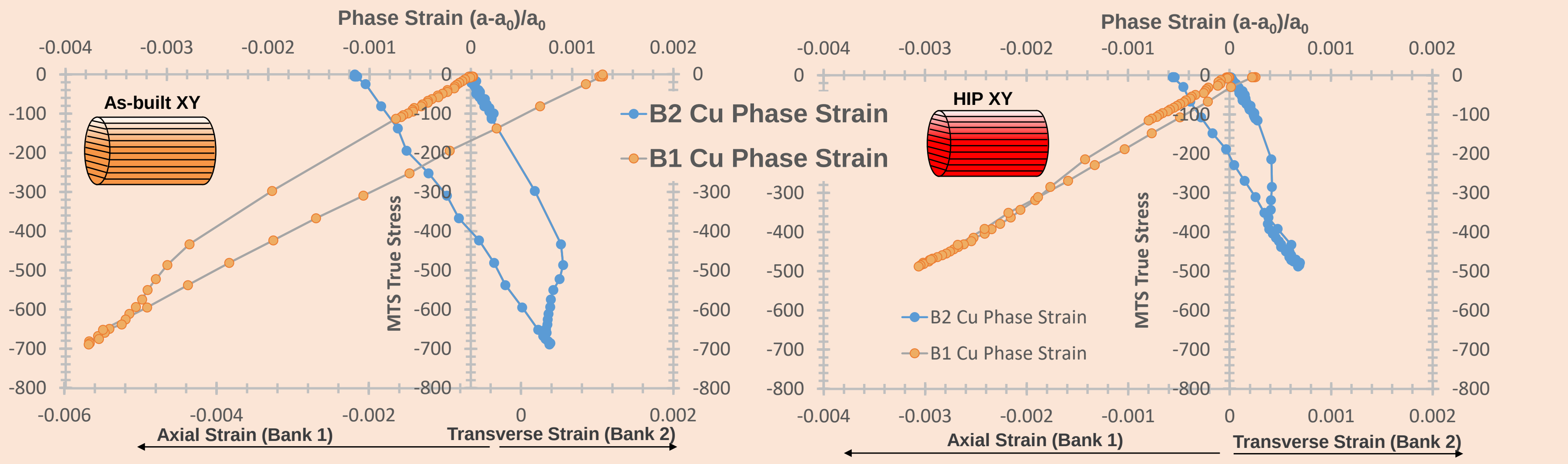


- ❖ Three distinct regions (I-III) of slope changes in Cu matrix
  - ❖ Should correlate to different yielding behavior between planes and phases
  - ❖ Cu (200) carries the most stress while (222) carries the least
- ❖ Cr_2Nb peaks are too broad to plot in as-built condition
  - ❖ Cr_2Nb increases rapidly in strain in region II
- ❖ As-built and HIP have significantly different behavior in transverse direction
  - ❖ Could be effect of matrix or precipitate change after HIP

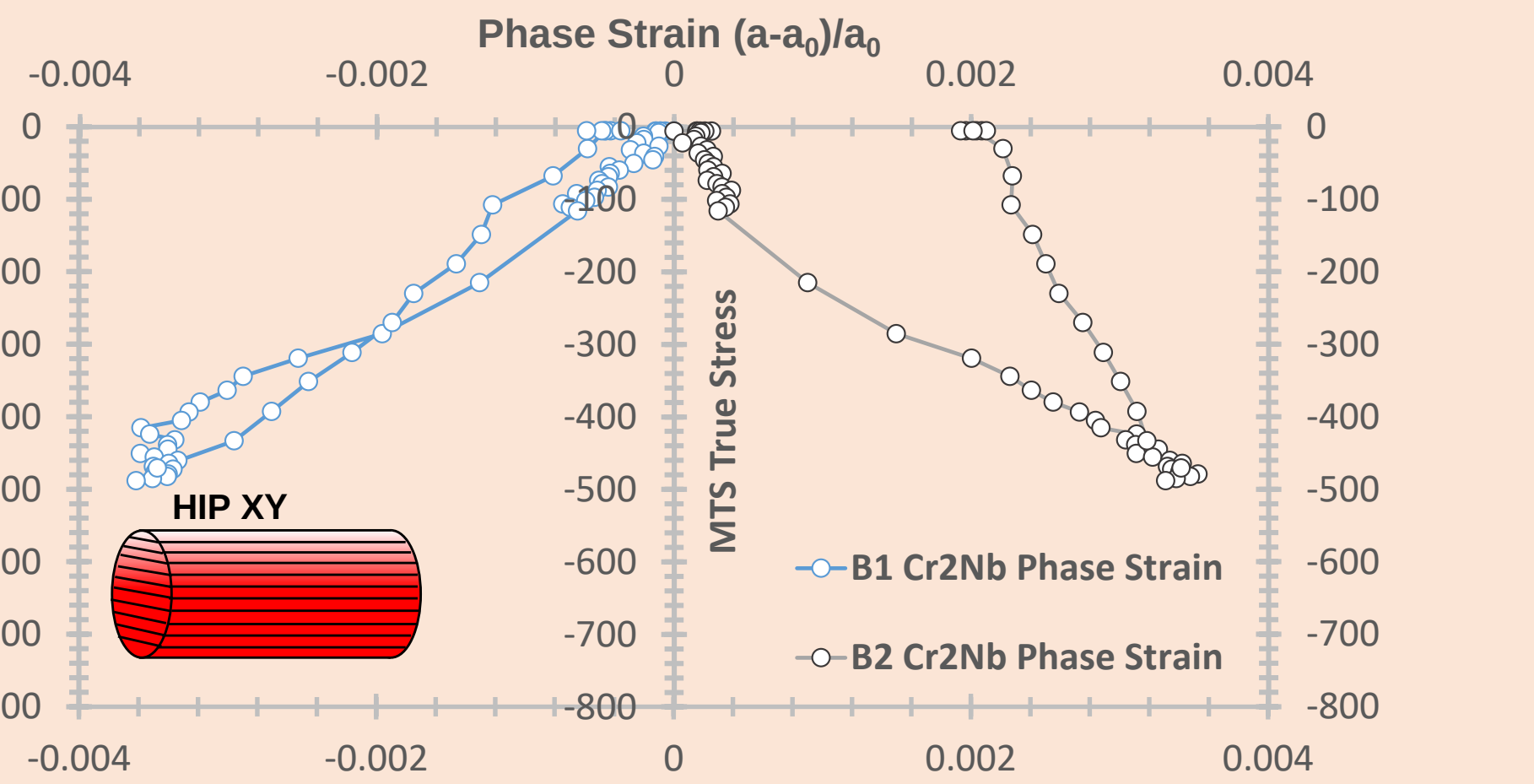


Matlab generated waterfall plots of HIP XY Cu (311)

Phase Strain



- ❖ Phase strain calculated from lattice parameters estimated by sequential Rietveld refinements
- ❖ Useful for estimating Poisson ratios and diffraction elastic constants (DEC), E_i
- ❖ Sufficient statistics for Cu in both conditions, but Cr_2Nb is limited in the as-built
- ❖ Cu phase's negative residual stress after deformation appears to be balanced by Cr_2Nb's positive residual stress
  - ❖ Significant transverse strain in Cr_2Nb



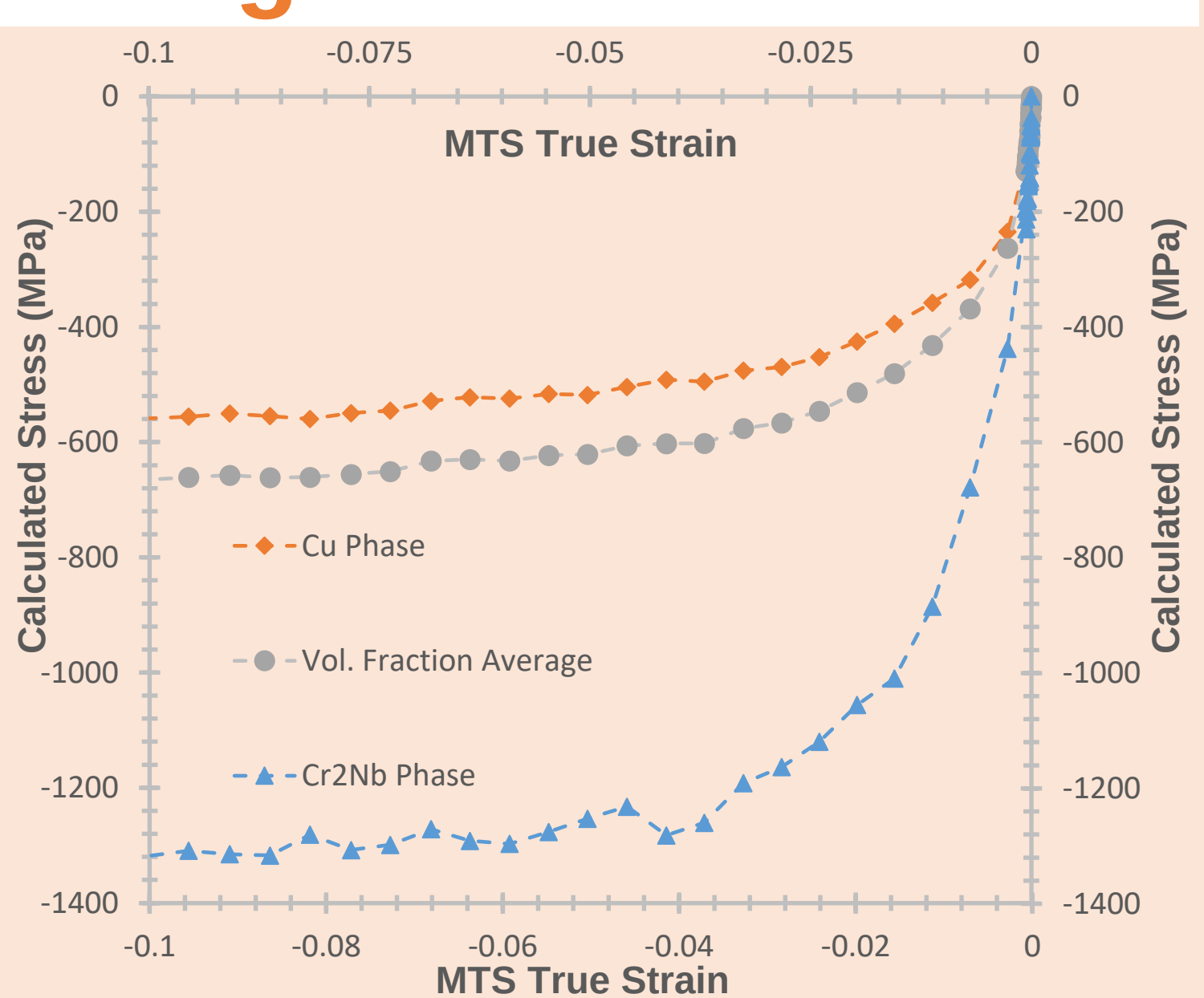
Phase Partitioning

$$\upsilon = \frac{da_{B2}}{da_{B1}} = \frac{\Delta a_{B2}}{\Delta a_{B1}}$$

		As-built XY		HIP XY	
		Cu	Cr2Nb	Cu	Cr2Nb
Poisson ratio, υ	Load	0.331	---	0.35	-0.49
	Unload	0.365	---	0.38	-0.45
	Average	0.348	---	0.365	-0.47
DEC (GPa)	Load	147	---	141	162
	Unload	129	---	146	162
	Average	138	---	143.5	162

- ❖ Poisson ratio estimated from comparison of axial and transverse lattice parameters
- ❖ DEC estimated from elastic regions
- ❖ **HIP XY Partitioning**
- ❖ Both phases share similar elastic regions
- ❖ Cr_2Nb rapidly strain hardens until ~1200 MPa
- ❖ Cu elongates steadily with limited hardening after ~600 MPa
- ❖ As-built Cr_2Nb statistics insufficient to plot, Cu shows similar trends to HIP

f_{Cu}≈0.86



$$\sigma_i = \frac{E_i}{(1+\nu_i)(1-2\nu_i)}\{(1-\nu_i)\varepsilon_{i,11} + \nu_i(\varepsilon_{i,22} + \varepsilon_{i,33})$$

$$\sigma_{average} = \sigma_{Cu} * f_{Cu} + \sigma_{Cr_2Nb} * (1 - f_{Cu})$$

Conclusions

Previous strain mapping showed evidence of strong compressive and tensile Cu matrix strain in the (311) which as the primary matrix component led to the assumption that the macro-stress behavior was similar; however, the stress partitioning behavior shown in this in-situ experiment requires re-evaluation of the strain mapping data. Wherever there is residual thermal strain in the matrix, there is likely balancing strain in the Cr_2Nb phase that reduces the overall stress in these areas.

The as-built's Cr_2Nb particles are significantly smaller and less uniformly distributed than the HIP condition and exhibits more brittle behavior. These could be accounted for by the Cr_2Nb being in a more unstable or less crystalline form than after it has been HIPed, or there could be a significant fraction of dissolved Cr_2Nb in the Cu matrix.

Future work includes analysis of EBSD on primary samples, further metallography, in-situ HTXRD, and in-situ mechanical EBSD to observe grain interactions in collaboration with current neutron data.

References

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