Nb_3Sn and Cu loading stress evolution in Rutherford cable stacks as a function of externally applied pressure

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Second workshop “Nb_3Sn Rutherford cable characterization for accelerator magnets”

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Outline

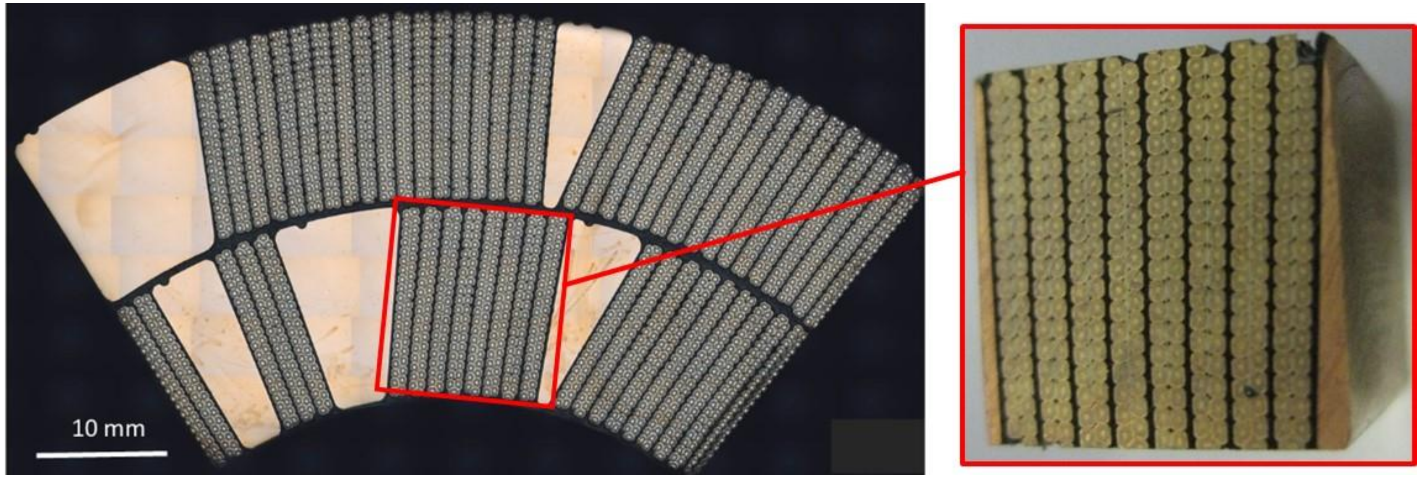
- Driving questions
- Loading strain and stress measurements in Nb_3Sn Rutherford cable stacks
  - Samples
  - Combined stress-strain and neutron diffraction measurements
- Nb_3Sn lattice strain and stress in 11 T dipole cable stacks
  - Transverse compressive loading
  - Loading in axial direction
- Discussion and conclusion

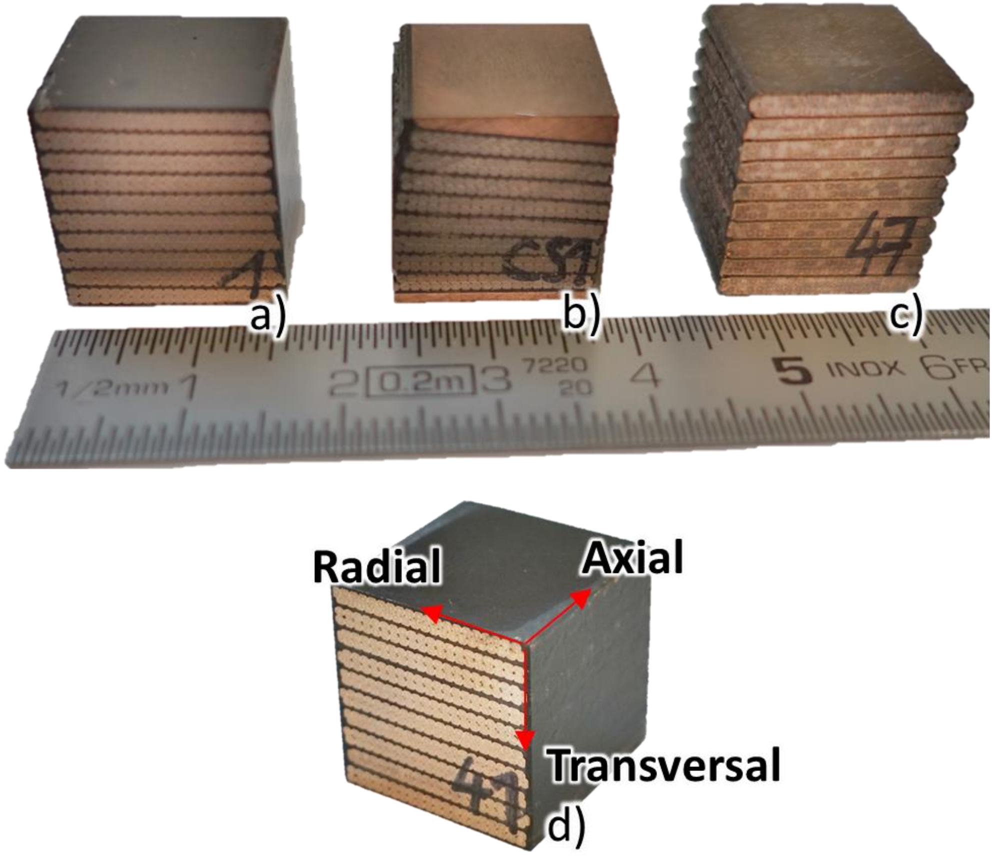
Driving questions

- What is the stress-strain behaviour of Nb_3Sn coils in accelerator magnets?
- What are the Nb_3Sn and Cu loading stresses at 150 MPa macroscopic transverse pressure (the assumed Nb_3Sn cable irreversible stress limit)?
- What would be the ideal mechanical properties of the impregnation material?

Samples for applied strain and stress measurements

- All samples are made of Nb_3Sn 11 T dipole Rutherford cables with mica and S2 glass insulation.
- (a) Ten-stack samples impregnated with epoxy resin CTD-101K with different epoxy volume fractions.
- (b) Cubes machined out of 11 T dipole conductor block, containing 8 Rutherford cables and part of the adjacent coil wedges to compensate for the cable keystone angles.
- (c) Non impregnated ten-stack samples.

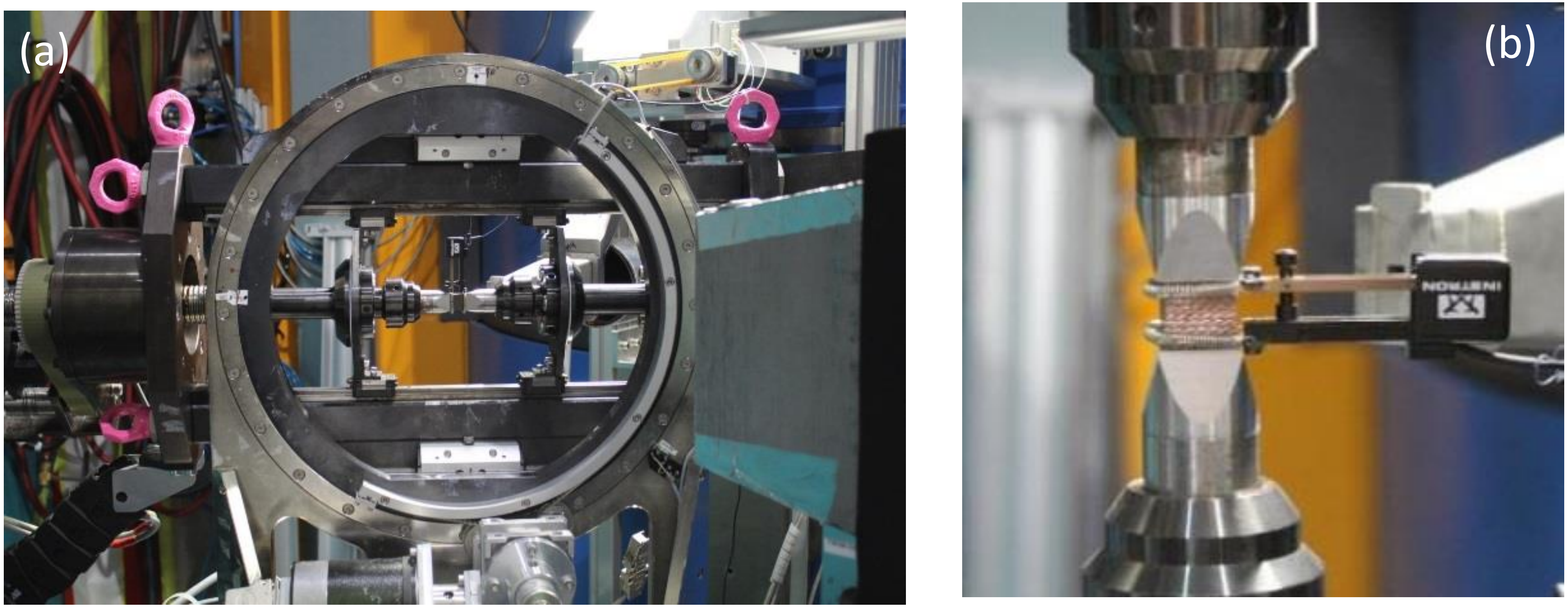




From Felix Wolf et al, "*Effect of epoxy volume fraction on the stiffness of Nb_3Sn Rutherford cable stacks*"

Set-up for combined stress-strain and diffraction measurements

- Lattice strain in Nb_3Sn and Cu is measured by neutron diffraction in the three principal stress directions upon compressive loading.
- Gauge volume 5×5×5 mm^3 in the center of the samples.
- Load frame combined with an Eulerian cradle enables rotation of the sample load axis with respect to the scattering geometry is integrated in the Stress-Spec neutron diffraction beamline of MLZ.
- Macroscopic sample strain is measured simultaneously with an extensometer (Instron 2620-602 with a gauge length of 12 mm).



(a) Load frame mounted in Eulerian cradle in the Stress-Spec beamline. (b) Ten-stack sample and extensometer mounted for combined stress-strain and diffraction measurements.

Calculation of loading strain and stress

- The Nb_3Sn and Cu loading strains caused by the externally applied stress are determined from the Nb_3Sn (321) and Cu (220) scattering angles.
- Loading strains in transverse, axial, and radial directions are calculated with respect to the assumed stress free scattering angle.

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0,hkl}}{d_{0,hkl}} = \frac{\sin(\theta_{0,hkl})}{\sin(\theta_{hkl})} - 1$$

- Loading stresses are calculated assuming that the transverse, axial and radial directions are the principal stress directions in the sample, and that there are no shear stresses in the sample.
- Elastic constants and Poisson ratios have been calculated from single crystal elastic constants ($E_{Nb3Sn(321)}$=131 GPa, $\nu_{Nb3Sn(321)}$=0.363, $E_{cu(220)}$=138.9 GPa, $\nu_{Cu(220)}$=0.333) [1,2,3].
- Nb loading stresses could not be calculated. Because of the strong Nb texture there are no peaks that could be detected in all directions.

$$\sigma_{ii} = \frac{E_{hkl}}{1+\nu_{hkl}} \left(\varepsilon_{ii} + \frac{\nu_{hkl}}{1-2\nu_{hkl}} \left(\varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \right) \right)$$

[1] K.R. Keller, J.J. Hanak, “Lattice softening in single crystal Nb_3Sn”, Phys. Lett., vol. 21(3), (1966), 263-264

[2] H. Wern, R. Johannes, H. Walz, "Dependence of the X-Ray Elastic Constants on the Diffraction Plane", phys. stat. sol. (b) 206(2), (1998), 545-557

[3] E. Kröner, “Berechnung der elastischen Konstanten des Vielkristalls aus den Konstanten des Einkristalls“, Zeitschrift für Physik, 151(4), (1958), 504–18

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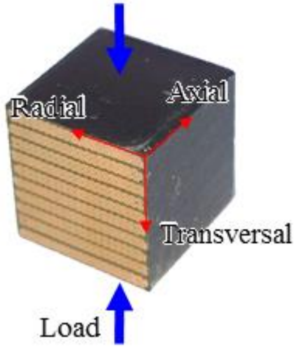
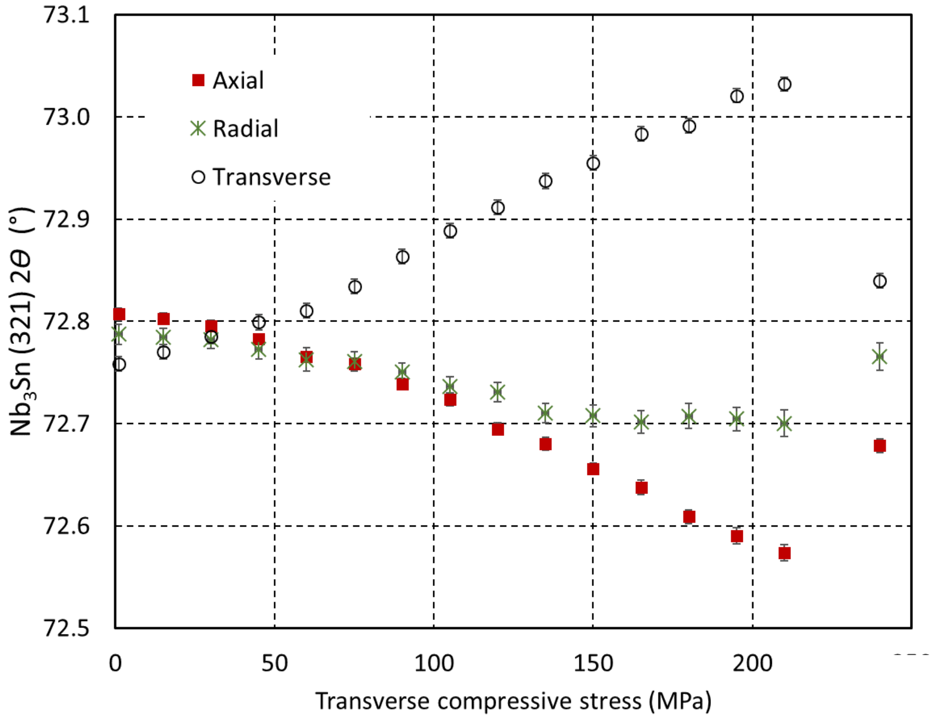
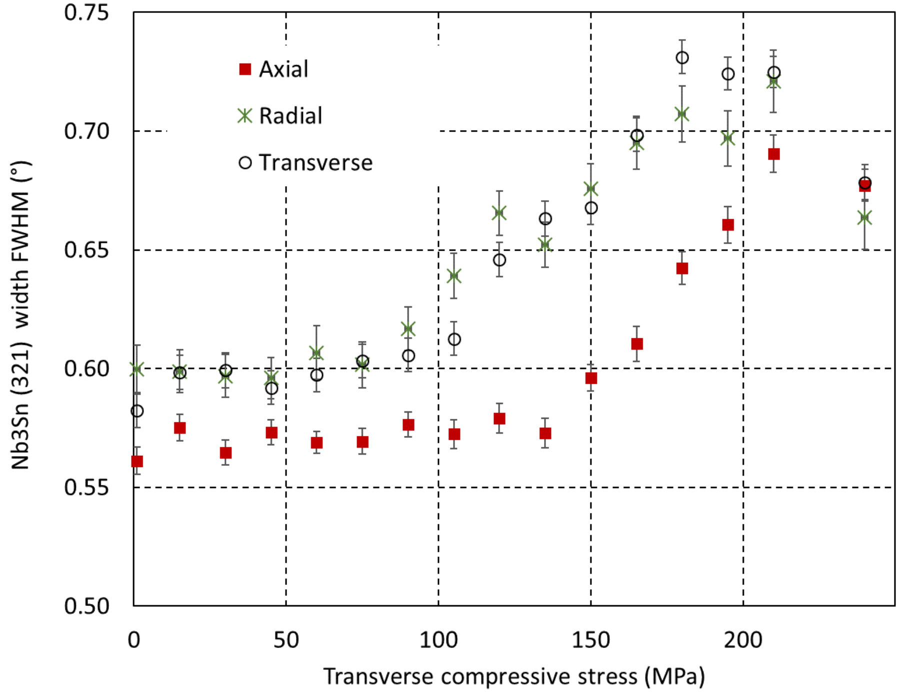
Transverse compressive loading of non-impregnated cable stack: **Nb_3Sn diffraction angle and peak width changes**



- Average diffraction angles within the 5×5×5 mm^3 gauge volume are recorded.
- Diffraction peak broadening indicates that the Nb_3Sn loading strain distribution becomes more inhomogeneous upon application of external stress.
- In axial direction the Nb_3Sn (321) peak is narrower than it is in radial and transverse directions, and the axial Nb_3Sn (321) peak width increase starts at higher stress.



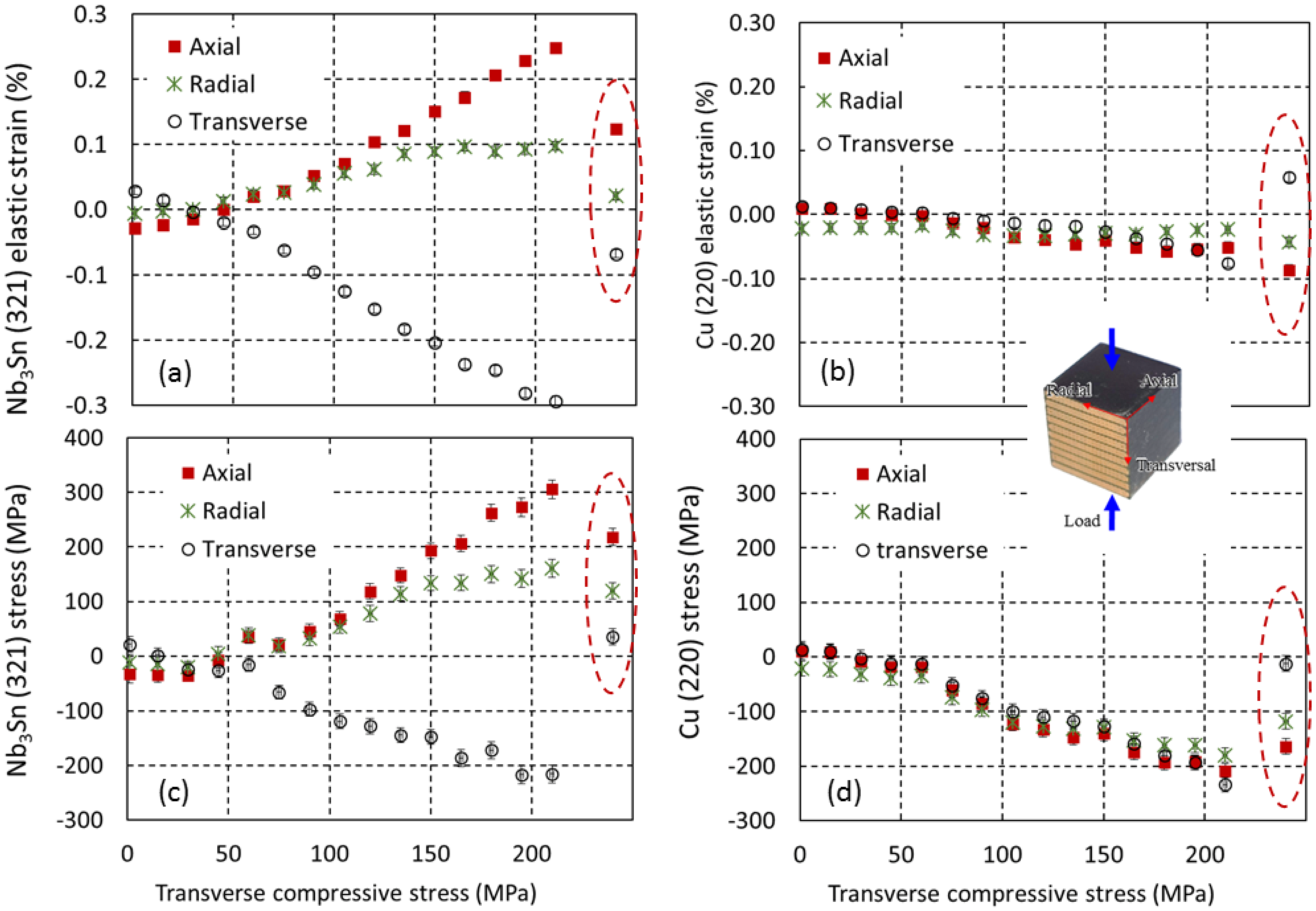
Nb_3Sn (321) diffraction angles as a function of externally applied transverse compressive stress.



Nb_3Sn (321) diffraction peak width evolution as a function of externally applied transverse compressive stress.

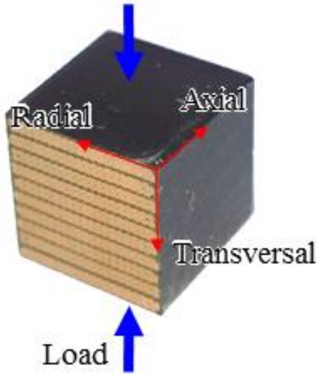
Nb_3Sn and Cu loading strains and stresses

- Loading strains and stresses are calculated from the relative changes of the diffraction angles with respect to the diffraction angle measured in the assumed stress free state.
- Cu is under similar compressive stress in all three directions.
- Transverse compression induces an important axial tensile stress in the Nb_3Sn.
- The transverse Nb_3Sn loading stress is an average value, the maximum Nb_3Sn stress is likely higher, as indicated by the Nb_3Sn diffraction peak broadening.

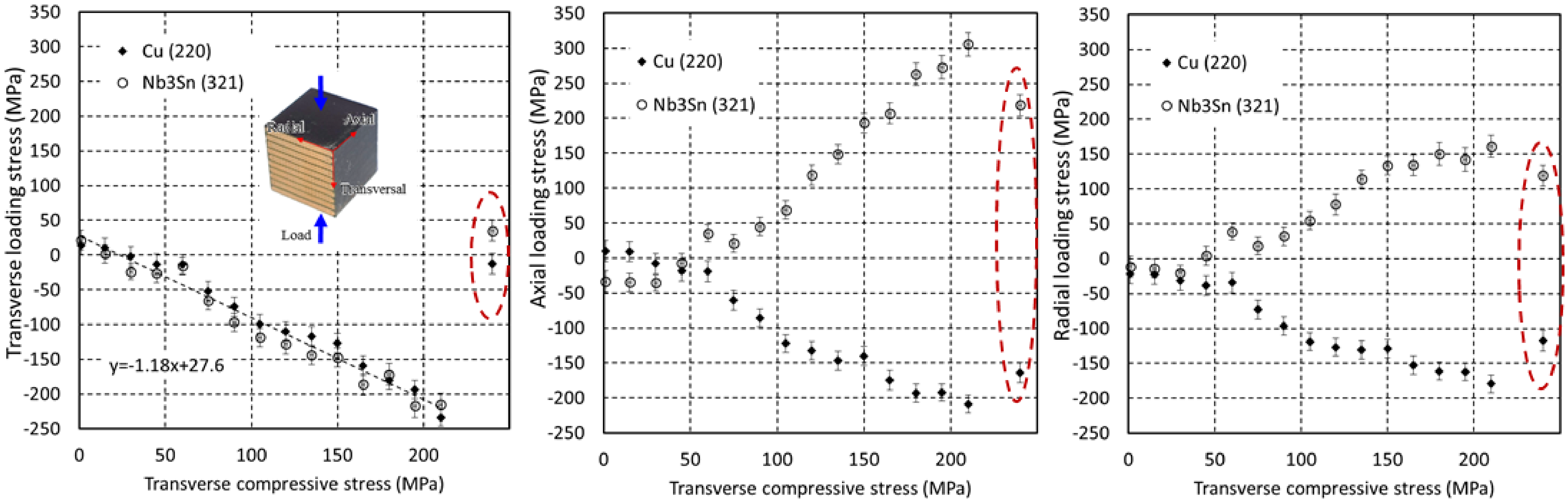


(a) Nb_3Sn (321) and (b) Cu (220) lattice strains and (c) Nb_3Sn (321) and (d) Cu (220) loading stresses as a function of externally applied transverse compressive stress.

Nb_3Sn and Cu loading stresses comparison



- The transverse Nb_3Sn and Cu loading stress increases linearly with the externally applied transverse stress (iso-stress conditions in the composite in transverse load direction).
- The transverse loading stress increase is about 20% higher than the externally applied stress increase, which can at least partly be explained by the presence of porosity in the sample.
- In the sample that is not constrained in axial and radial directions, the isotropic Cu pressure induces an important axial and radial tensile stress in Nb_3Sn.
- In magnet coils that are constraint in all directions, the axial and radial Nb_3Sn stress may be much smaller.



Comparison of Nb_3Sn (321) and Cu (220) loading stress evolution in (a) transverse, (b) axial and (c) radial direction.

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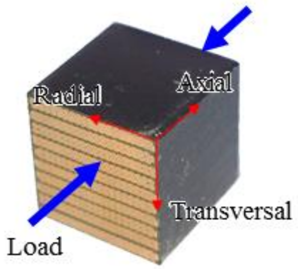
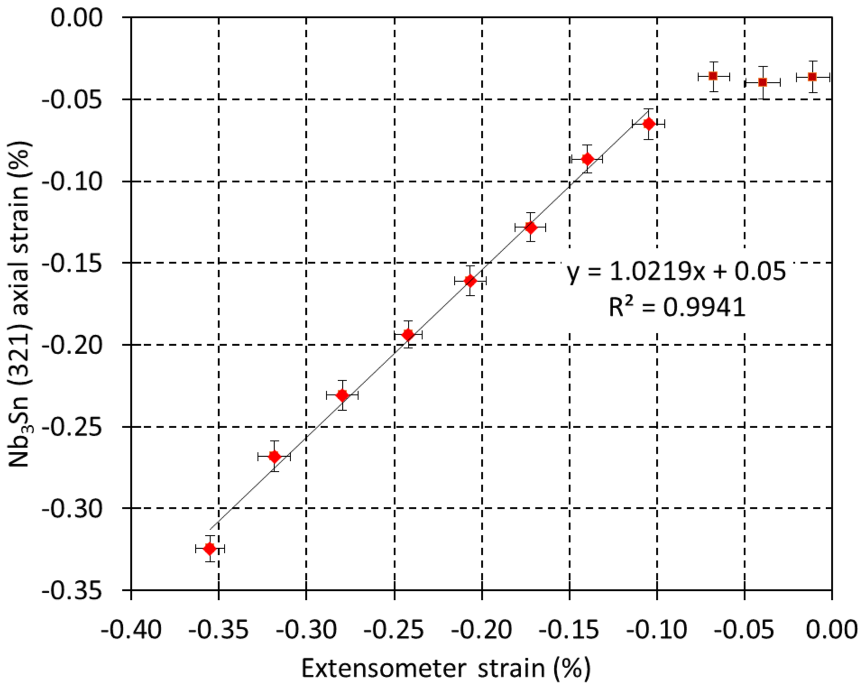
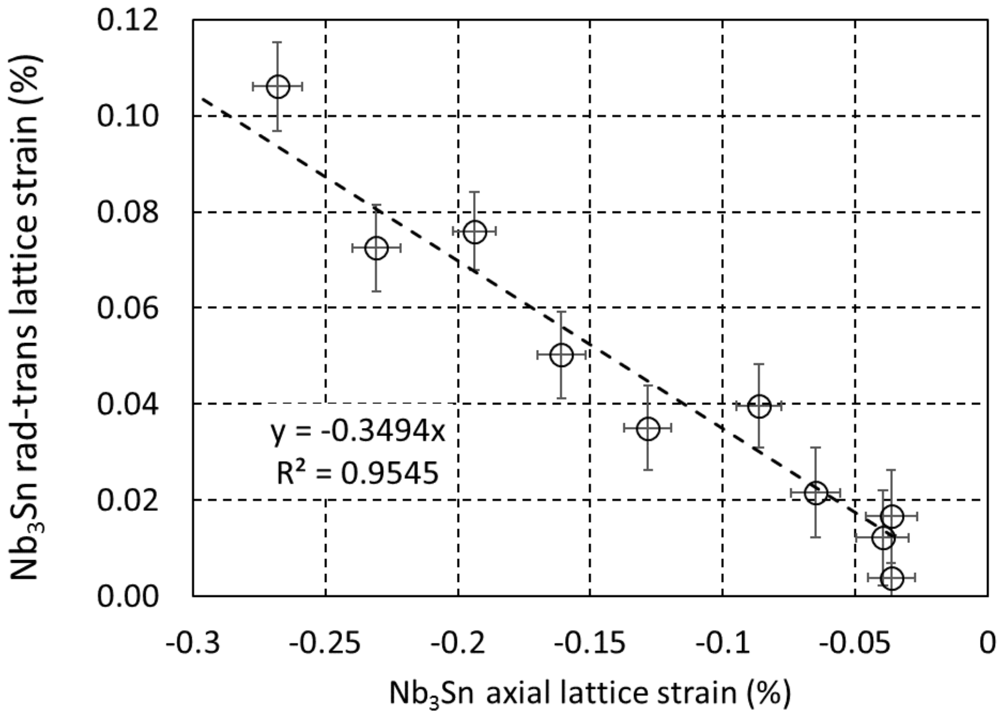
Monotonic axial loading: Nb_3Sn loading strain vs macroscopic sample strain



- When the macroscopic strain exceeds 0.1%, the elastic Nb_3Sn strain increases with a slope close to unity.
- Transverse and radial Nb_3Sn lattice spacing changes are mainly caused by the Poisson effect (assuming a Poisson's ratio of about 0.36).



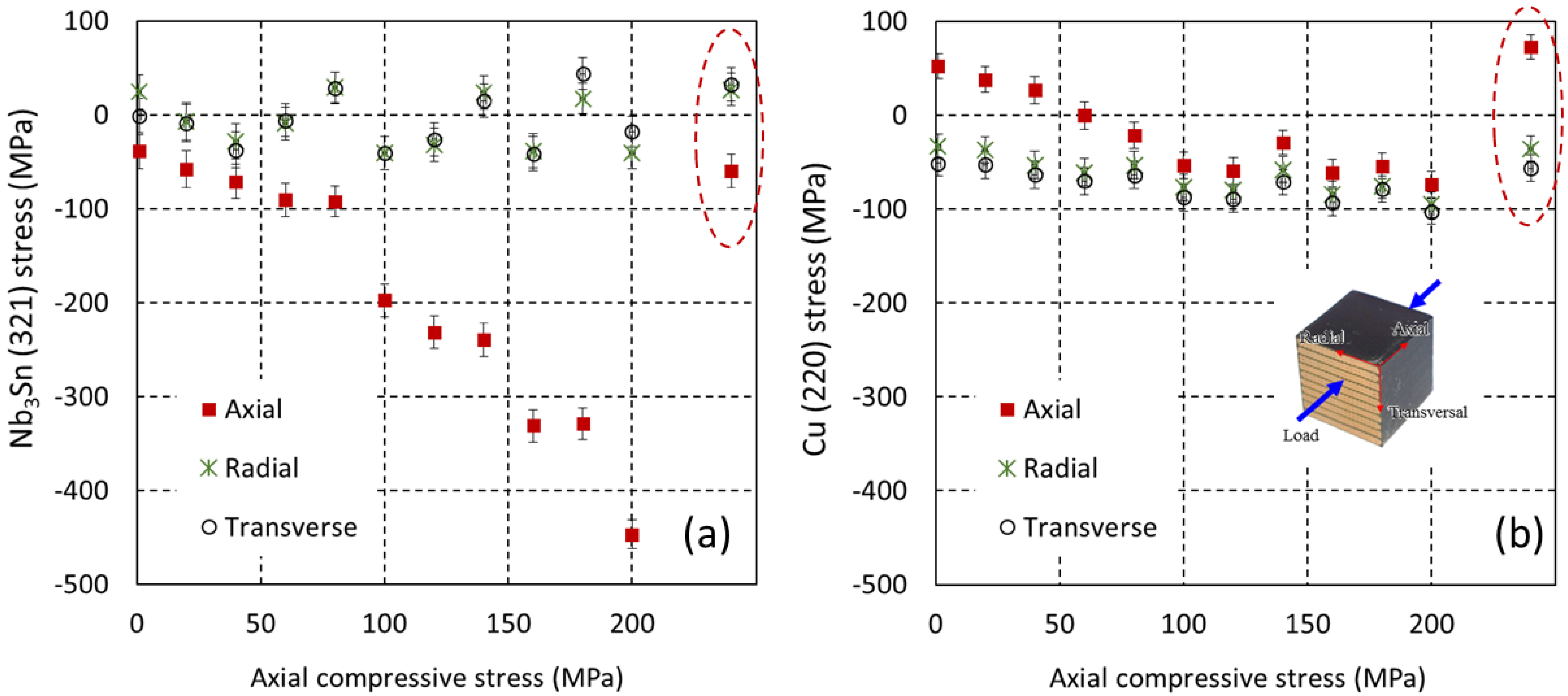
Elastic axial strain derived from neutron diffraction data as a function of the macroscopic sample strain measured with an extensometer.



Average transverse and radial Nb_3Sn (321) strain as a function of axial strain.

Monotonic axial loading: Nb_3Sn and Cu loading stresses

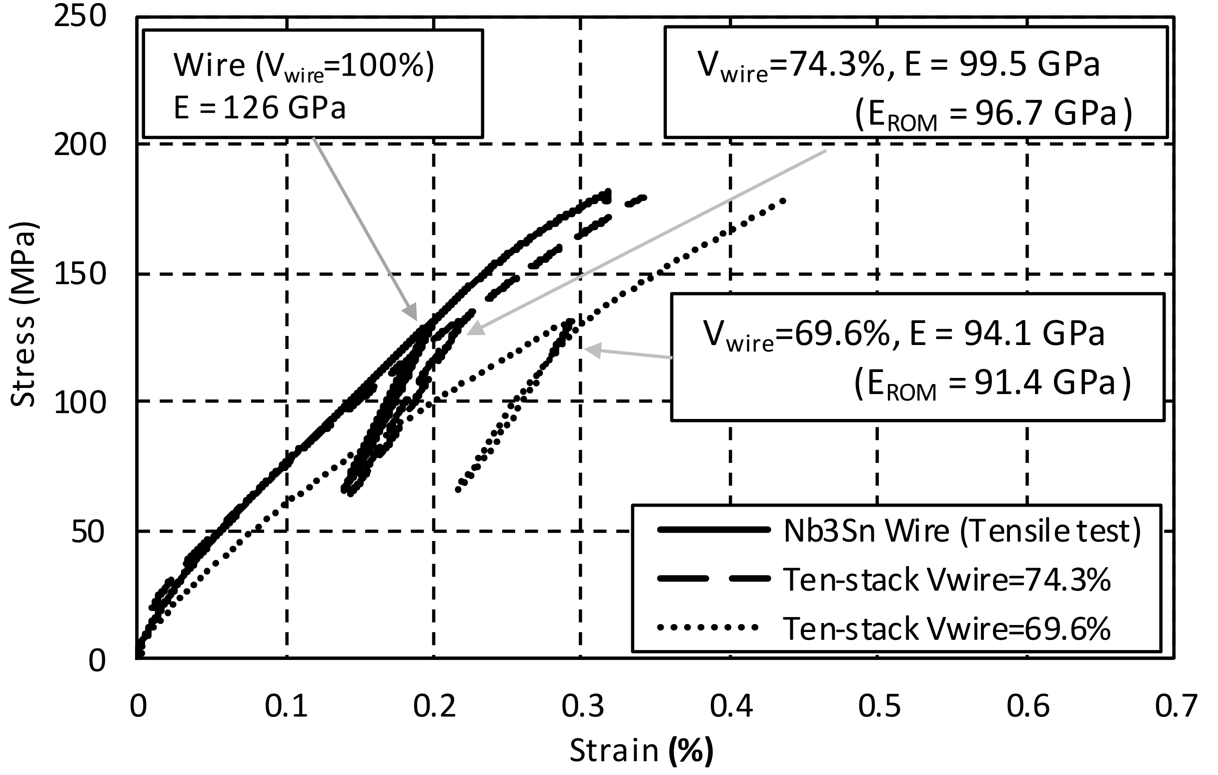
- When the macroscopic axial pressure on the cable stack exceeds about 100 MPa, the Cu elastic strain remains constant and the load is mainly carried by Nb_3Sn (and probably also by Nb).
- At 150 MPa externally applied pressure the axial Nb_3Sn (321) and Cu (220) loading stresses are about 300 MPa and 100 MPa, respectively.



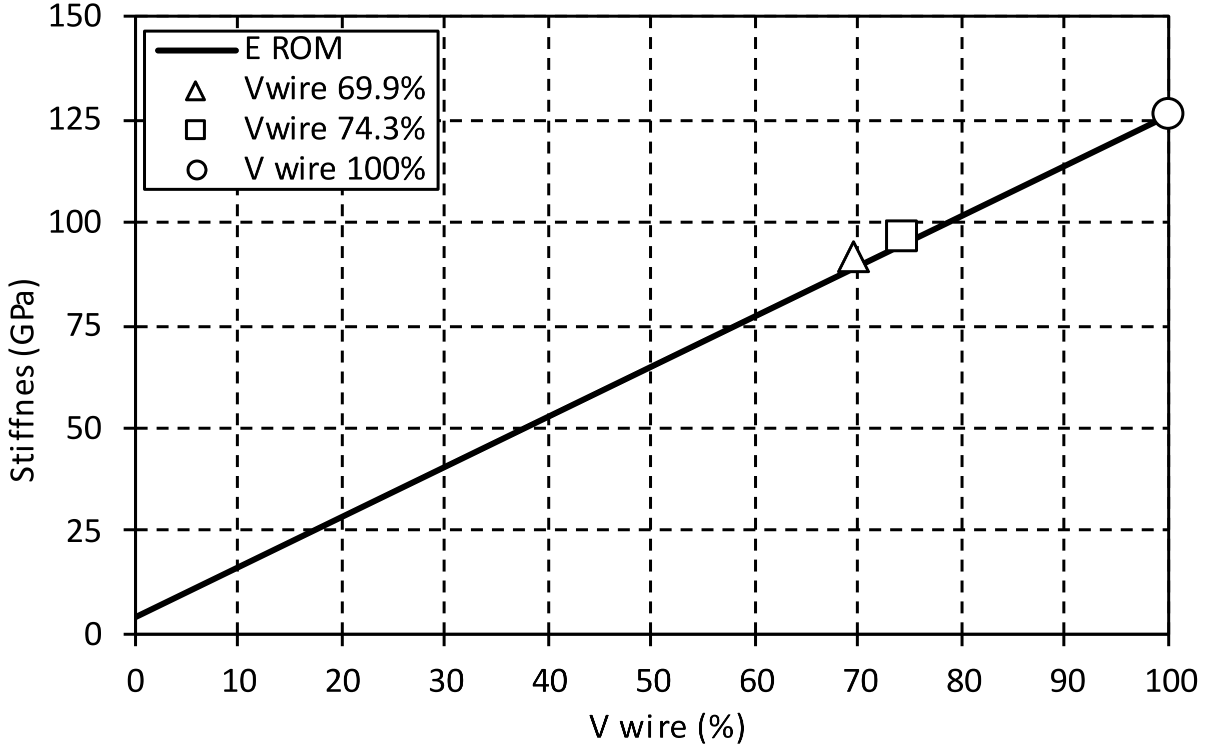
(a) Nb_3Sn and (b) Cu loading stresses in impregnated cable stack as a function of axial compressive stress. Encircled data points show the residual strain when the external stress is released.

Monotonic axial loading: Experiment vs rule of mixture (ROM) estimate

- Stress strain measurements in axial compression with ten stack samples with different epoxy volume fraction.
- Assuming $E_{wire\text{-}axial}$=126 GPa and E_{epoxy}=4 GPa.
- Stiffness can be predicted assuming iso-strain conditions. The load is essentially carried by the wire, and the stress in the epoxy remains small.



Comparison of stress-strain curves of Nb_3Sn wire (axial tension) and ten-stack samples wire different volume fraction (V_{wire}) (axial compression).



ROM estimation (upper bound) of the axial compression stiffness dependence on V_{wire} and comparison with experiment.

From Felix Wolf et al, "*Effect of epoxy volume fraction on the stiffness of Nb_3Sn Rutherford cable stacks*"

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Stress-strain behaviour of Nb_3Sn coils in accelerator magnets

- For the first time it was possible to determine experimentally Nb_3Sn and Cu loading strains and stresses in Rutherford cable stacks.
- These results are a new opportunity to validate FE models.
- Ten-stack samples are representative for coils made of the same conductor with the same epoxy volume fractions (see presentation of F. Wolf).
- The load case of transverse compression of the unconstrained cable stacks is probably not representative for the mechanical loading in magnets where the coils are constrained in axial and radial directions.
- Nb_3Sn coils can be considered as a fiber reinforced composite. The three main results of this study are valid for magnets too:
  - Iso-strain conditions in axial load direction
  - Iso-stress conditions in transverse compression
  - Isotropic compressive stress in the annealed Cu stabilizer

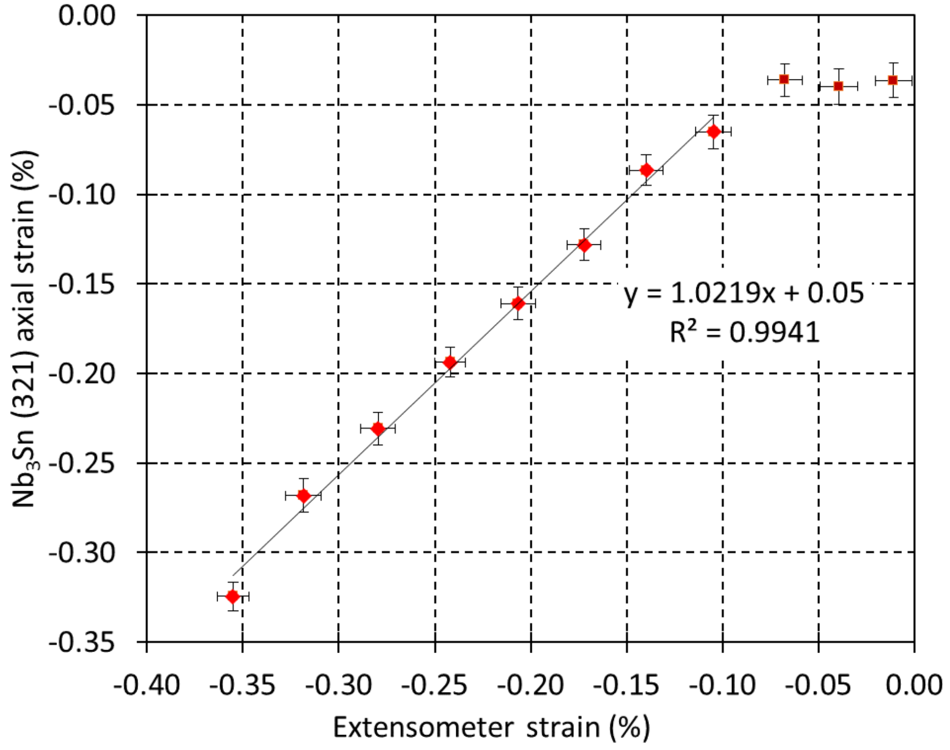
Stress-strain behaviour of Nb_3Sn coils in axial and transverse load direction

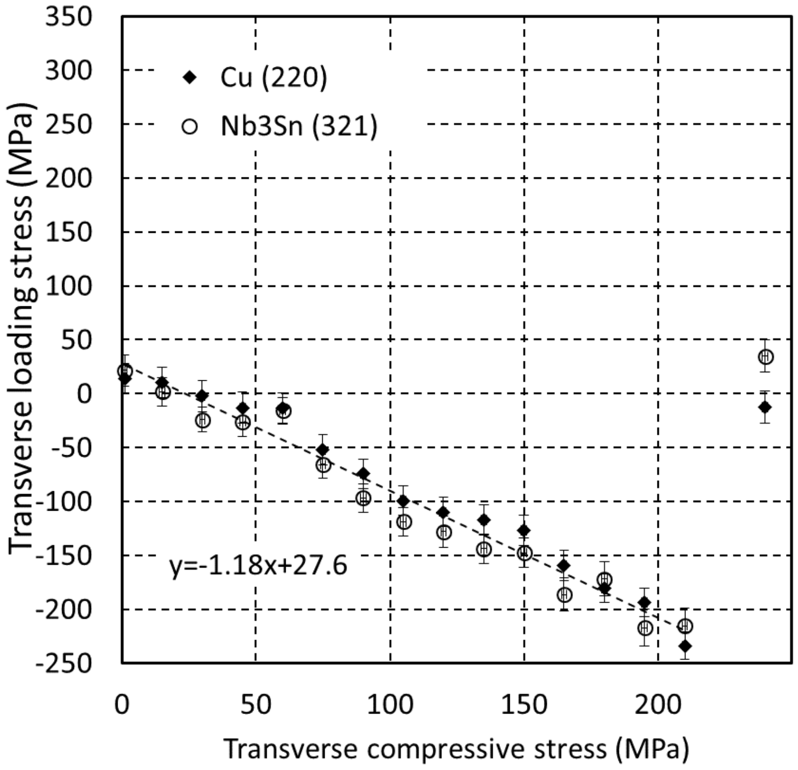
Axial loading

- Iso-strain conditions
- Transverse and radial Nb_3Sn lattice spacing changes are mainly caused by the Poisson effect.
- Axial coil stiffness can be predicted from the epoxy volume fraction and the wire stiffness (at RT the 11 T dipole coil axial stiffness is about 95 GPa).

Transverse loading

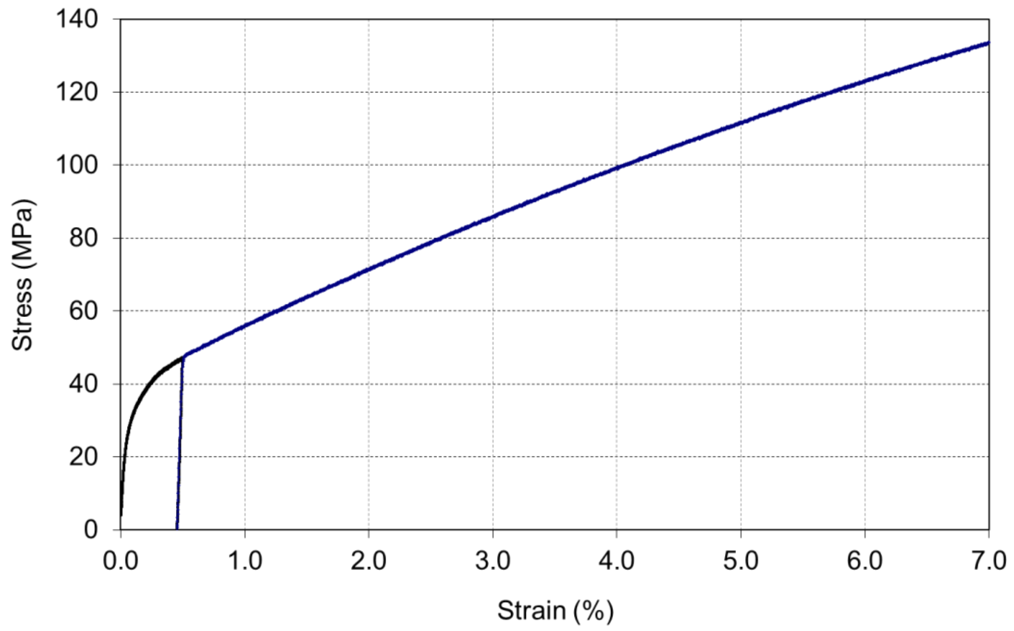
- Iso-stress conditions
- Cu is under similar compressive stress in all three directions.
- Transverse compression induces an important axial tensile stress in the Nb_3Sn.



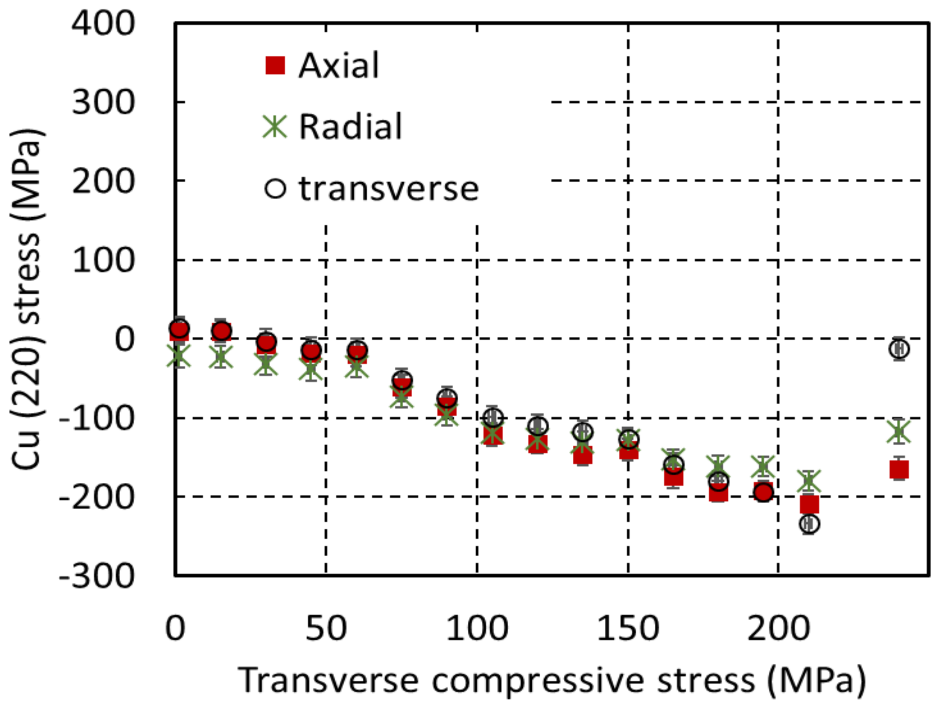


Stress-strain behaviour of the fully annealed Cu stabiliser

- The unconstrained annealed Cu stabiliser yields at about 20 MPa ($R_{p0.2}$ is 40 MPa).
- Therefore, under tension annealed Cu cannot carry high loads.
- Under compression in hydrostatic conditions the annealed Cu provides an isotropic pressure around the Nb_3Sn filaments.
- The magnitude of the Cu pressure corresponds approximately with the externally applied transverse compressive stress.
- In unconstrained cable stacks Cu creeps at high stresses.



Tensile stress-strain curve of fully annealed Cu wire.



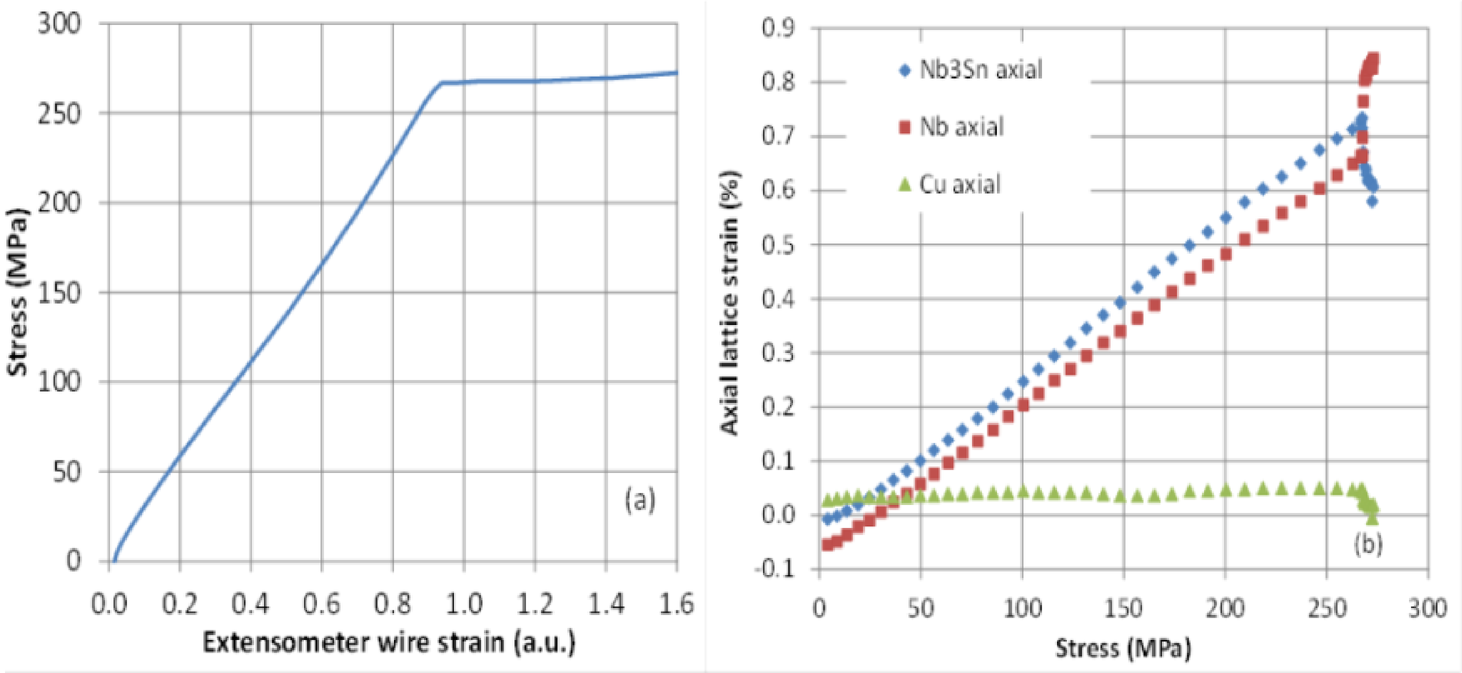
Effect of the impregnation material mechanical properties

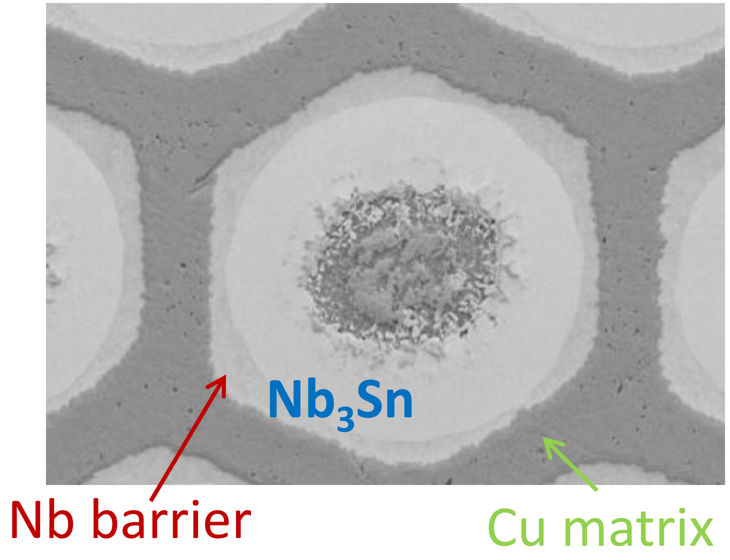
- Axial loading:
  - At 150 MPa axial pressure the Nb_3Sn and Cu axial loading stresses are about 300 MPa and 100 MPa, respectively.
  - Under axial loading the effect of the epoxy (E_{epoxy}=4 GPa) on coil stiffness and Nb_3Sn loading stress is negligible.
  - A reinforcement in axial load direction should have highest possible E-modulus.
- Transverse compression:
  - At 150 MPa transverse pressure the average transverse Nb_3Sn and Cu loading stresses are about 150 MPa.
  - Under transverse compression the epoxy impregnation can reduce the Nb_3Sn loading stresses.
  - Assuming iso-stress behavior, the elastic properties of the impregnation material should not strongly influence the Nb_3Sn coil stiffness.

Back-up slides

Mechanical behaviour of Nb_3Sn/Cu PIT wire constituents studied by simultaneous stress-strain-XRD measurements at 4.2 K

- Loading strain is measured in two directions (axial and transverse/radial)
- Linear elastic behaviour of Nb and Nb_3Sn
- Nb and Nb_3Sn axial pre-compression in the unloaded wire
- Load transfer from Nb_3Sn to Nb at a wire stress of about 270 MPa and a strain of about 0.7%.



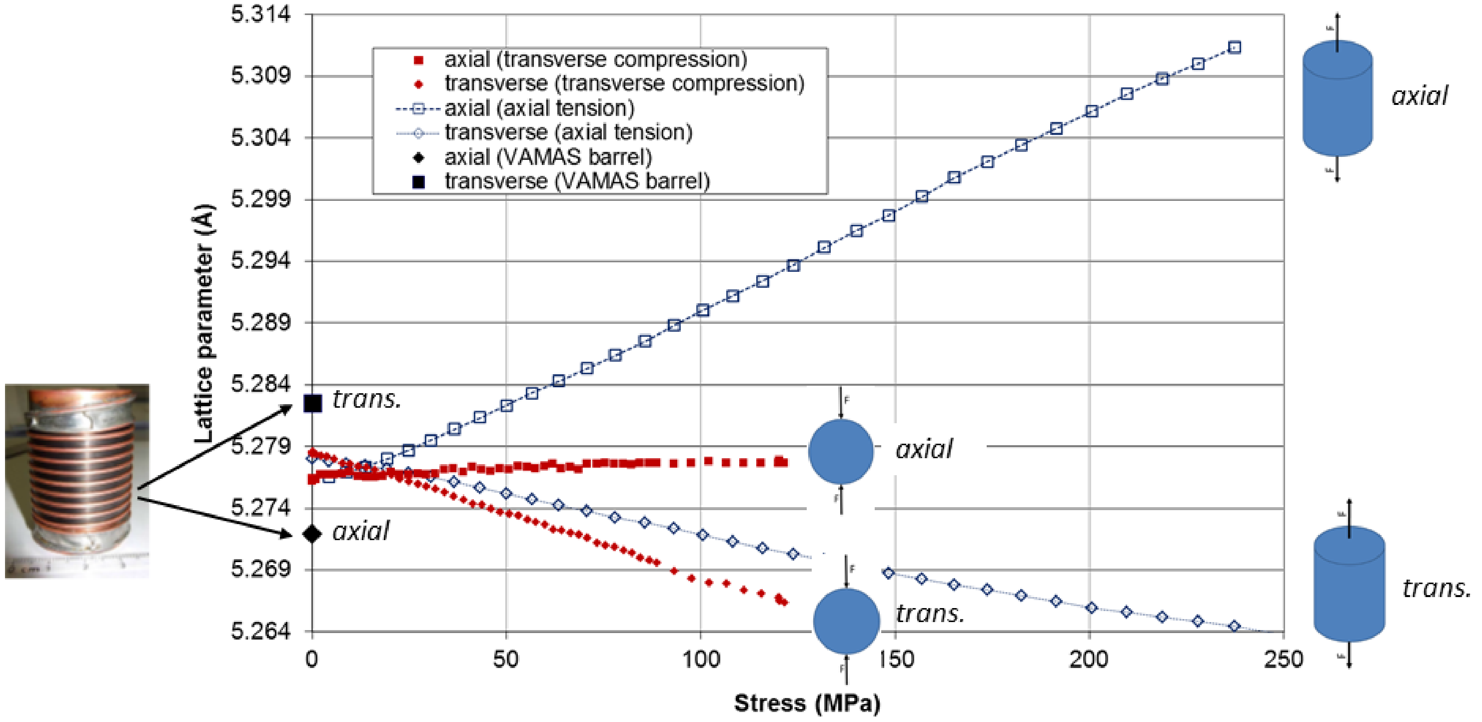


Supercond. Sci. Technol. 27, (2014), 044021.

Nb_3Sn PIT wire (a) 4.2 K stress-strain curve and (b) axial lattice strain vs uniaxial tensile stress.

Axial and transverse Nb_3Sn lattice parameter changes in a PIT wire as a function of externally applied axial tensile and transverse compressive stress

- Measured by high energy synchrotron X-ray diffraction
- Loading strain was measured in two principal directions (axial and transverse), but not in radial direction.
  →Loading stresses cannot be calculated.
- Nearly linear lattice spacing vs stress dependence.
- Slight d-spacing increase in axial direction under transverse compression.



Supercond. Sci. Technol. 27, (2014), 044021.

IEEE Trans. Appl. Supercond. 19(3), (2009), 2645-2648

Nb_3Sn lattice parameter in axial and transverse direction as a function of axial tensile or transverse compressive stress. The lattice parameters for the same PIT wire on a VAMAS barrel are shown for comparison.

Elastic modulus of RRP type Nb_3Sn wire

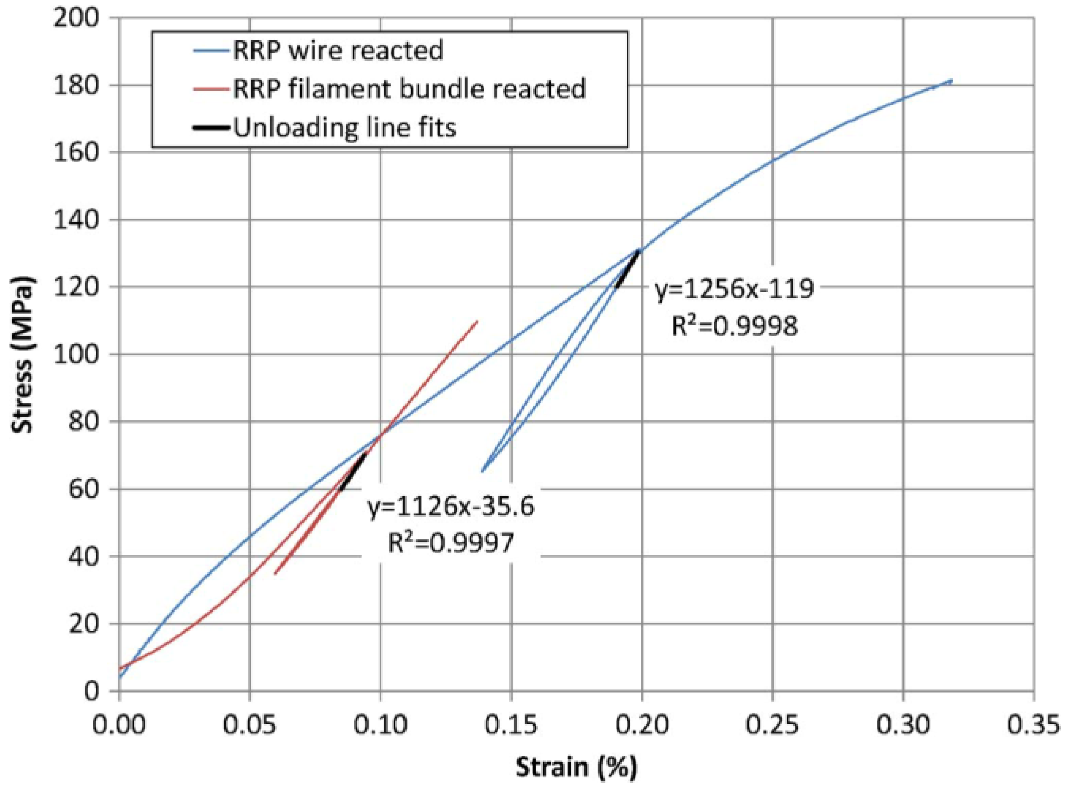


Fig. 3. Stress-strain curves measured at room temperature on a reacted RRP wire and its extracted filaments.

IEEE Trans. Appl. Supercond., 25(6), (2015), 8400605

- E is defined as the initial linear slope of the unloading curve.
- Determined elastic modulus of the reacted RRP wire: **126 GPa**

TABLE II
Nb_3Sn ELASTIC MODULI IN AXIAL AND TRANSVERSE DIRECTIONS CALCULATED FOR THE RRP AND PIT WIRES AT RT AND AT 4.2 K

		PIT B215	RRP #7419
RT	E_{axial}	130	140
	E_{trans}	135	129
4.2 K	E_{axial}	106	127
	E_{trans}	116	104

Stress-strain behaviour of 11 T dipole materials

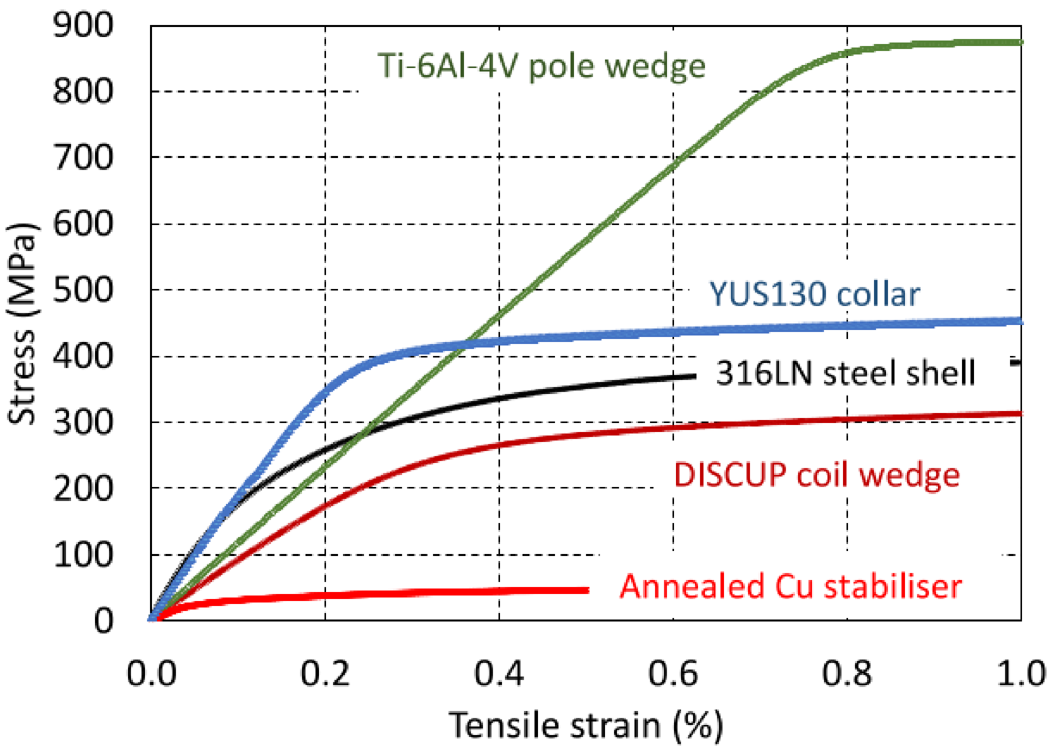


Fig. 1. Comparison of the RT engineering stress-strain curves of annealed superconducting wire Cu stabilizer, DISCUP C3/30 coil wedge, Ti6Al4V pole wedge, YUS130 collar, and stainless steel 316LN (magnet shell and reaction fixture) [4].

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