Uncertainties in the measurement of the mechanical properties of Nb_3Sn coil constituents and cable stacks

C. Scheuerlein, F. Lackner

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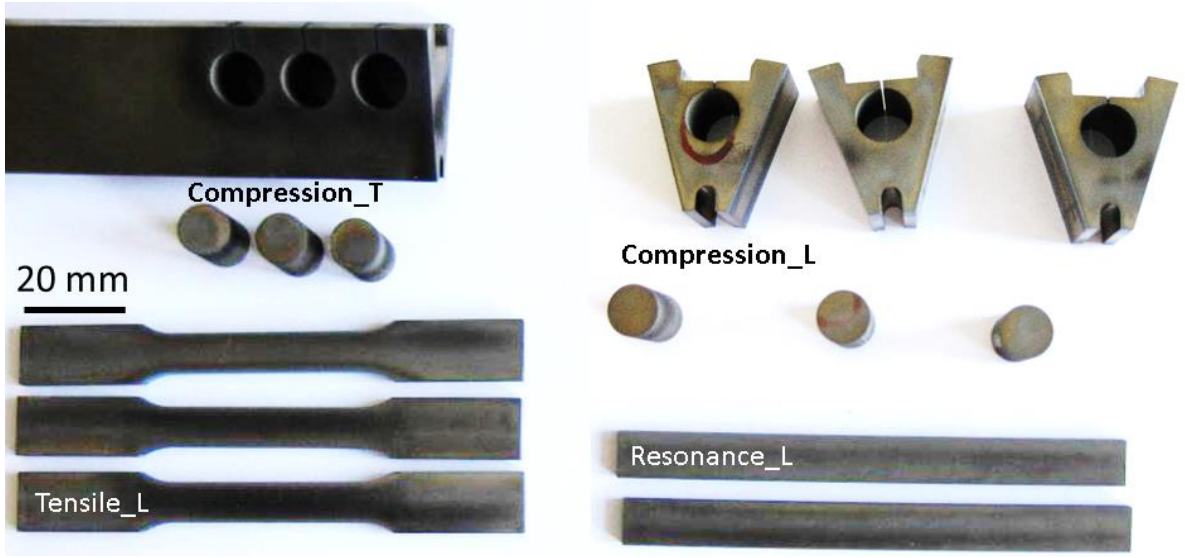
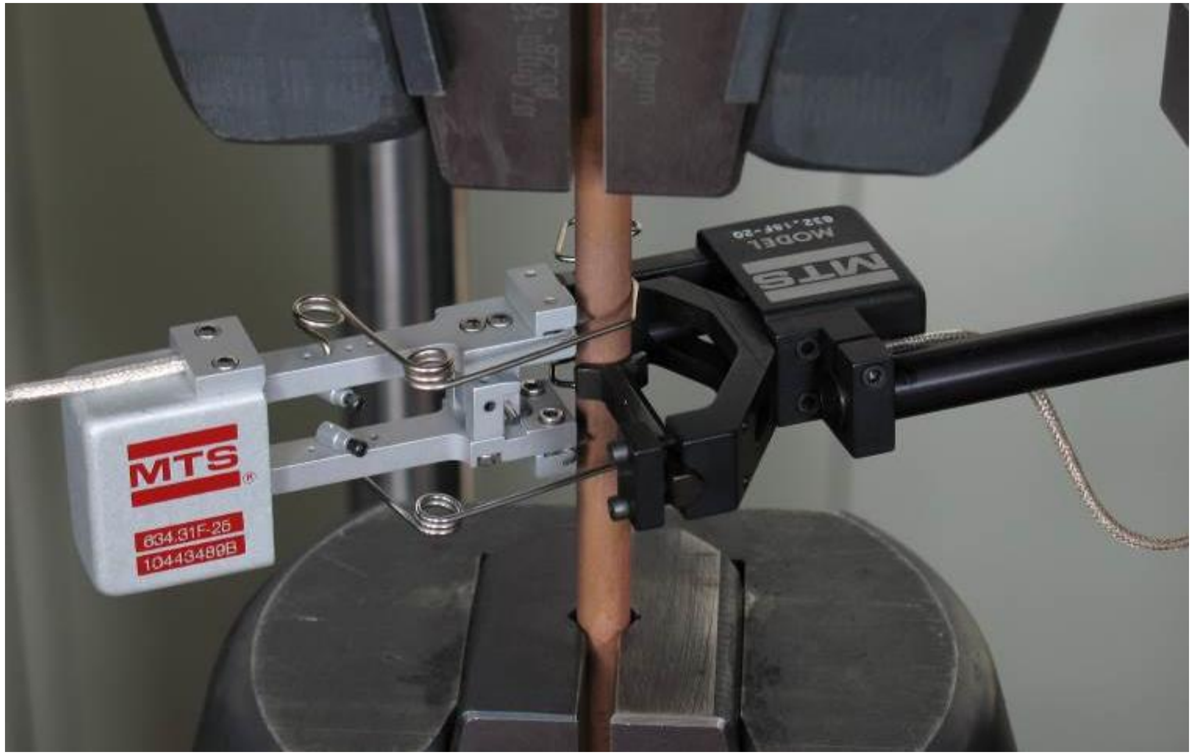
Outline

- Test sample geometries
- Uncertainties in dynamic Young's modulus measurements
- Uncertainties in stress-strain measurements using homogeneous samples with ideal testing geometry
  - Stress strain behaviour dependence on the load direction
  - Non linear stress-strain behaviour
  - Elastic anisotropy of the coil constituent materials
- Uncertainties in Nb_3Sn composite wire stress-strain measurements
- Uncertainties in the determination of the Nb_3Sn mechanical properties
- Uncertainties in stress-strain measurements of reacted and impregnated Nb_3Sn Rutherford cable stacks
- Conclusion

Sample geometries for standardised mechanical testing



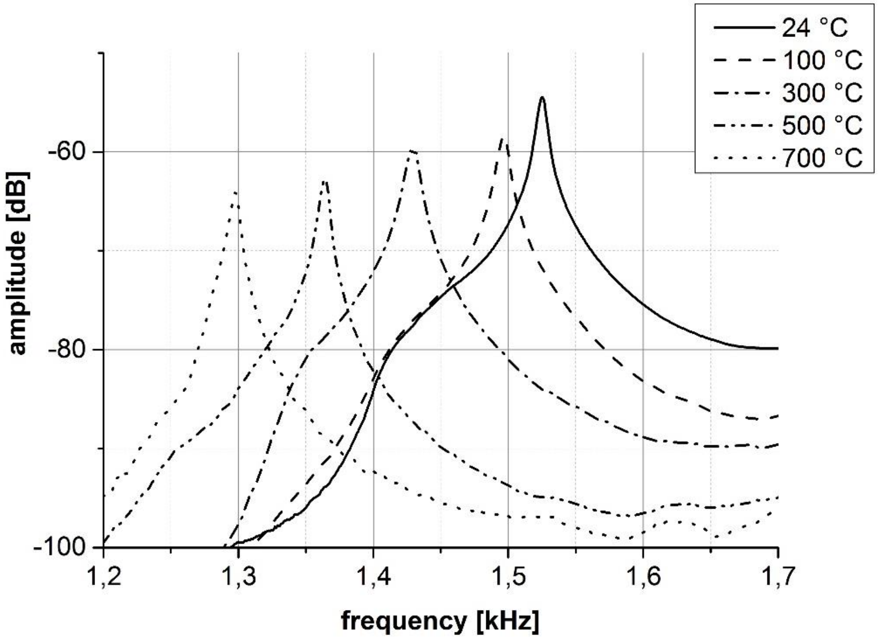
Standardized test samples for dynamic and static tensile and compression tests. All samples have been extracted from a Ti6Al4V pole wedge.



Sample for Poisson's ratio measurement and extensometers for axial and transverse strain measurements. The sample has been extracted from a DISCUP coil wedge.

Dynamic Young’s modulus measurements

- For dynamic test methods (resonance and impulse excitation) the key elements defining the measurement uncertainty are the mass and physical size of the specimen [i].
- For both test methods a measurement uncertainty < 1 % is realistic [ii,iii].
- Typical differences between dynamic and static Young’s moduli (adiabatic vs isothermal modulus) are <1 % [ii].
- Since dynamic Young´s modulus measurements are non destructive temperature dependent measurements are possible [iv].



Resonance peak of the first bending oscillation of rectangular 316LN specimen at different temperatures [iv].

[i] J.D. Lord, R. Morrell, NPL Good Practice Guide No. 98 “*Elastic Modulus Measurement*”, NPL London 2006

[ii] F.H. Newmann, V.H.L. Searle, The general properties of matter. Issue 5, Edward Arnold, 1962

[iii] ASTM E 1875 “*Standard Test Method for Dynamic Young´s Modulus, Shear Modulus, and Poisson´s Ratio by Sonic Resonance*”. 2013, ASTM International.

[iv] C. Scheuerlein, F. Lackner, F. Savary, B. Rehmer, M. Finn, C. Meyer, “*Thermomechanical behavior of the HL-LHC 11 Tesla Nb_3Sn magnet coil constituents during reaction heat treatment*”, IEEE Trans. Appl. Supercond., submitted

Stress-strain behaviour dependence on the load direction at the example of stainless steel

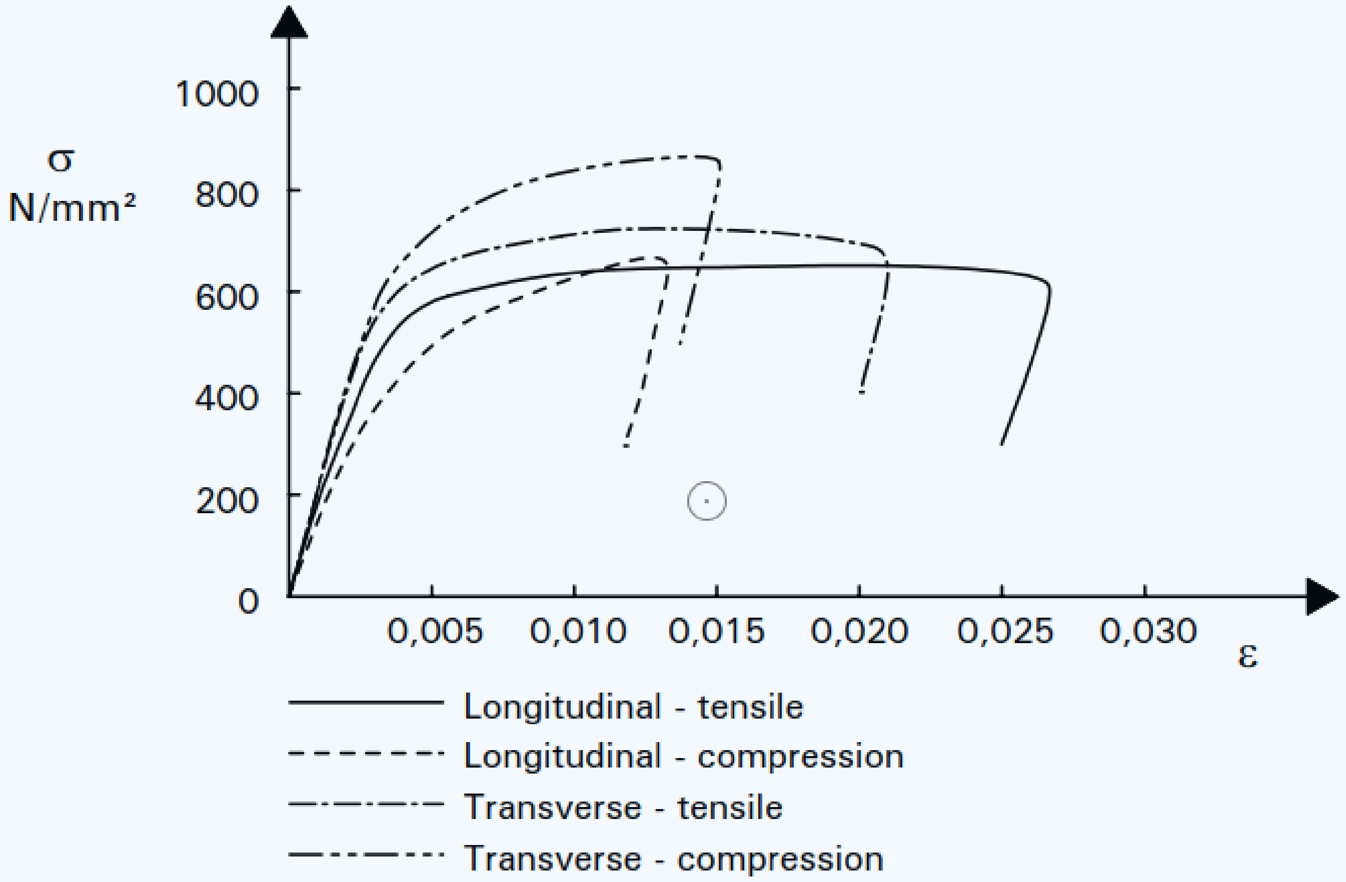
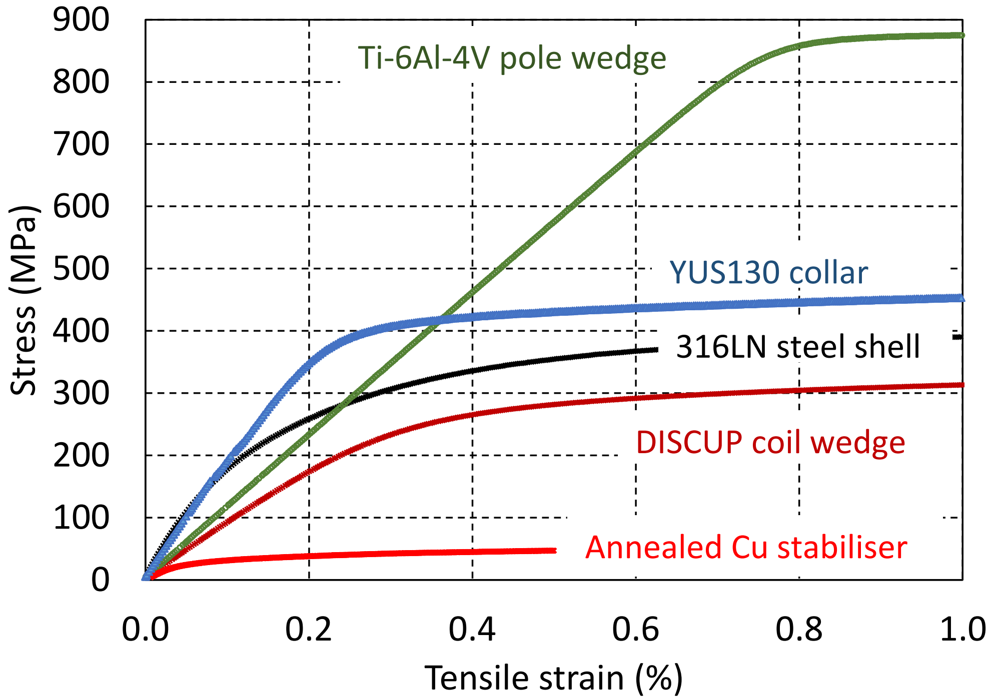


Figure 3.2 *Typical stress-strain curves for grade 1.4318 cold worked to strength level C850*

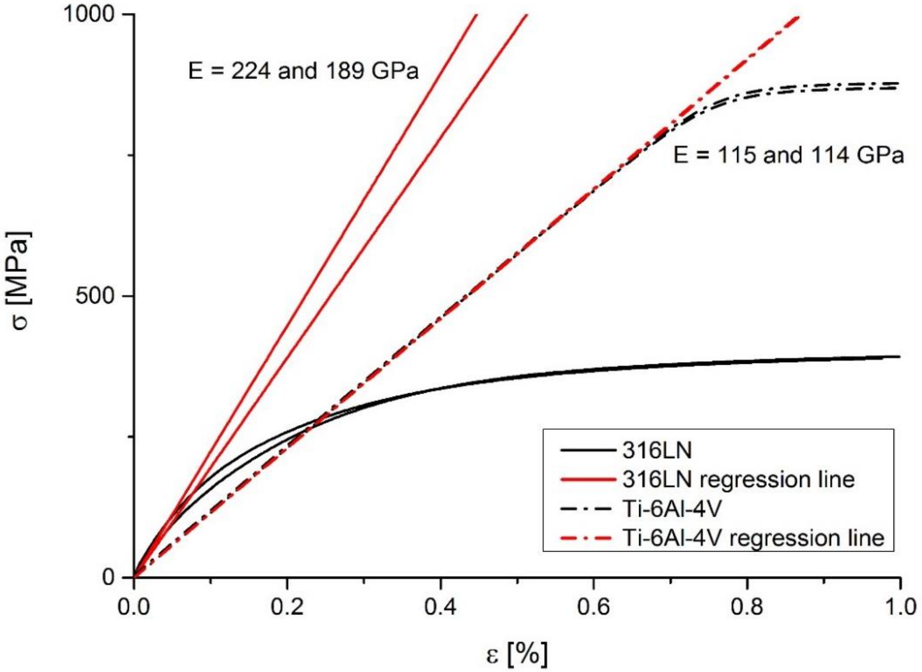
From: The European Stainless Steel Development Association Euro Inox and The Steel Construction Institute, Design manual for structural stainless steel-Commentary (2nd Edition), 2003

Uncertainties in static Young’s modulus measurements

- Precise Young’s moduli can be derived from stress-strain measurements of materials that exhibit pronounced linear elastic behaviour (e.g. Ti6Al4V).
- Comparatively large uncertainty in the Young’s modulus results of materials that do not exhibit linear behaviour, like stainless steels.



Comparison of the RT engineering stress-strain curves of different coil and magnet materials [iv].



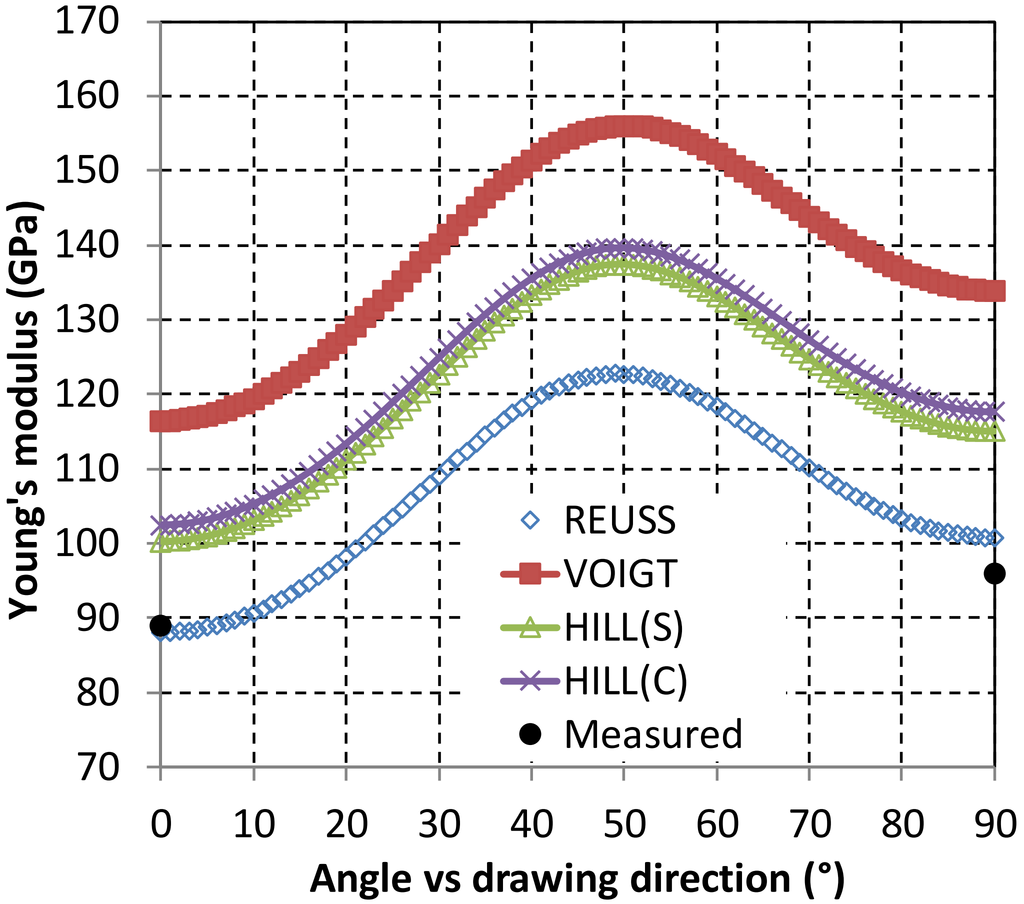
Comparison of 316LN and Ti6Al4V stress-strain curves and linear fits for the determination of Young’s modulus [v].

[iv] C. Scheuerlein, F. Lackner, F. Savary, B. Rehmer, M. Finn, C. Meyer, “*Thermomechanical behavior of the HL-LHC 11 Tesla Nb_3Sn magnet coil constituents during reaction heat treatment*”, IEEE Trans. Appl. Supercond., submitted

[v] C. Scheuerlein, F. Lackner, F. Savary, B. Rehmer, M. Finn, P. Uhlemann, “*Mechanical properties of the HL-LHC 11 Tesla Nb_3Sn magnet constituent materials*”, IEEE Trans. Appl. Supercond., 27(4), (2017), 4003007

Elastic anisotropy in the 11 T dipole DISCUP coil wedges

- The DISCUP Young’s moduli derived from stress-strain compression tests are 89 GPa in the wedge extrusion direction and 96 GPa perpendicular to the extrusion direction [v].
- These values are substantially lower than the values between 115 to 130 GPa found for ODS Copper in literature.
- The angular dependence of Young’s modulus has been calculated from texture data obtained by neutron diffraction and from Cu single crystal elastic constants.
- The DISCUP wedges are strongly textured (multiples of random orientation MRD=16), which causes a strong elastic anisotropy of about 30%.



Angular DISCUP Young’s modulus dependence with respect to the wedge extrusion direction. Calculated assuming equal strains (Voigt) and equal stresses (Reuss) in all grains, respectively. Measurement results from [v] are shown for comparison. ***Courtesy of W. Gan, Helmholtz-Zentrum Geesthacht.***

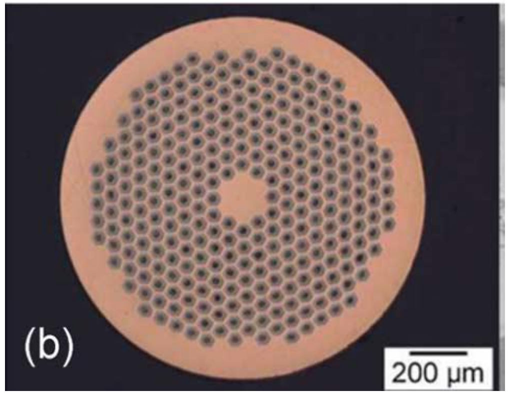
Summary: Uncertainties in Young’s modulus measurement with ideal test samples, according to well established standards

- Dynamic Young’s modulus measurement uncertainty <1 %.
- Static Young’s modulus measurement by tensile tests uncertainty is typically 3% [ii], provided the material exhibits pronounced linear elastic behaviour.
- Static Young’s modulus measurement by compression tests uncertainty is typically 5% [iii].
- For materials that do not exhibit pronounced linear stress strain behaviour (e.g. stainless steel and annealed copper), the uncertainty of the E-modulus derived from static tests can be >10% [v,vi].
- Important elastic anisotropy of textured coil materials (as an example DISCUP elastic anisotropy is>30%).

[vi] Ch. Weißmüller, H. Frenz, “Messunsicherheit bei der Ermittlung des E-Moduls im Zugversuch an Stahl“, *Materials Testing*, vol. 55, no. 9, 2013, pp. 643-647

Uncertainties in stress-strain measurements of Nb_3Sn/Cu composite wires

- The most easy to study wire load case is uniaxial tensile loading in the wire drawing direction.
- Nb_3Sn/Cu composite wires are not suitable tensile test samples.
    - the wire constituents are not stress free
    - the filaments contain porosity
    - at zero axial load the wires are always bended
- No linear part in the loading stress-strain curve. Therefore, the wire stiffness is estimated from the linear slope of unloading curves.
- The Nb_3Sn/Cu wire stiffness is stress and strain dependent, even in the wire drawing direction.



Strain (%)	Stiffness (GPa)
0.02	139
0.04	120
0.06	117
0.08	118
0.10	118
0.12	116
0.14	117
0.16	117

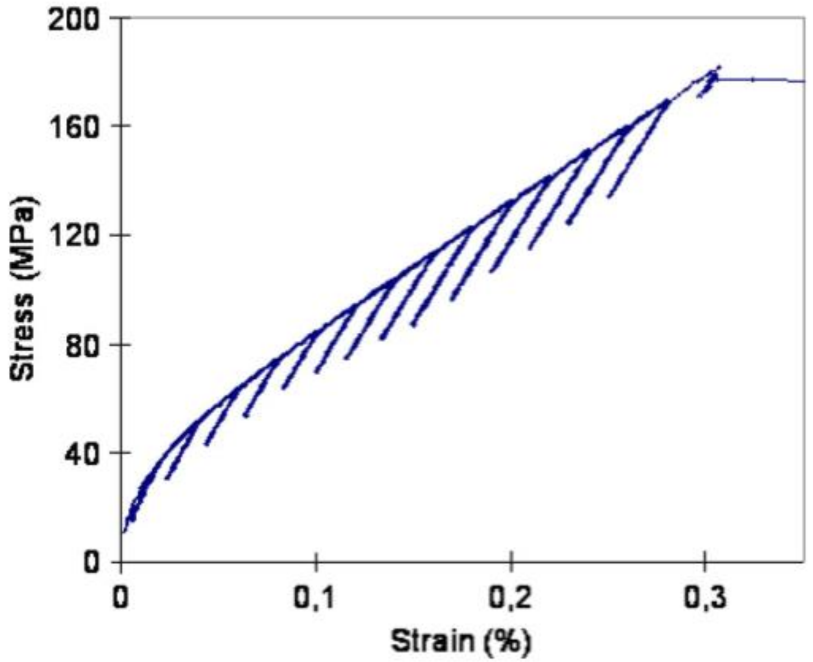
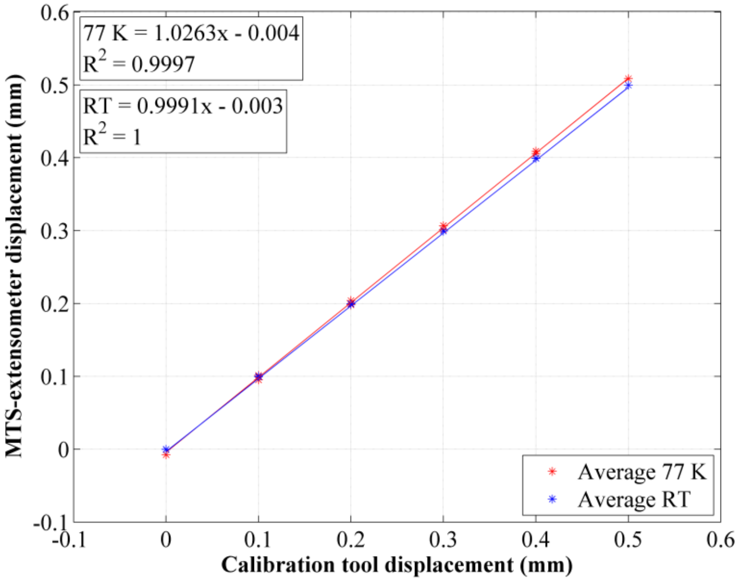
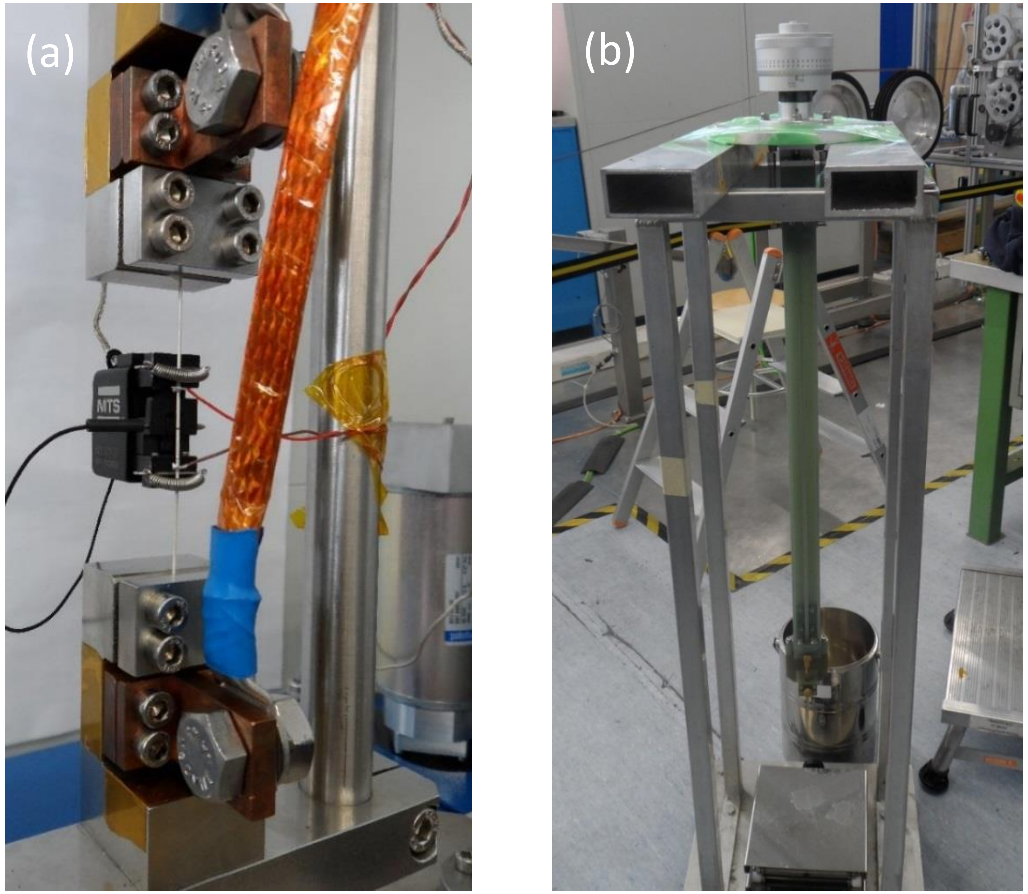


Fig. 2. Engineering stress-strain curve of the reacted PIT B215 composite strand measured at RT. The stress has been partly released every 0.02% in order to measure the apparent composite E-modulus as a function of axial composite strain. Courtesy B. Rehmer and M. Finn, Federal Laboratory for Materials Research, Berlin.

Extensometry for wire uniaxial stress-strain measurements

- The precision of stress-strain measurements relies mainly on careful extensometer strain measurements.
- Extensometers for strain measurements in wire drawing direction are commercially available.
- Extensometer calibration at RT can be performed by the supplier.
- Calibration at 77K and 4.2 K is not easily available and requires the setting up of dedicated calibration tools [vii].





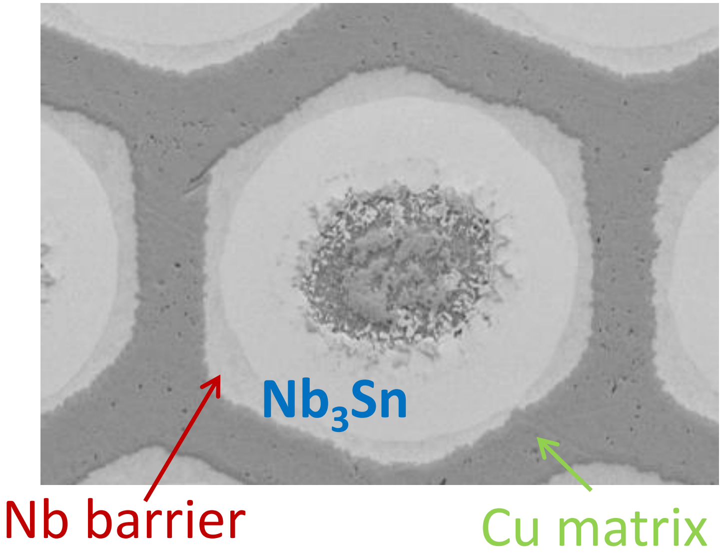
(a) MTS-clip on extensometer type 632.27F-21 with gauge length of 25 mm and (b) calibration tool.

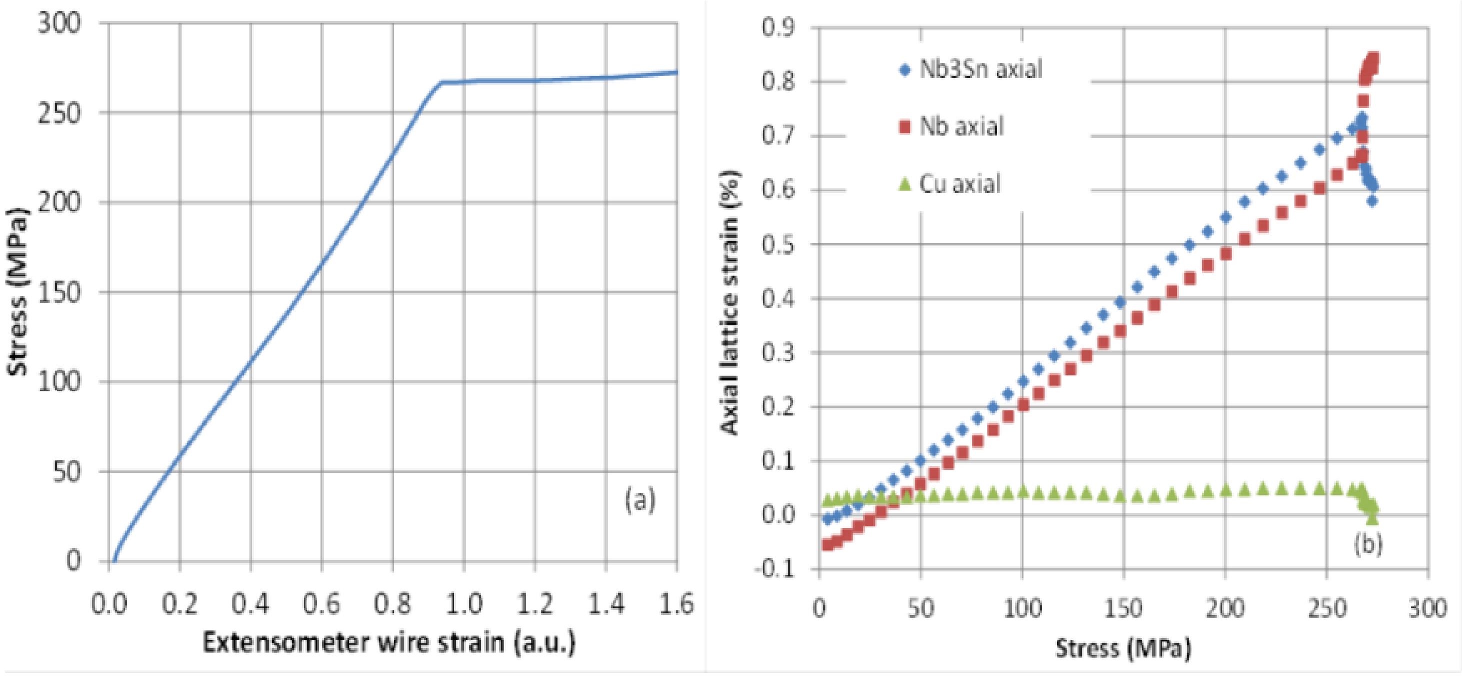
[vii] http://snf.ieeecsc.org/abstracts/stp466-simultaneous-measurement-critical-current-stress-strain-and-lattice-distortions

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

The effect of different wire constituents on the wire mechanical behaviour can be understood from combined X-ray diffraction-stress-strain results :

- Almost no load is carried by the annealed Cu matrix
- 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%





(a) 4.2 K stress-strain curve and (b) axial lattice strain vs uniaxial tensile stress [viii].

[viii] C. Scheuerlein, M. Di Michiel, F. Buta, B. Seeber, C. Senatore, R. Flükiger, T. Siegrist, T. Besara, J. Kadar, B. Bordini, A. Ballarino, L. Bottura, "*Stress distribution and lattice distortions in Nb_3Sn/Cu multifilament wires under uniaxial tensile loading at 4.2 K*", Supercond. Sci. Technol. 27, (2014), 044021.

Summary: Sources of uncertainty in uniaxial tensile stress-strain measurements of Nb_3Sn/Cu composite wires

- Nb_3Sn/Cu composite wires are not suitable for precise tensile tests. Their constituents are not stress free, the filaments contain porosity and at zero axial load the wires are always bended.
- There is no linear part in the wire loading stress-strain curves.
- The wire stiffness is commonly estimated from the linear slope of unloading stress-strain curves. The slope of these curves is stress and strain dependent.
- Wire stiffness results depend strongly on test and data analysis procedures.
- Wire stress-strain results cannot be easily compared with results obtained with alternative test methods.
- Only few laboratories perform the challenging stress-strain measurements at 4.2 K.

Nb_3Sn mechanical properties at RT

- Published RT Nb_3Sn Young's modulus values vary between 32 GPa to 165 GPa.
- Measuring the mechanical properties of Nb_3Sn is very tricky because:
  - The intermetallic phase Nb_3Sn is stable with Sn contents ranging from about 18-25 at.%.
  - Preparation of Nb_3Sn bulk samples which properties are representative for the Nb_3Sn filaments in multifilament wires is extremely difficult (e.g. because of different Sn gradients, alloying elements, grain size and orientation distribution, and presence of contaminating phases).
  - Determining Nb_3Sn/Nb sub-element Young's moduli from tensile tests, for instance using extracted (brittle) Nb_3Sn filaments, is very delicate.
  - The filaments are a composite, containing Nb_3Sn, unreacted Nb diffusion barriers, porosity and other material. For such materials rule-of-mixture estimates may not be appropriate.

The unusual temperature dependence of the Nb_3Sn mechanical properties and calculation of Nb_3Sn elastic anisotropy in PIT and RRP type wires

- During cooldown Nb_3Sn undergoes a phase transformation at roughly 40 K, which causes a lattice softening.
- This is for instance revealed by the slope of the stress-strain curves acquired at RT and at 4.2 K [viii].
- The Nb_3Sn elastic properties in PIT and RRP wires can be calculated using the Nb_3Sn grain orientation distribution and published Nb_3Sn single crystal elastic constants.
- The results illustrate the different elastic anisotropy in RRP and PIT type wires.
- How reliable are the Nb_3Sn single crystal elastic constants?

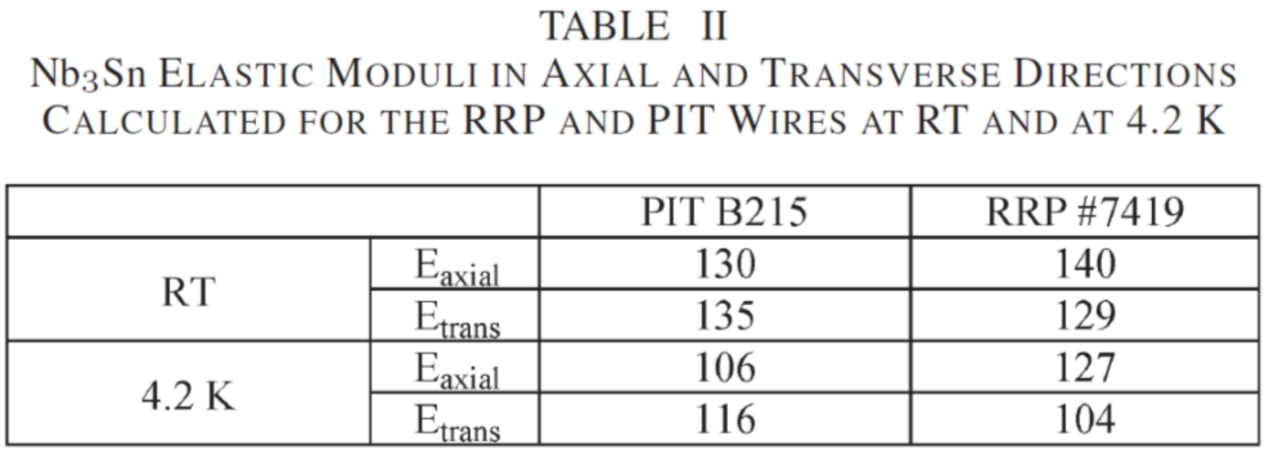


TABLE II

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

From: “Elastic Anisotropy in Multifilament Nb_3Sn Superconducting Wires”, IEEE Trans Appl. Supercond., 25(3), (2015), 8400605

[viii] Supercond. Sci. Technol. 27, (2014), 044021.

Summary: Uncertainties of Nb_3Sn mechanical properties at RT and 4.2 K

- Preparation of Nb_3Sn bulk samples which are representative for the Nb_3Sn in wires for mechanical testing is nearly impossible.
- The mechanical Nb_3Sn properties in the filaments of IT, PIT and Bronze route wires are different.
- Nb_3Sn Young’s moduli calculations rely on the availability of accurate single crystal elastic constants.
- During cooling to below 77 K a Nb_3Sn lattice softening occurs. 77 K mechanical test results do not allow to predict 4.2 K Nb_3Sn mechanical properties.

Transverse compression test of reacted and impregnated Nb_3Sn Rutherford cable stacks

- Transverse compressive loading of a composite is a highly complex load case.
- Transverse compression tests of reacted and impregnated Nb_3Sn Rutherford cable stacks can provide qualitative estimates of the stress-strain behaviour of the Nb_3Sn conductor in magnet coils under monotonic and cyclic azimuthal loading.
- Reacted and impregnated Nb_3Sn Rutherford cable stacks are sometimes also used to determine a so-called "Elastic modulus" of the Nb_3Sn conductor in magnet coils.
- Since Rutherford cable stacks do not exhibit linear elastic behaviour at any stress level, the use of the term "Elastic modulus" in the context of stress-strain measurements of Nb_3Sn cable stacks is misleading.

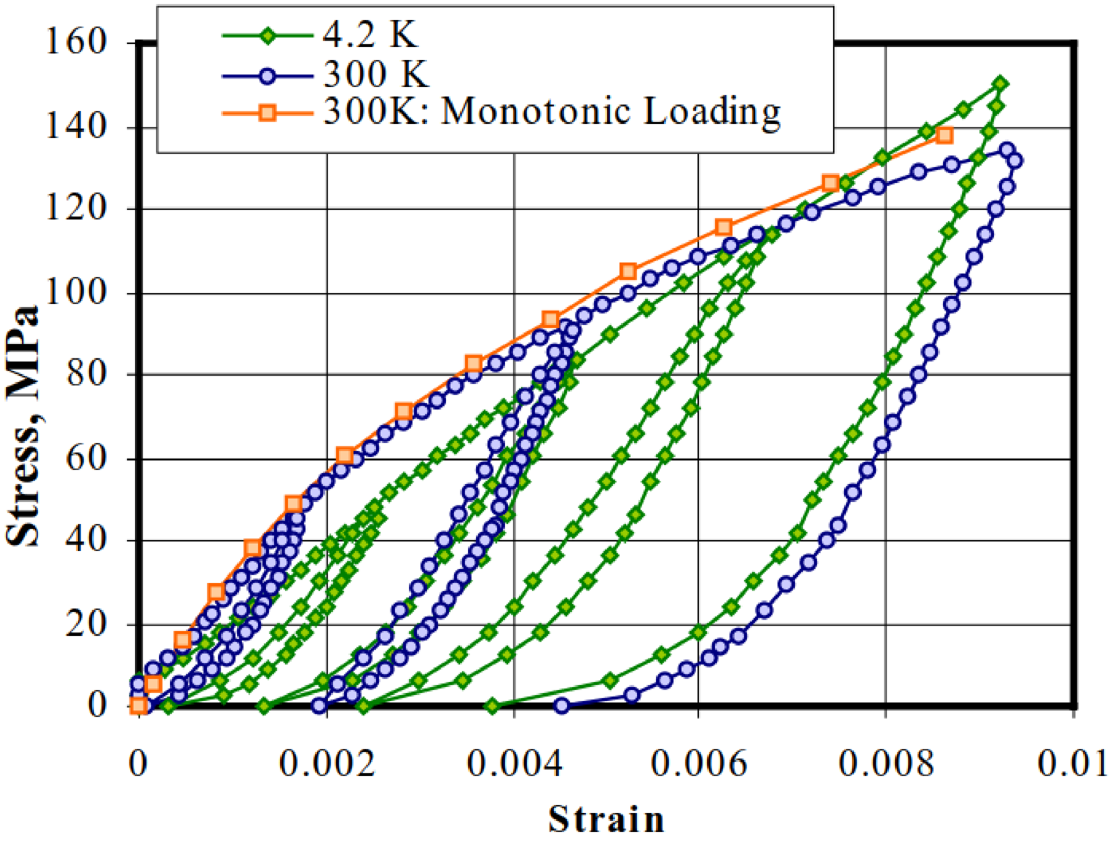


Figure 6: Load-Unload-Reload Tests.

From: D.R. Chichili, T.T. Arkan, I. Terechkine, J.A. Rice, "Niobium-Tin Magnet Technology Development at Fermilab", Proceedings of the 1999 Particle Accelerator Conference, New York, 1999

Sources of uncertainties in transverse compression experiments using reacted and impregnated Nb_3Sn Rutherford cable stacks

- Geometry of Rutherford cable stacks is not suited for precise mechanical testing.
- Stiffness of Rutherford cable stacks is not uniform across the loaded area.
- Geometry of Rutherford cable stacks is only partly representative for the conductor in magnet coils.
- Strong influence of load rate and mechanical cycling on stress-strain behaviour.
- No standard procedures available. Very strong influence of data analysis procedures on stiffness results.
- Stiffness depends on the applied strain and stress.
- Very strong influence of the load direction on stress-strain behaviour.
- Integration of an extensometer in the test set-up is in many cases not possible.
- No easy cross check with other mechanical test methods is possible.

Conclusion

- Nb_3Sn coil and magnet materials properties are anisotropic and load direction dependent.
- Highly accurate Young's moduli can be obtained from dynamic measurements.
- In favourable cases (e.g. Ti6Al4V) Young's moduli can be derived from static stress-strain measurements, using standardised test sample geometries and test procedures.
- Transverse compression tests of reacted and impregnated Nb_3Sn Rutherford cable stacks can provide qualitative estimates that may be representative for the stress-strain behaviour of the Nb_3Sn conductor in magnet coils under monotonic and cyclic loading.
- Results of transverse compression tests of reacted and impregnated Nb_3Sn Rutherford cable stacks cannot be used to precisely predict stress levels in magnets.
- The use of the term Young's modulus or elastic modulus in the context of stress-strain measurements of Rutherford cable stacks is misleading.
- Stress-strain tests at 77 K do not allow to predict Nb_3Sn behaviour at 4.2 K.

Back-up slides

Calculation of Young’s modulus from resonance frequencies

For long thin beams with rectangular cross section the Young´s modulus (E) is calculated from the mass (m), length (L), width (b) and thickness (t) of the beam, and its fundamental frequency in bending (f_f).

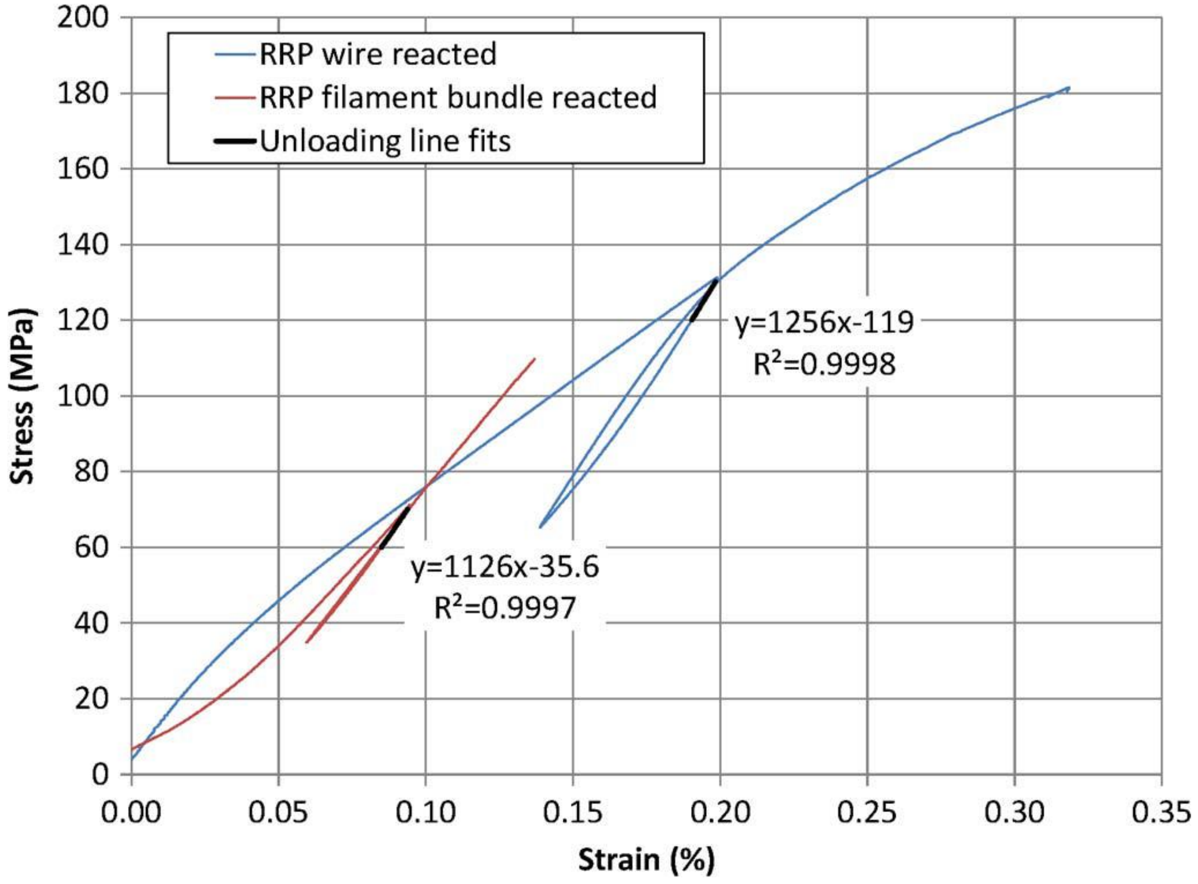
$$E = 0.9465\left(\frac{m{f_f}^2}{b}\right)\left(\frac{L^3}{t^3}\right)T$$

where

$$T = 1 + 6.858\left(\frac{t}{L}\right)^2$$

[iii] ASTM E 1875 “*Standard Test Method for Dynamic Young´s Modulus, Shear Modulus, and Poisson´s Ratio by Sonic Resonance*”. 2013, ASTM International

Uniaxial tensile testing of extracted Nb_3Sn filaments



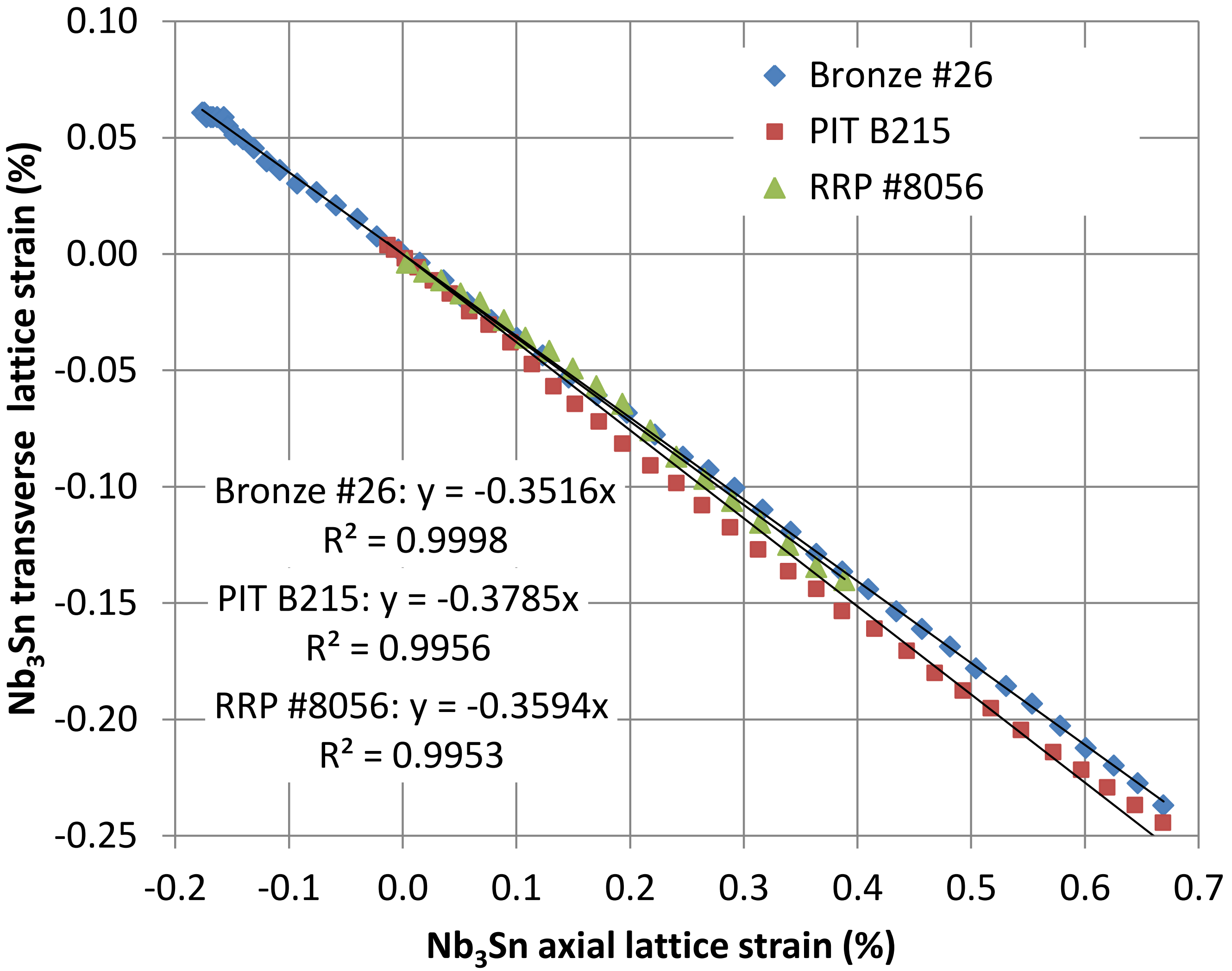
Stress-strain curves of a reacted RRP wire and its extracted filaments measured at room temperature. From : IEEE TAS, 25(3), (2015), 8400605

Summary of 11 T dipole materials elastic and plastic properties

Material	$R_{p0.2}$ (MPa)	R_m (MPa)	A (%)	Z (%)	Young's modulus dynamic (GPa)		Young's modulus static (GPa)	
					Resonance	Impulse	Tensile	Compr.
316LN_L	351±12	674±2	54±5	63±2	191±0.3	191±0.3	183±7	n.m.
316LN_T	324±4	658±1	53±5	63±1	n.m.	n.m.	203±15	n.m.
Magnetil_L	117±3	241±1	n.m.	73±3	196±0.8	196±0.3	208±19	n.m.
Magnetil_T	124±2	267±1	47±2	71±4	219±0.1	218±0.3	213±3	n.m.
YUS-130_L	401	793	71	66	196±0.9	196±0.3	196	n.m.
YUS-130_T	415	749	51	66	193±1.1	192±0.3	189	n.m.
Ti-6Al-4V_L	868±5	930±12	17±1	28±2	115	114	115±1	120±2
Ti-6Al-4V_T	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	116±2
DISCUP no-HT_L	332±2	387±1	22±2	43±4	92.9±0.2	93.8±0.3	87±1	89±1
DISCUP no-HT_T	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	n.m.	96±2
DISCUP HT_L	284±1	376±1	26±1	48±1	96.7	96.3	91±1	87±2

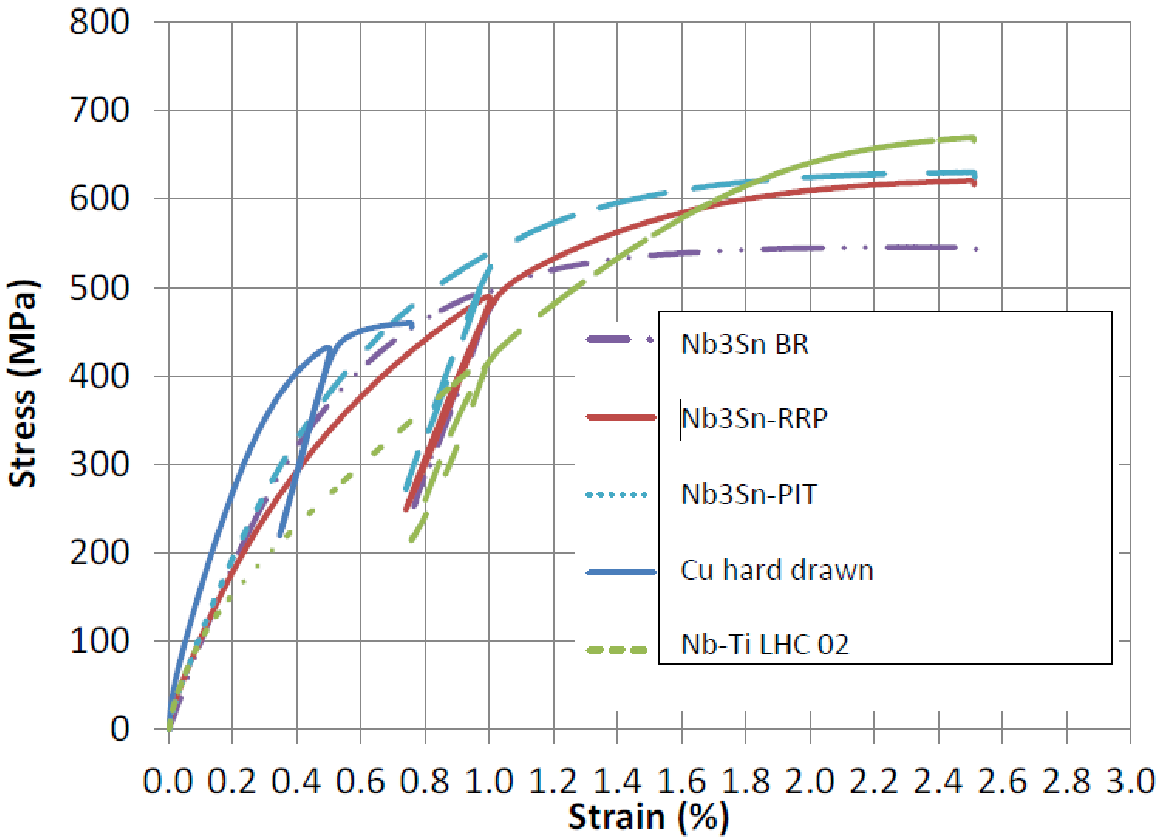
[v] C. Scheuerlein, F. Lackner, F. Savary, B. Rehmer, M. Finn, P. Uhlemann, "*Mechanical properties of the HL-LHC 11 Tesla* Nb_3Sn *magnet constituent materials*", IEEE Trans. Appl. Supercond., 27(4), (2017), 4003007

Nb_3Sn Poisson ratio at 4.2 K



Comparison of the 4.2 K Nb_3Sn Poisson ratio in the BR, PIT and RRP wire.
From: Supercond. Sci. Technol. **27** (2014) 044021 (7pp)

Mechanical properties of unreacted Nb_3Sn wires



Comparison of the stress-strain curves of unreacted Nb_3Sn (PIT, RRP and BR), hard drawn Cu and LHC Nb-Ti wire.

From: R. Bjoersted et al, "Mechanical properties of unreacted Nb_3Sn/Cu composite wires used for cable production", CERN, Technical note EDMS Nr: 1421825