Thermo-mechanical properties of Nb_3Sn coil and magnet materials

C. Scheuerlein, EuroCirCol preparation meeting, 24 January 2018

Table II: Material Data for the exploration of 16T dipole design options						
Material	Stress limit (MPa, Von Mises)		E (GPa)		ν	α
	293 K	4.2 K	293 K	4.2 K*	293 K /4.2 K	293 K→4.2 K
Coil	150	200	EX=52 EY=44 GXY=21	EX=52 EY=44 GXY=21	0.3	X=3.1E-3 Y=3.4E-3
Austenitic steel 316LN	350	1050	193	210	0.28	2.8E-3
Al 7075	480	690	70	79	0.3	4.2E-3
Ferromagnetic iron	180	720	213	224	0.28	2.0E-3
Pole (Ti6Al4V)	800	1650	130	130	0.3	1.7E-3

**In accordance to the experience of the LARP program, we use the same coil elastic modulus at warm and at cold. This may evolve when performing the final design if new data will be available.*

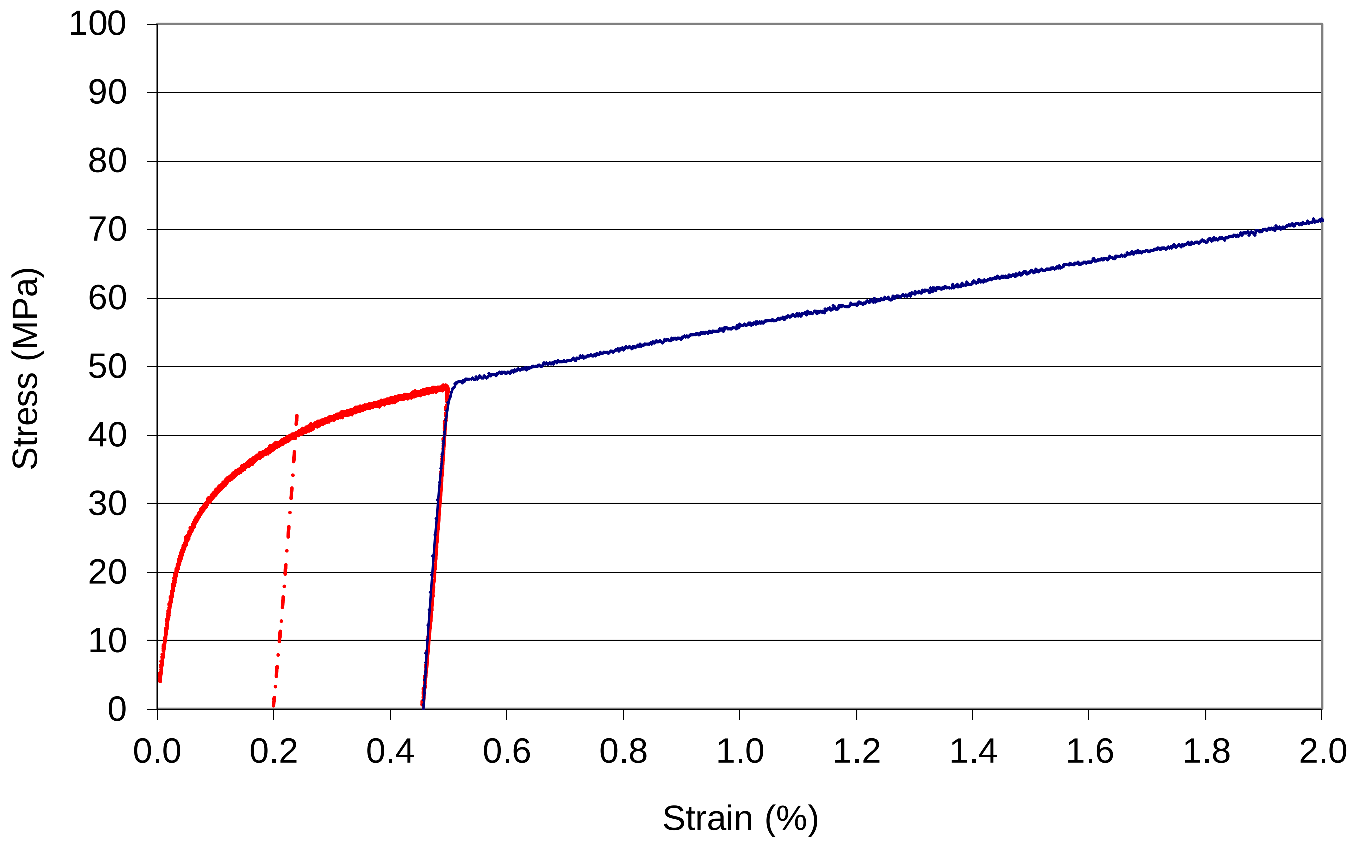
X cable side direction (radial in cos-theta), Y cable face direction (azimutal in cos-theta).

What are the mechanical materials properties required as input in the SC magnet FE models?

- For which materials need the mechanical properties be known?
- How is "stress limit" defined? How much plastic deformation is acceptable?
- Can the 0.2% proof stress ($R_{p0.2}$) be exceeded? As an example at RT $R_{p0.2}$ of Magnetil is about 120 MPa.
- How are shear moduli taken into account in the FE models?
- Is fatigue taken into account? If yes, how many load cycles need to be considered?
- What are the principal stress directions (e.g. needed to take into account anisotropic materials properties)?
- What is the meaning of the RT and 4.2 K conductor bock stress limits of 150 MPa and 200 MPa, respectively? How much plastic coil deformation is acceptable? ($R_{p0.2}$ of fully annealed OFE Cu is at RT about 40 MPa)
- For which materials pairs are the friction coefficients taken into account in the FE models?

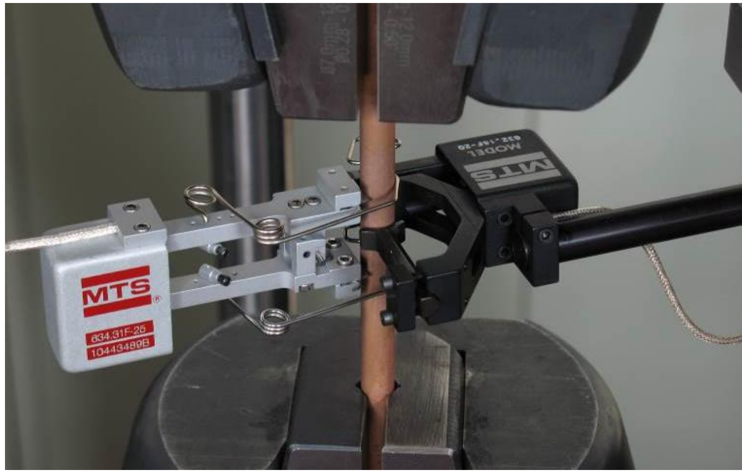
Annealed Cu in the Nb_3Sn conductor block

- The 0.2% proof stress ($R_{p0.2}$) of the annealed Cu in the Nb_3Sn conductor block is about 40 MPa.
- The yield strength of annealed Cu is very difficult to measure, but it is probably roughly 10 MPa.



Stress-strain curve of fully annealed Cu wire (cold-drawn and after subsequent 695 °C HT) [ii].

Young's modulus (E), shear modulus (G), Poisson's ratio (μ) relationship



- For isotropic materials: $$\mu = \frac{E}{2G} - 1$$ Equation 1

- Equation 1 is confirmed for instance for the 11 T dipole Ti6Al4V pole wedges ($E_{Ti6Al4V}$=116 GPa, $G_{Ti6Al4V}$=44.1 GPa and $\mu_{Ti6Al4V}$=0.32±0.03 are measured, and μ=0.32 is calculated from the measured E and G values).
- The relationship is not valid for the strongly textured DISCUPC30/3 coil wedges ($E_{DISCUP-L}$=98.7 GPa, $G_{DISCUP-L}$=53.2 GPa and μ_{DISCUP}=0.43±0.02 are measured).
- For DISCUP Equation 1 is not valid (it would give a negative μ value).

[i] 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., 28(3), 2018, DOI 10.1109/TASC.2018.2792485

Friction coefficients

- At RT in air at a pressure of 100 MPa Ti6Al4V shows smooth and stable sliding against 316LN with a friction coefficient of ~0.4.
- At 4.2 K@100 MPa a strong stick-slip effect is observed, which could be one potential origin of magnet quenches.
- Application of the solid lubricant MoS_2 lowers the 4.2 K friction coefficient to about 0.08.
- In liquid He at 100 MPa Polyimide shows smooth and stable sliding against steel 316 LN with a friction coefficient of ~0.2.

Fig. 2. Samples: left: Ti6Al4V pads; right: steel 314LN cylinders

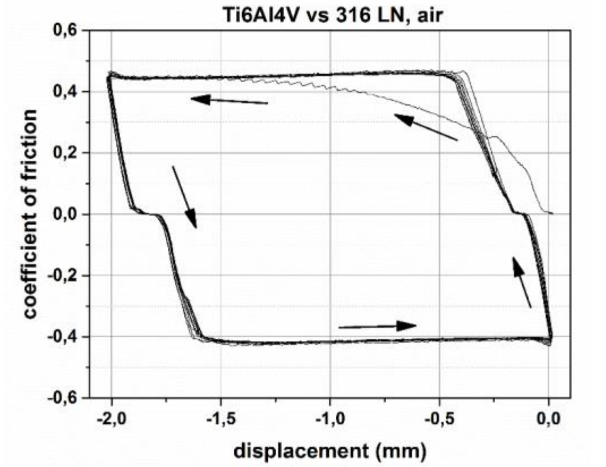


Fig. 3. Friction coefficient vs. displacement of Ti6Al4V against stainless steel 316LN in air at room temperature: smooth sliding, no static friction peak, no stick-slip

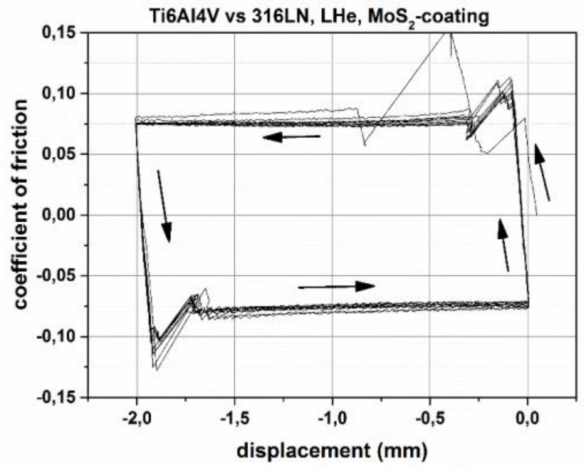


Fig. 5. Friction coefficient vs. displacement of Ti6Al4V with MoS2 coating against stainless steel 316LN in liquid helium (T = 4.2 K): smooth and stable sliding but distinct static friction peak

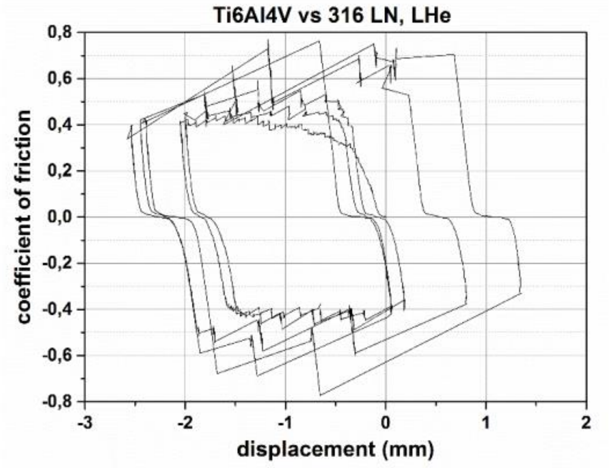
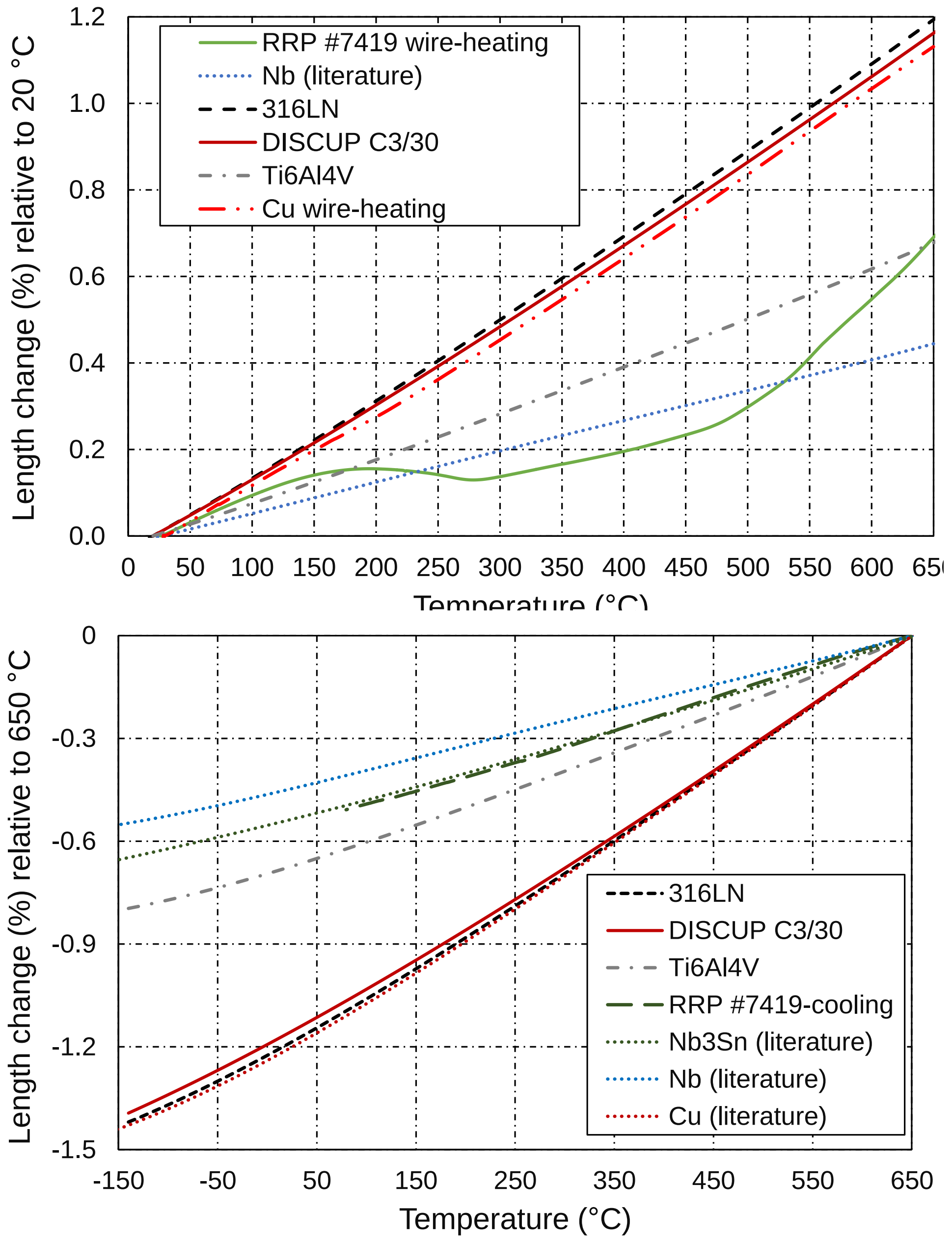


Fig. 4. Friction coefficient vs. displacement of Ti6Al4V against stainless steel 316LN in liquid helium (T = 4.2 K): strong stick-slip effect after the first friction cycle

T. Gradt, C. Scheuerlein, F. Lackner, F. Savary, "*Friction-coefficient between the Ti6Al4V loading pole and the 316LN steel shims of the HL-LHC 11 T magnets*", IEEE Trans. Appl. Supercond., 28(3), 2018, 10.1109/TASC.2018.2792469

Temperature dependent expansion

- Can be measured with a dilatometer using stress-free, homogeneous rectangular samples with typical dimensions 4 mm × 4 mm × 25 mm.
- Nb_3Sn composite wires are not suited for dilation experiments, but the overall wire length change behaviour maybe described qualitatively.



Relative length change of DISCUP C30/3, Ti6Al4V, 316LN and Nb3Sn RRP type wire during (a) first heating and (b) cool down from 650 °C. The thermal expansions of Cu, Nb and Nb_3Sn bulk are shown for comparison.

Back-up slides

Magnetil mechanical properties

TABLE III
TENSILE TESTS AT DIFFERENT TEMPERATURES, SAMPLES FROM LONGITUDINAL AND TRANSVERSAL ROLLING DIRECTIONS (FROM PALLET 956 030 0001 IN [7])

	Temperature (K)	Young's Modulus (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)
L direction	295	205	115	249	32	52
T direction	295	200	123	282	26	44
L direction	233	196	151	260	~25	~50
T direction	90	210	642	653	5.9	20
-	77	221	821	828	-	10.1
L direction	7	200	-	723	0.5	0.5
T direction	7	211	-	926	0.5	0.5

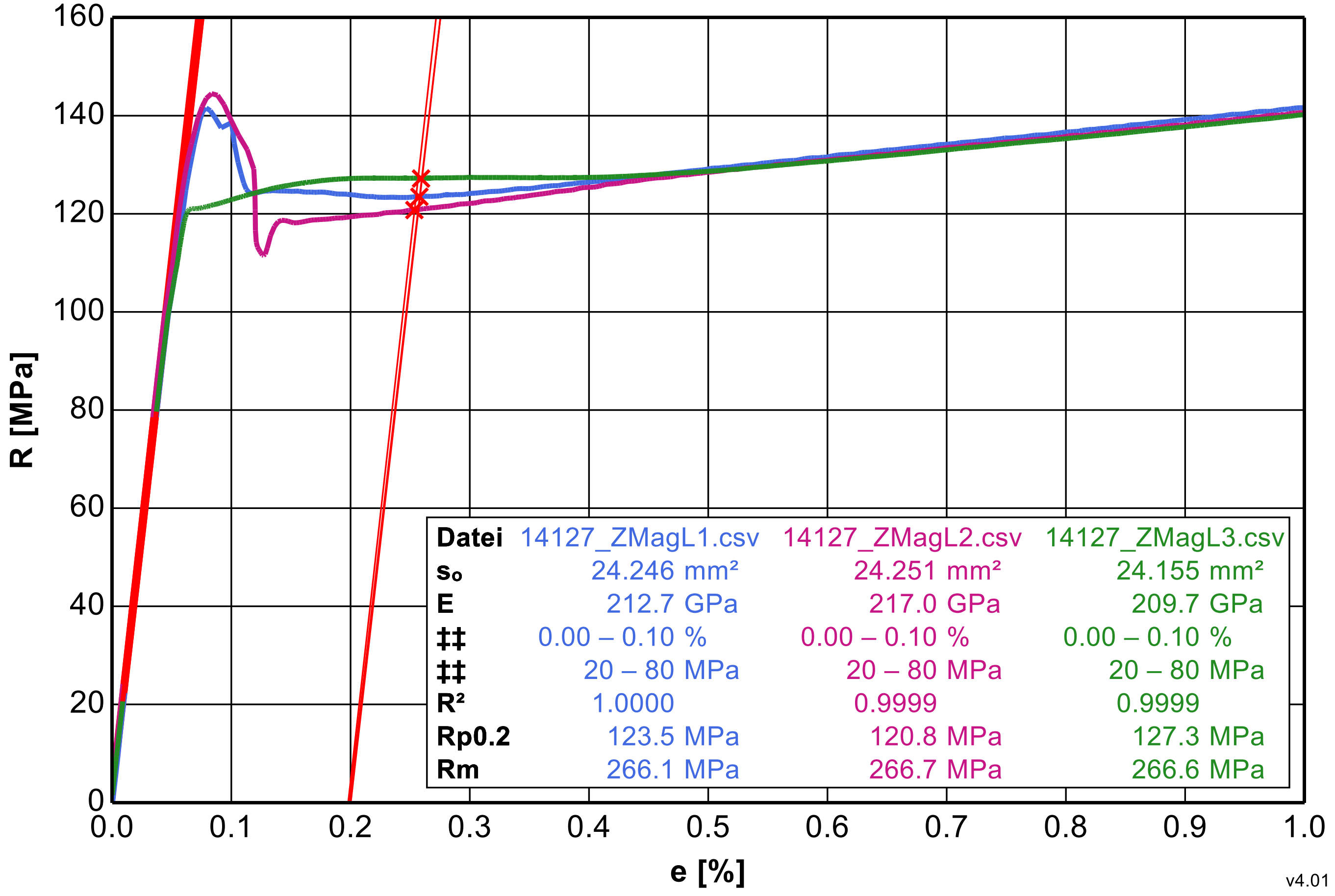
From: F. Bertinelli, S. Comel, P. Harlet, G. Peiro, A. Russo, A. Taquet, “Production of Low-Carbon Magnetic Steel for the LHC Superconducting Dipole and Quadrupole Magnets”, *IEEE Trans. Appl. Supercond.* vol. 16, no. 2, 2006, pp 1777-1781

Summary of some 11 T dipole elastic and plastic RT materials 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

[ii] 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

Magnetil



Magnetil stress strain curves in longitudinal direction at RT.

Courtesy B. Rehmer, Federal Laboratory for Materials Research and Testing (BAM).

Summary elastic properties of Ti6Al4V pole wedge

- [i] Ti6Al4V **at RT:**

  E=116 GPa G=44.1 GPa μ=0.32±0.03

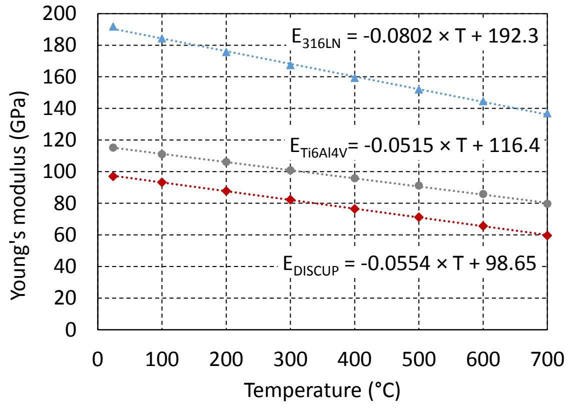
- [ii] Ti6Al4V at RT:

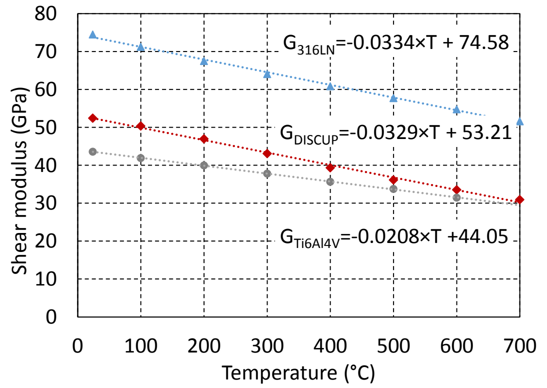
  E=113.8 GPa G=44.0 GPa μ=0.342.

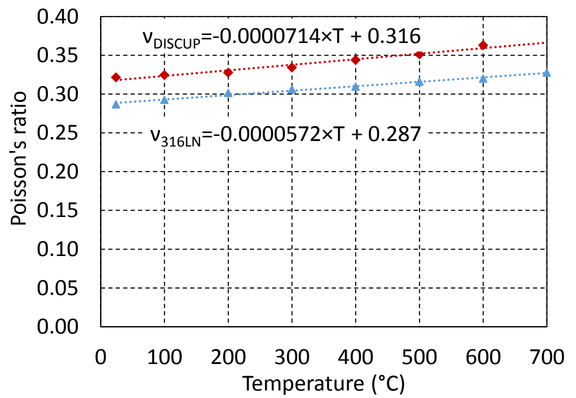
- [i] Ti6Al4V **at 4.2 K*:**

  E=130 GPa G=50 GPa μ=0.34

- *4.2 K values are extrapolated from temperature dependent measurements in the range 20 °C-700 °C [i].
- Ti6Al4V exhibits linear elastic behaviour up to about 800 MPa (at RT), and mechanical properties are not strongly anisotropic.







[i] C. Scheuerlein, F. Lackner, F. Savary, B. Rehmer, M. Finn, C. Meyer, “Thermomechanical behavior of the HL-LHC 11 Tesla Nb3Sn magnet coil constituents during reaction heat treatment”, IEEE Trans. Appl. Supercond., 28(3), 2018, DOI 10.1109/TASC.2018.2792485

[ii] http://www.matweb.com/search/DataSheet.aspx?MatGUID=a0655d261898456b958e5f825ae85390

Summary mechanical properties of DISCUP C30/3 coil wedge

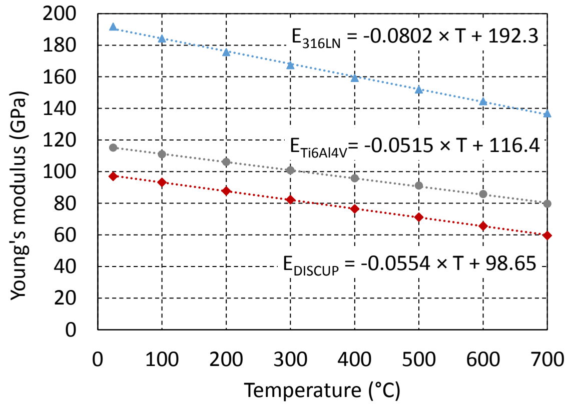
- [i] DISCUP C30/3 **at RT in longitudinal direction:**

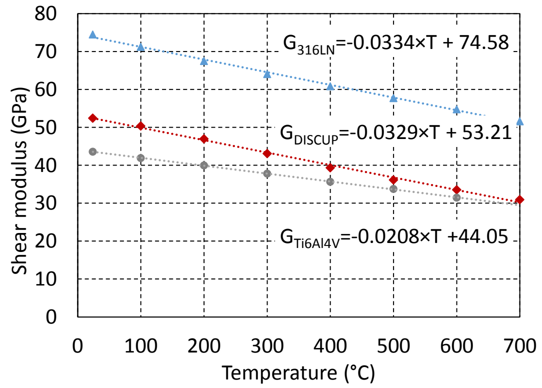
  E=92 GPa G=54 GPa μ=0.43±0.02

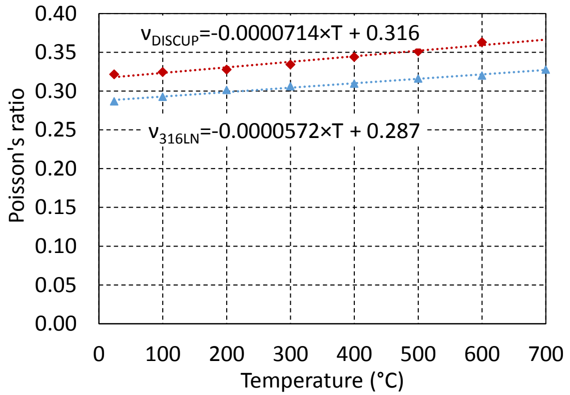
- [i] DISCUP C30/3 **at 4.2 K in longitudinal direction*:**

  E=113 GPa G=62 GPa μ=???

- *4.2 K values are extrapolated from temperature dependent measurements in the range 20 °C-700 °C [i].
- Strong elastic anisotropy, maximum E at an angle of about 50° with respect to wedge extrusion direction.



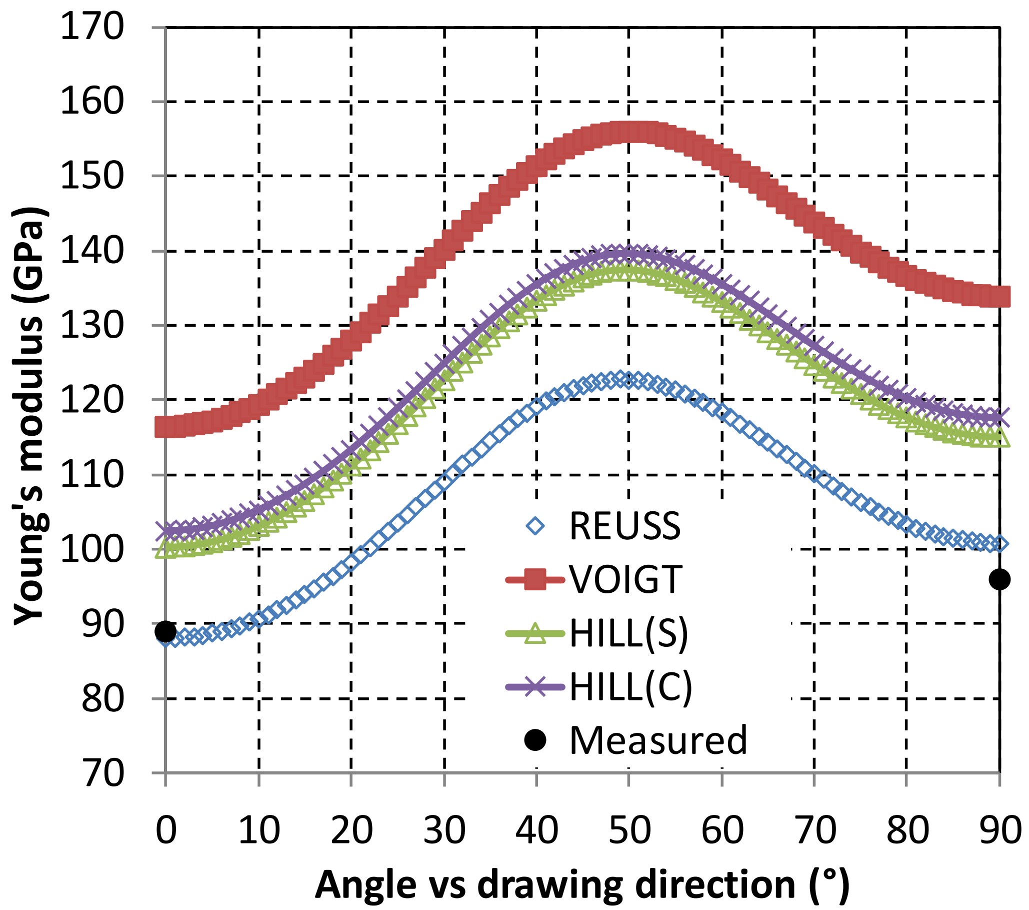




[i] DOI 10.1109/TASC.2018.2792485

Elastic anisotropy in the 11 T dipole DISCUP coil wedges

- In order to take into account anisotropic materials properties the principal stress directions need to be known.
- The angular dependence of the DISCUP 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%.
- 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 [i].
- These values are substantially lower than the values between 115 to 130 GPa found in literature for ODS Copper.



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 [i] are shown for comparison. ***Courtesy of W. Gan, Helmholtz-Zentrum Geesthacht.***