Discussion

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8th of November 2016, Annual EuroCirCol meeting

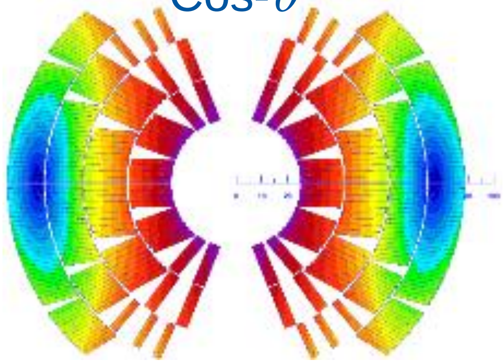
Discussion

- Comparison of different design options in terms of performance to be able to take a decision on the reference option or options for the CDR
- Distribution of the work for the reference option(s)
- Structural FEA analysis, possible options and optimization criteria
- Material properties of materials used in the magnet (focus on wedges)
- Required loadline margin in the ends
- Yield strength in the iron/steel
- Cost model considerations

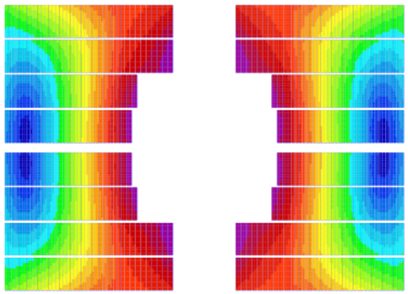
Magnet design for 16 T (EuroCirCol – 18%)

Design		Cos-θ	Block	Common-C
Operating current	(kA)	10.275	8.47	9.0
Field in the aperture	(T)	16.0	16.0	16.0
Margin at 4.2 K	%	10.0	9.3	10.0
Intrabeam spacing	(mm)	250	250	280
Stored magnetic energy per unit length/ap	(MJ/m)	1.5	1.7	2.4
Inductance/aperture	(mH/m)	25	44	58
LI/aperture	(H.A/m)	257	374	522
Diameter IL	(mm)	1.1	1.1	1.1
Strands/cable IL	-	28	24	24
Cu/Non-Cu IL	-	1.0	1.0	1.0
Diameter OL	(mm)	0.7	0.7	1.05-1.1
Strands/cable OL	-	38	37	14-12
Cu/Non-Cu OL	-	2.0	1.0	1.8-2.2
Total area of Cu/aperture	(mm^2)	5004	4751	5400
Total area of Non-Cu/aperture	(mm^2)	3403	4751	3470
Total mass of Non-Cu for FCC-hh	(t)	3876	5412	3954
Total mass of conductor for FCC-hh	(t)	9576	10824	10104
J_{eng} IL	(A/mm^2)	386	371	394
J_{eng} OL	(A/mm^2)	703	595	789
J_{overal} IL	(A/mm^2)	270	260	265
J_{overal} OL	(A/mm^2)	459	386	480
Hot spot temperature	(K)	328	308	350
Voltage to ground	(V)	1400	1200	TBA
Voltage turn-to-turn	(V)	103	82	TBA
V layer-to-layer	(V)	1800	1100	TBA

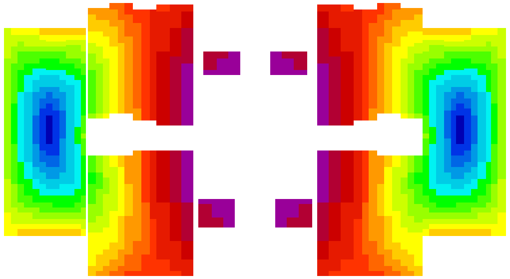
Cos-θ



Block



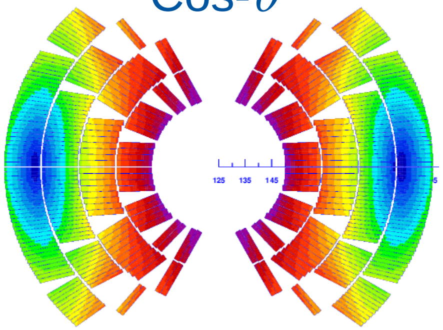
Common-Coil



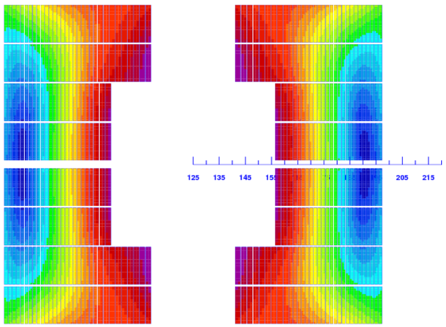
Magnet design for 16 T (EuroCirCol – 14%)

Design		Cos-θ	Block	Common-C
Operating current	(kA)	11.18	10.93	9.17
Field in the aperture	(T)	16.0	16.0	16.0
Margin at 1.9 K	%	14.0	14.0	14.0
Intrabeam spacing	(mm)	250	250	320
Stored magnetic energy per unit length/ap	(MJ/m)	1.3	1.5	2.1
Inductance/aperture	(mH/m)	19.9	24	49
LI/aperture	(H.A/m)	222	262	452
Diameter IL	(mm)	1.1	1.1	1.2
Strands/cable IL	-	22	24	18
Cu/Non-Cu IL	-	0.85	0.8	1
Diameter OL	(mm)	0.712	0.7	1.2-1.15
Strands/cable OL	-	36	39	10
Cu/Non-Cu OL	-	2.15	1.6	2.2-3.5
Total area of Cu/aperture	(mm^2)	3920	4300	4971
Total area of Non-Cu/aperture	(mm^2)	2730	3295	2572
Total mass of Non-Cu for FCC-hh	(t)	3110	3750	2930
Total mass of conductor for FCC-hh	(t)	7590	8650	8590
J_{eng} IL	(A/mm^2)	540	480	450
J_{eng} OL	(A/mm^2)	780	730	760
J_{overal} IL	(A/mm^2)	360	330	320
J_{overal} OL	(A/mm^2)	510	480	490
Hot spot temperature	(K)	344	350	*384*
Voltage to ground	(V)	770	1200	*3200*
Voltage turn-to-turn	(V)	86	105	*100*
V layer-to-layer	(V)	910	-	*4300*

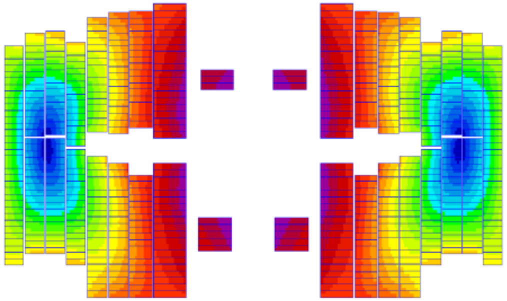
Cos-θ



Block



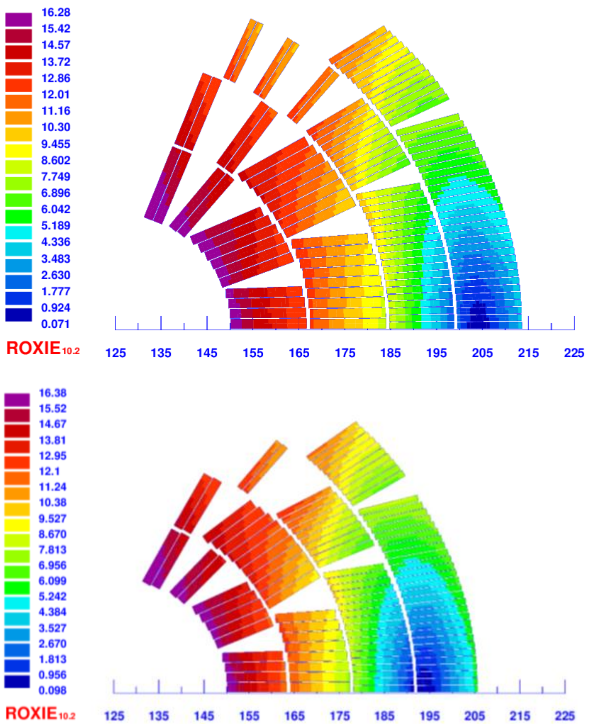
Common-Coil



Auxiliary coils not shown

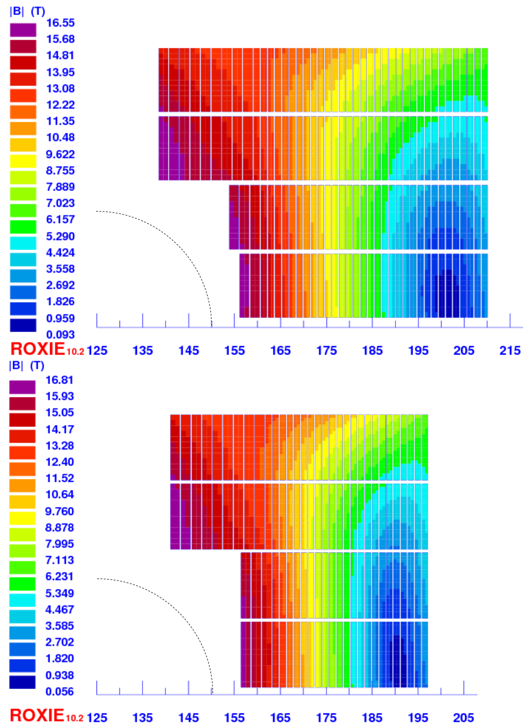
EuroCirCol-Design options

A specific feature of this program is that different design options are being considered with the same specification and analysis tools so that they can be compared relatively to each other.



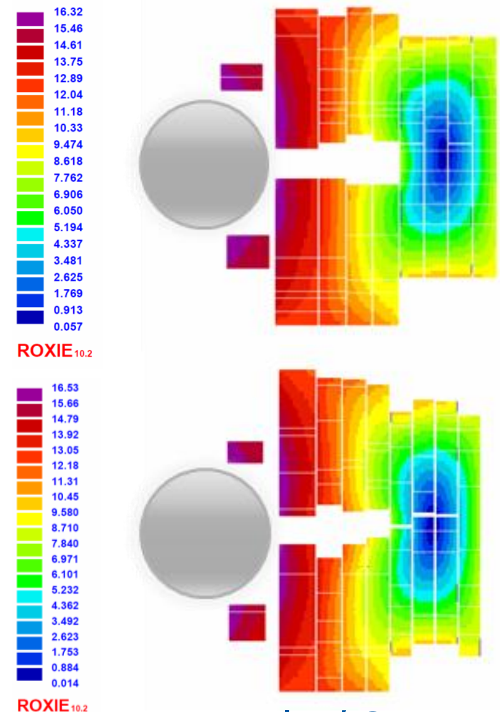
2LPo1D-02

M.Sorbi; G.Bellomo; P.Fabbricatore; S.Farinon; V.Marinozzi; G.Volpini



2LPo1D-03

C.Lorin; M.Durante; M.Segreti



scale / 2

2LPo1D-08

F.Toral; J.Munilla; T.Martinez; L. Garcia-Tabares

The reference parameter space has been finalized considering recommendations from the 1st WP5 EuroCirCol Review (11-13 May 2016, http://indico.cern.ch/event/516049)

Distribution of the work

Structural FEA analysis, possible options and optimization criteria (1/12)

- Von Mises, Third Principal Stress, Azimuthal stress -> Barbara/Stefania
- Plane stress vs strain -> Barbara/Stefania
- Stress pattern within the cos-theta coil -> Barbara/Stefania

Plane stress vs plane strain (2/12)

Plane stress:

- All stress components that are associated with magnet longitudinal dimension are zero (shear and normal stress)

Plane Stress Problem: $\sigma_{33} = \sigma_{13} = \sigma_{23} = 0 \quad \sigma_{11} \neq 0 \quad \sigma_{22} \neq 0 \quad \sigma_{12} \neq 0$

$$\varepsilon_{11} = \frac{1}{E}\left[\sigma_{11} - \nu\sigma_{22}\right] + \alpha_T \Delta T \qquad \varepsilon_{22} = \frac{1}{E}\left[\sigma_{22} - \nu\sigma_{11}\right] + \alpha_T \Delta T$$

$$\varepsilon_{33} = \frac{-\nu}{E}\left(\sigma_{11} + \sigma_{22}\right) + \alpha_T \Delta T \qquad \varepsilon_{12} = \frac{1-\nu}{E}\sigma_{12}$$

Plane strain:

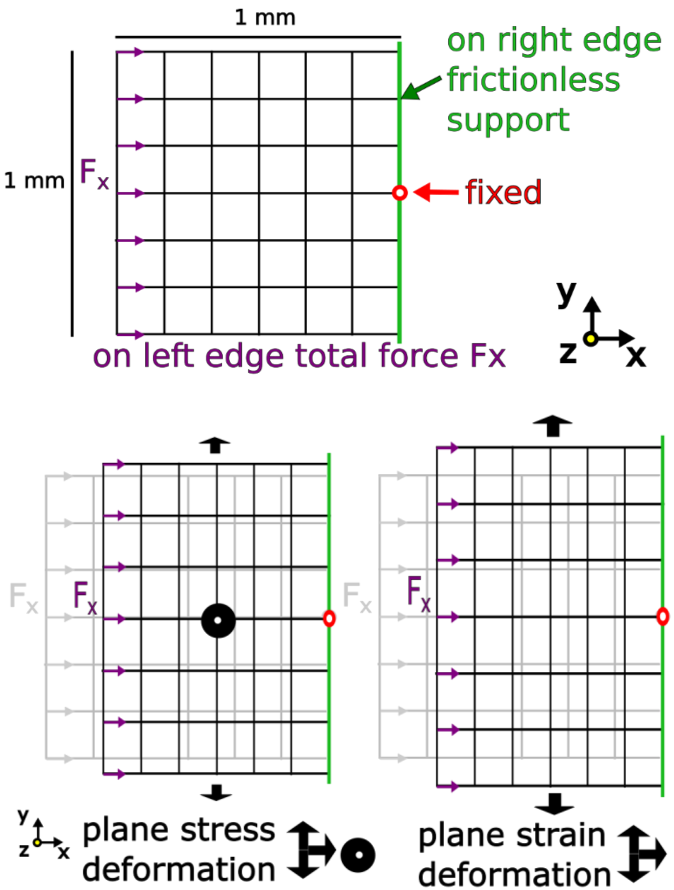
- All strain components that are associated with magnet longitudinal dimension are zero (shear and normal strain)

$$\varepsilon_{11} = \frac{1}{E}\left[\sigma_{11} - \nu\left(\sigma_{22} + \sigma_{33}\right)\right] + \alpha_T \Delta T \qquad \varepsilon_{22} = \frac{1}{E}\left[\sigma_{22} - \nu\left(\sigma_{11} + \sigma_{33}\right)\right] + \alpha_T \Delta T$$

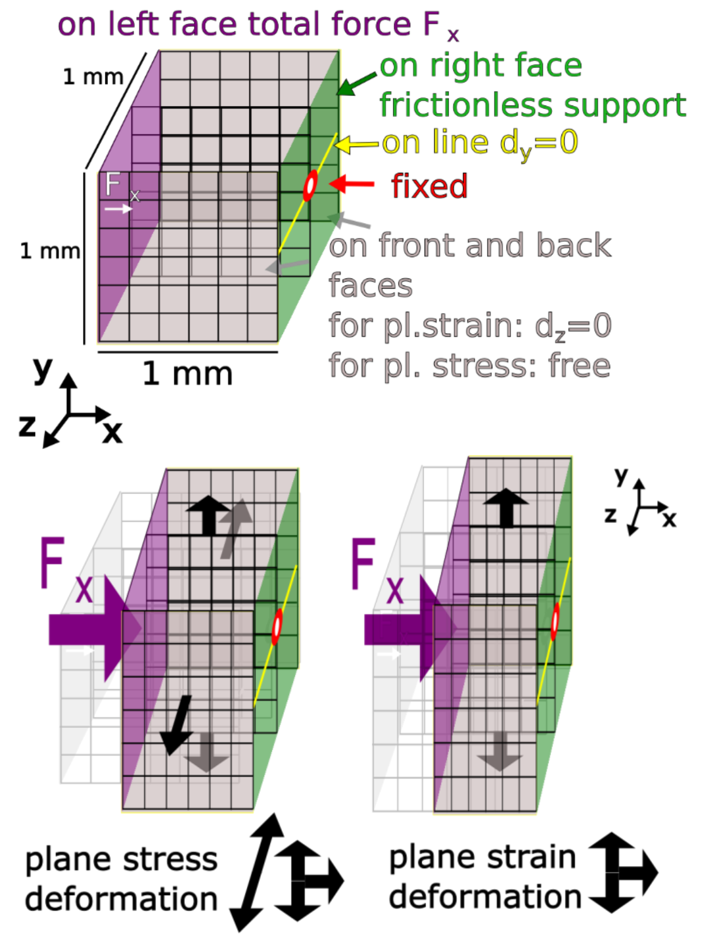
$$0 = \frac{1}{E}\left[\sigma_{33} - \nu\left(\sigma_{11} + \sigma_{22}\right)\right] + \alpha_T \Delta T \qquad \varepsilon_{12} = \frac{1-\nu}{E}\sigma_{12}$$

2D and 3D model (3/12)

2D model boundary conditions, $F_x = 68$ N



3D model boundary conditions, $F_x = 68$ N



E = 200 GPa, $\nu = 0.3$

Plane strain vs stress (4/12)

- Plane stress allows *z*-displacement and plane strain does not
- Plane-strain assumption e_33: $0 = \frac{1}{E}[\sigma_{33} - \nu(\sigma_{11} + \sigma_{22})] + \alpha_T \Delta T$
- Plane stress: $F_z = \nu F_x$ (friction less boundary)

Von Mieses:

$$\sigma_v = \sqrt{[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}$$

Plane stress:

$$\sigma_v = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1\sigma_2}$$

Plain strain:

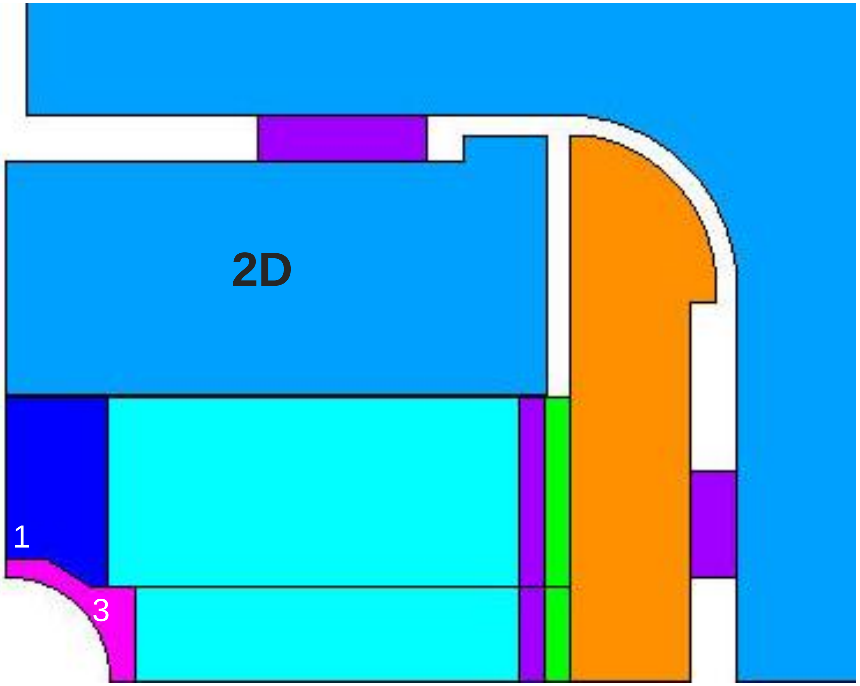
$$\varepsilon_3 = \frac{1}{E}[\sigma_3 - \nu(\sigma_1 + \sigma_2)] = 0$$

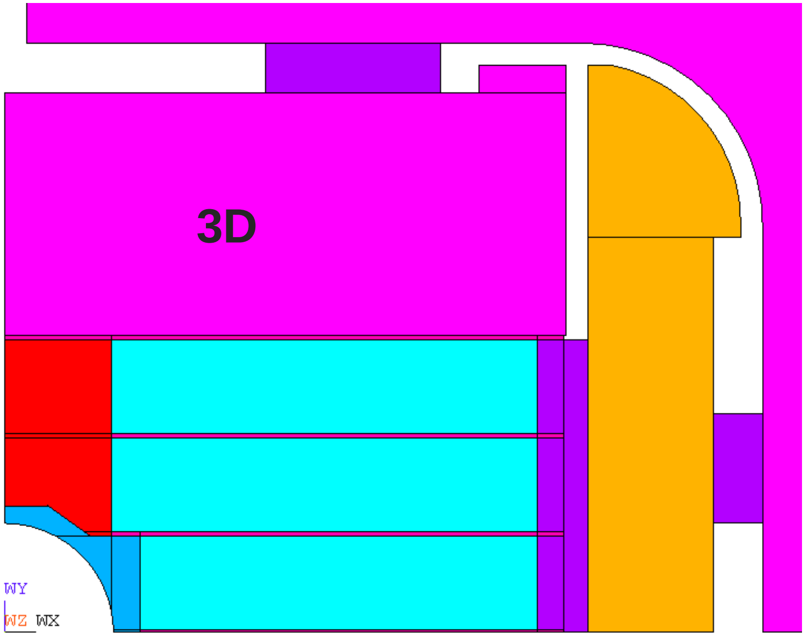
$$\sigma_3 = \nu(\sigma_1 + \sigma_2)$$

$$\sigma_v = \sqrt{(\sigma_1^2 + \sigma_2^2)(\nu^2 - \nu + 1) + \sigma_1\sigma_2(2\nu^2 - 2\nu - 1)}$$

Uniform result values over the cube				
type		analytic, FEM 2D / 3D	analytic, FEM 2D / 3D	
Bound Cond		pl. strain	pl. stress	
	Dim			Unit
Strain	X	-0.3094	-0.34	mm/m
	Y	0.1326	0.102	mm/m
	Z	0 (Bound cond!)	0.102	mm/m
Stress	X	-68	-68	MPa
	Y	0	0	MPa
	Z	-20.4	0 (Bound cond!)	MPa
Von-Mises		60.44	68	MPa
Shear Strain	XY YZ XZ	ε xy=0, ε yz=ε xz=0 (BC!)	ε xy=0, ε yz=0, ε xz=0	mm/m
Shear stress	XY YZ XZ	S xy=0,S yz=0, S xz=0	S xy=0, S yz=S xz=0 (BC!)	MPa

RMM: Geometry (5/12)





Contacts:
- Pole – pole: sliding (contacts 1 and 3 only)
- Middle coil – external coil: sliding
- Inside coil (pole, layer, inter-layer): bonded

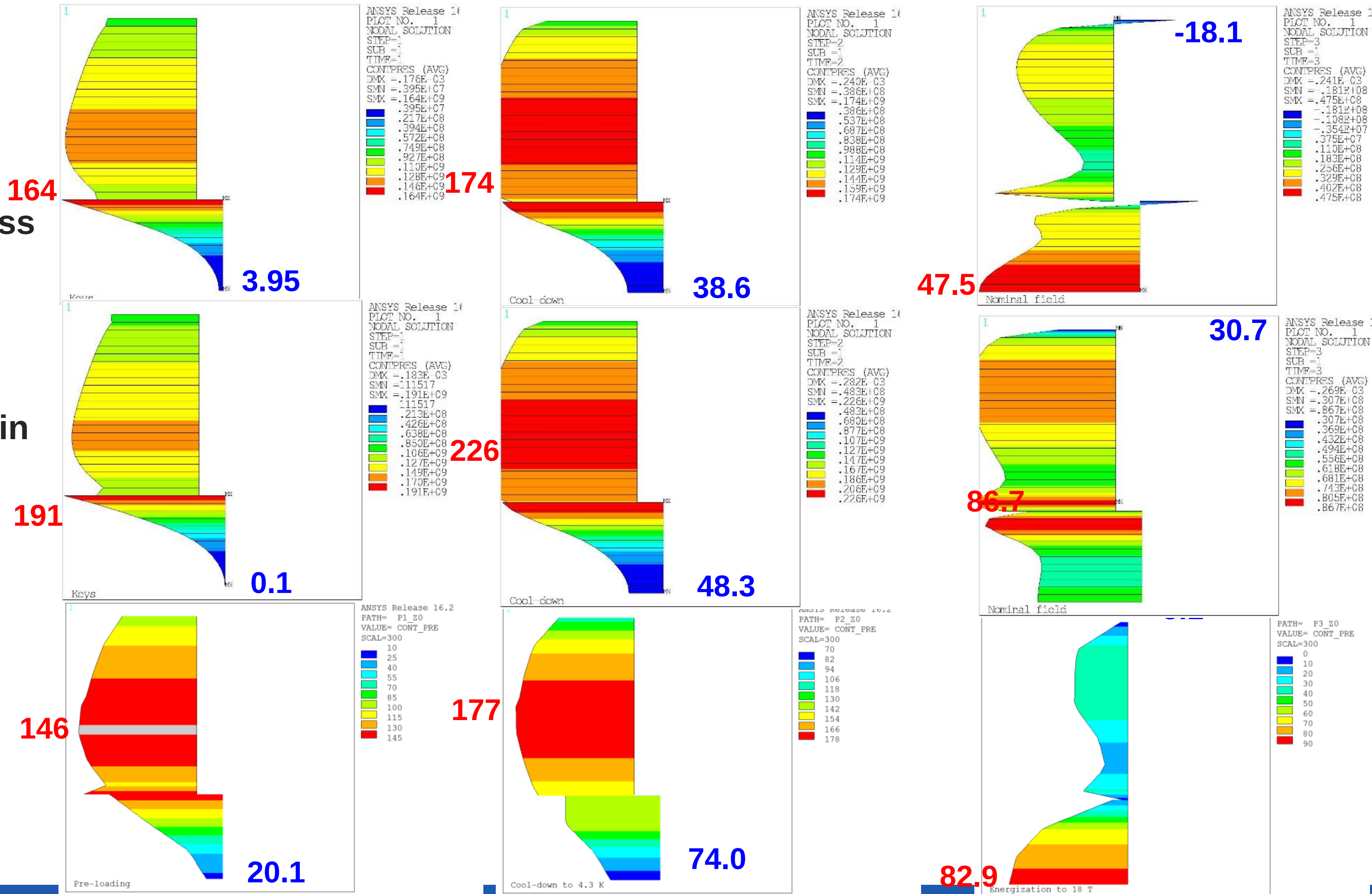
Coil properties:
- 44 GPa isotropic cold and warm
- 3.36/3.08 mm/m orthotropic

RMM: Contacts (6/12)

2D Pl Stress v18

2D Pl Strain v18

3D v5d

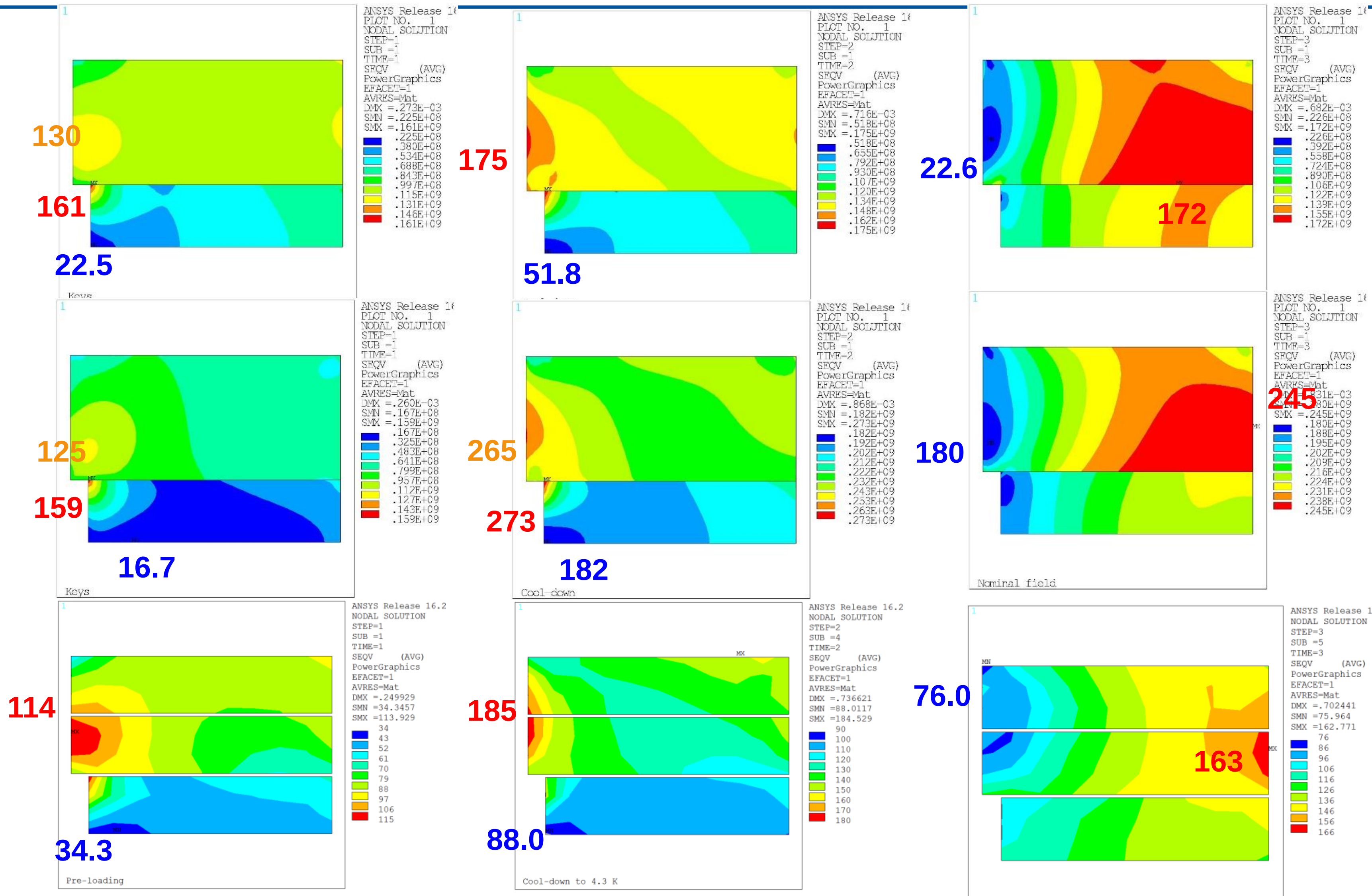


RMM: Coil Seqv (7/12)

2D
Pl Stress
v18

2D
Pl Strain
v18

3D
v5d



RMM: Summary (8/12)

	Contact [MPa]			Seqv [MPa]		
	Loading	4.2 K	18 T	Loading	4.2 K	18 T
3D	20.1..146	74.0..177	5.1..82.9	34.3..114	88.0..185	76.0..163
2D P. stress	4.0..164	38.6..174	-18.1[1]..47.5	22.5..130[2]	51.8..175	22.6..172
2D P. strain	0.1..191	48.3..226	30.7..86.7	16.7..125[2]	182..265[2]	180..245

+/-10%

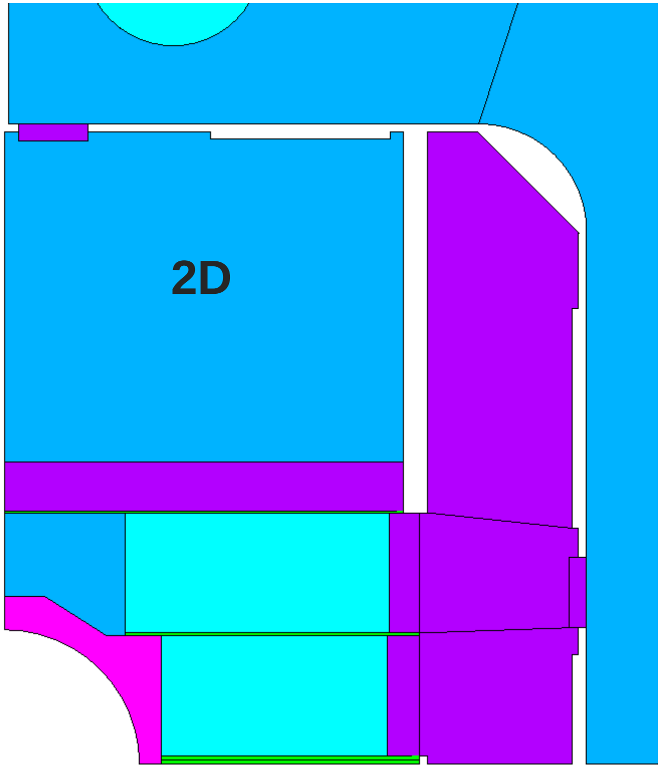
+/-20%

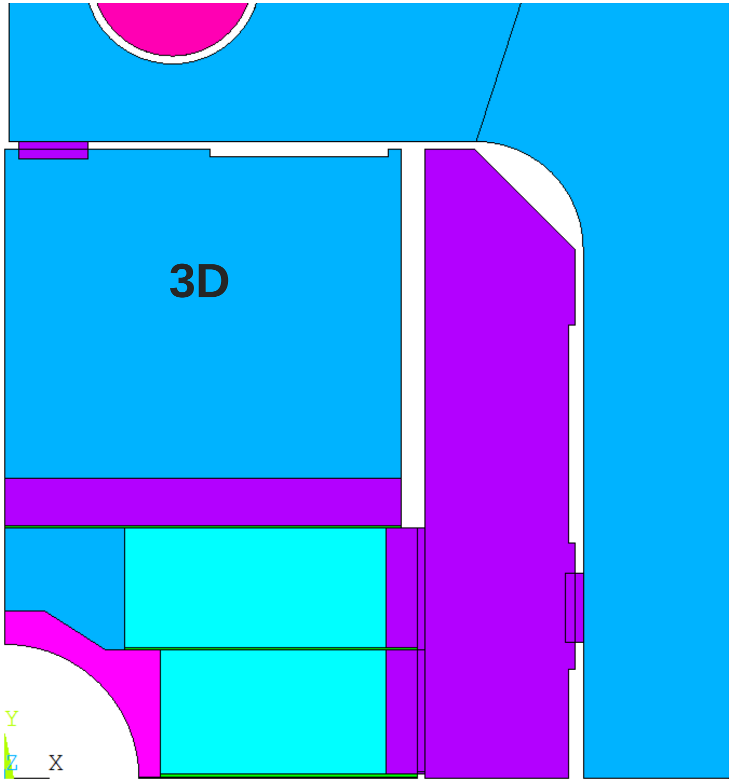
No match in value or location

[1]Sharp peak effect

[2]discarding corner effects

Fresca2: Geometry (9/12)





Contacts:

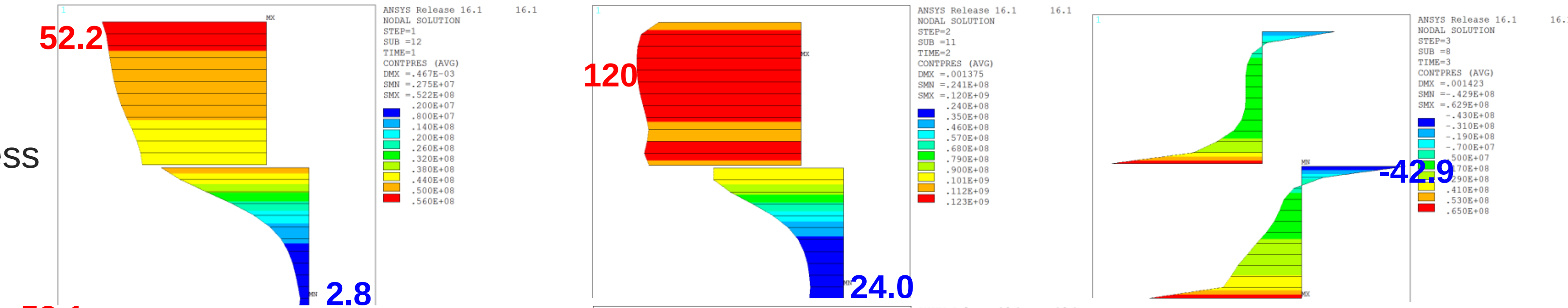
- Pole – pole: sliding
- Middle coil – external coil: sliding
- Inside coil (pole, layer, inter-layer): bonded

Coil properties:

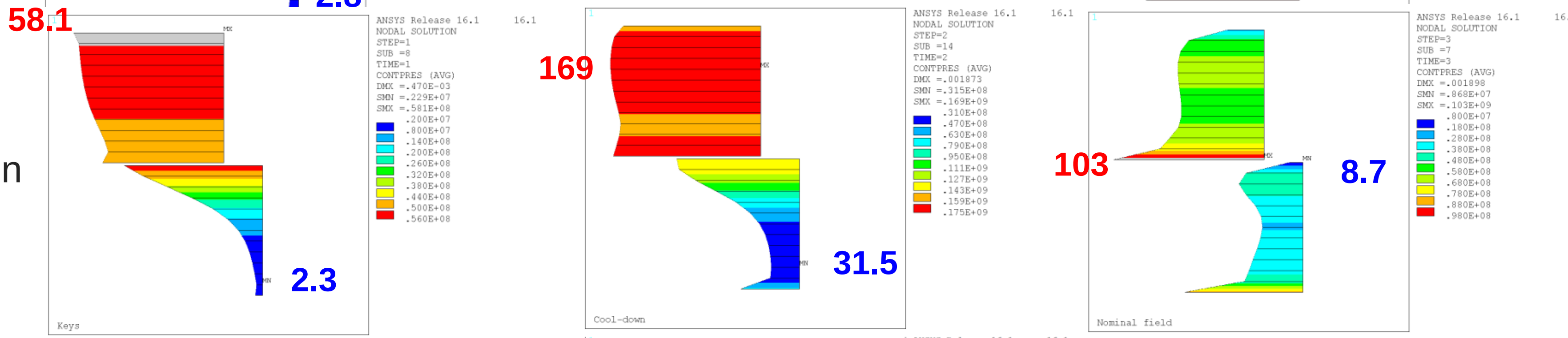
- 44/52 GPa orthotropic cold and warm
- 3.36/3.08 mm/m orthotropic

Fresca2: Contacts (10/12)

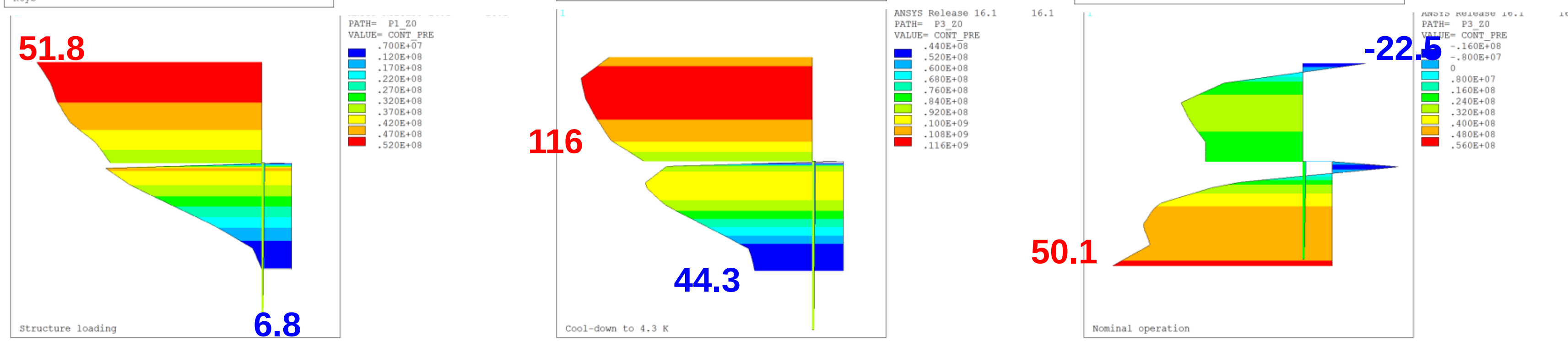
2D
Pl. stress
13T
0.6 mm



2D
Pl. strain
13T
0.6 mm



3D
V3,13T
0.6 mm

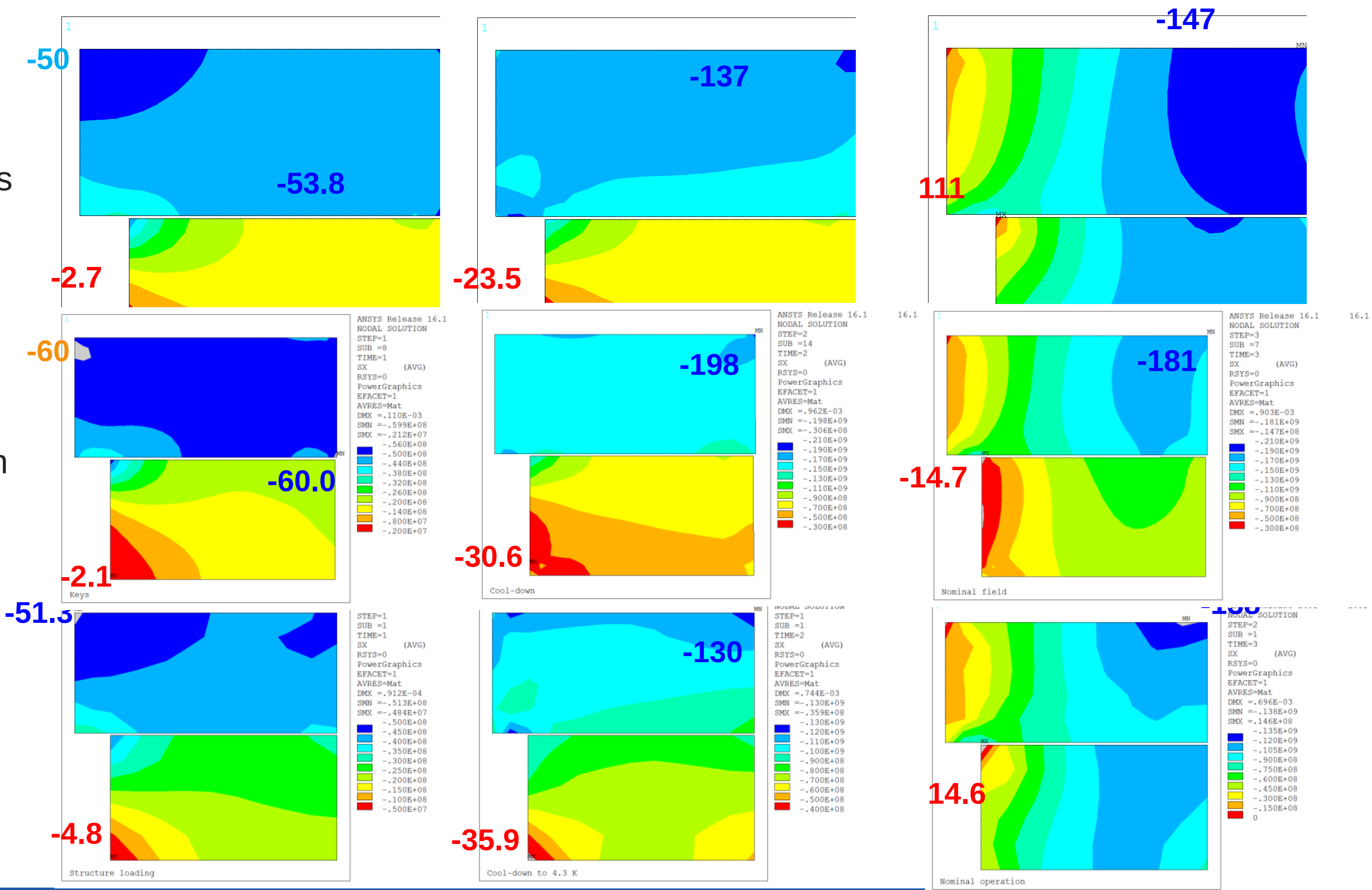


Fresca2: Coil Sx (11/12)

2D
Pl. stress
13T
0.6 mm

2D
Pl. strain
13T
0.6 mm

3D
V3,13T
0.6 mm



Fresca2: Summary (12/12)

	Contact [MPa]			Sx [MPa]		
	Loading	4.2 K	18 T	Loading	4.2 K	18 T
3D	6.8..51.8	44.3..116	-22.5..50.1	-51.3..-4.8	-130..-35.9	-138..14.6
2D P. stress	2.8..52.2	24.0..120	-42.9..62.9	-50[2]..-2.7	-137..-23.5	-147..111
2D P. strain	2.3..58.1	31.5..169	-8.7..103	-60[2]..-2.1	-198..-30.6	-181..-14.7

+/-10%

+/-20%

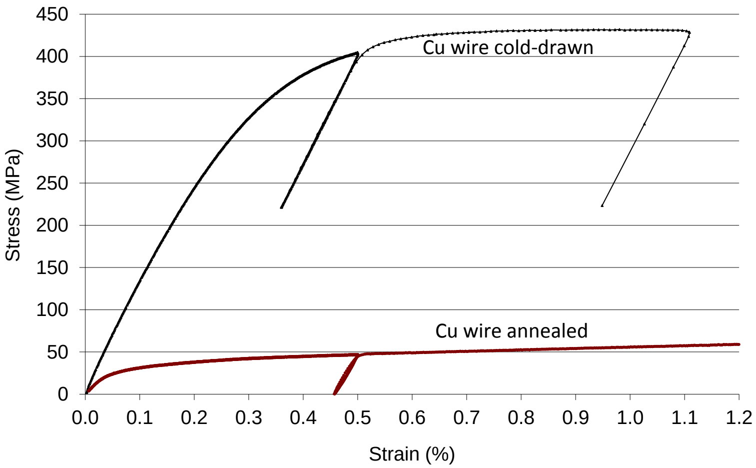
No match in value or location

[1]Sharp peak effect

[2]discarding corner effects

Mechanical properties of Cu wedges (1/4)

- The stress-strain behaviour of annealed Cu is non linear. Plastic behaviour is already observed when the stress exceeds about 20 MPa. The 0.2% proof stress ($R_{p0.2}$) is less than 50 MPa.
- Young‘s modulus cannot be derived from the initial loading curve. Instead it is estimated from the unloading curve (E_a).
- Even at 4.2 K annealed Cu cannot cary substantial loads.



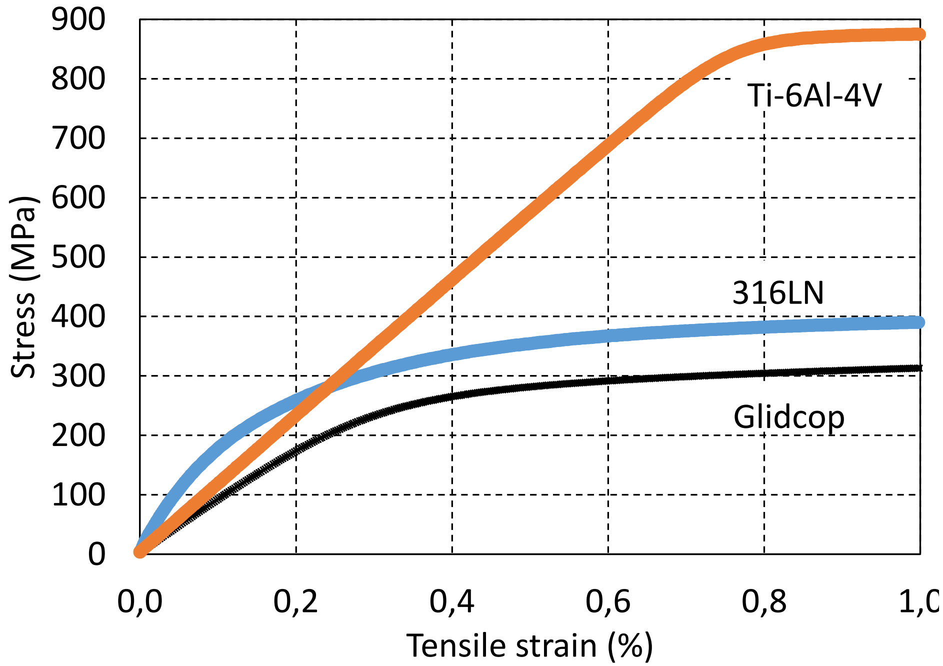
Tensile properties of cold drawn Cu wire before and after annealing at 695 °C (measured at RT).

	E_a (GPa)	$R_{p0.2}$ (MPa)	R_m (MPa)
Cold-worked Cu wire	127±0.8	397±15	427±5.9
Annealed Cu wire	108±2.1	46.2±2.6	204±1.6

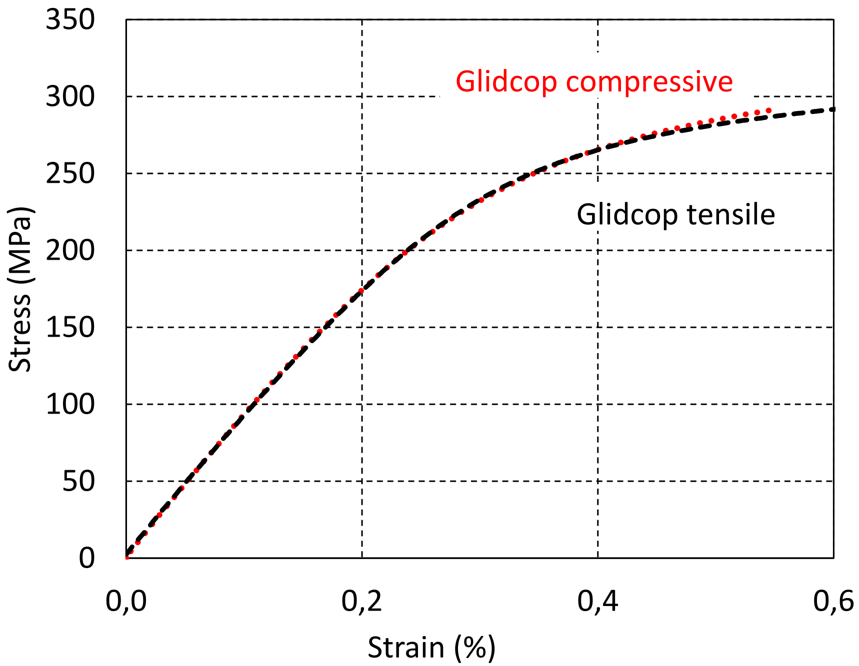
From: C. Scheuerlein, F. Lackner, F. Savary, B. Rehmer, M. Finn, P. Uhlemann, "*Mechanical properties of the HL-LHC 11 Tesla Nb_3Sn magnet constituent materials*", IEEE Trans. Appl. Supercond., submitted

Mechanical properties of Glidcop wedges (2/4)

- RT properties



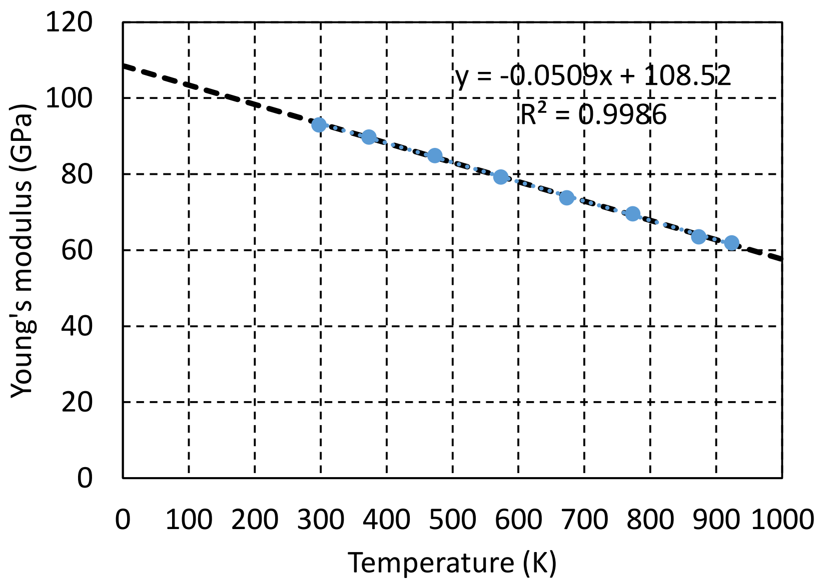
Al oxide dispersion strengthened Cu (tradename Glidcop) RT mechanical properties measured after prior 650°C coil reaction heat treatment. Stres-strain curves of Ti-6Al-4V and 316LN stainless steel are shown for comparison.



Comparison of Glidcop stress strain curvers under longitudinal tensile and transverse compressive loading.

Glidcop Young's modulus temperature dependence (3/4)

- Temperature dependent Young's and shear moduli are measured by the resonance method in the temperature range 20-650 °C.
- A 4.2 K Glidcop Young's modulus of 109 GPa is obtained by fitting and extrapolating the 20-650°C data.



Glidcop, some add. information (4/4)

- The raw material is patented (http://www.cep-freiberg.de/en/), owned by a professor of Technical University Bergakademie Freiberg.
- The production process of the wedges is such that CEP Freiberg produces the granulate and does a first extrusion, with a die produced by Luvata. Then this raw material is transported to Luvata, which are then probably performing some annealing to reduce internal stress, do acid cleaning to clean the surface and bring the wedges to final shape. Their extrusion is limited to 5 kg (currently). We at CERN have 6 m long wedges received from Luvata. The price is around 200 EUR/kg.
- The material was selected because it does not transform its state during the heat treatment (no grain growth), it has a high specific heat and thermal conductivity. Another suitable material would be Ni-super-alloy, but it is very expensive and maybe magnetic (to be checked).
- Should we start a study if the extrusion amount can be increased and the cost reduced?

Required loadline margin in the ends

- A reduction of the field of around 1 T (loadline margin around 20%) in the ends seems appropriate?

Yield strength in the iron/steel (1/6)

Material	Production	Thickness [mm]
Magnetil	Hot-rolled Laminations	2.5-8
ST430	Laminations	
Armco	Hot-rolled Laminations	1.5-30
HSLA	Hot-rolled pole sheets	2-12
Silicon steels	Cold-rolled	<1.5

Mechanical properties (2/6)

Material	Modulus [GPa]		$R_{p0.2}$ [MPa]		Contraction [μm/m/K]
	RT	4.2 K	RT	4.2 K	To 4.2 K
SS 316LN	**203 [1]**, **193***	**210***	**324 [1], 286***	**930***	**10.3 [2], 9.83***
Magnetil	**213* [1],** 200 [4]	211 [4], **224***	117/124 [1], 115/123 [4] (rolling/perp.); **180* [4]**	**821 (77K) [4], 723***	**7.5 (11.5K) [4], 6.28***
ST430	**200* [3],** 200 [5,6]	**210* [3]**	205 [5], **310* [3]**,[6]	**830***	**6.03***
Armco	200 [6], **213***	**224***	305 [6], 170 [3], **233 [8]**, **180***	**723***	**6.28***
HSLA	~200 [7]		**250-900 [7]**		
Silicon steels			**295 (2.5% Si) [3],** 450?		

***RMM baseline, best reference**

[1] Scheuerlein et al., Mechanical properties of the HL-LHC 11 Tesla Nb3Sn magnet constituent materials, ASC 2016
[2] Collings, *Applied Superconductivity, Metallurgy, and Physics of Titanium Alloys*. International Cryogenics Monograph Series, 1986.
[3] Sgobba, Private Communication + ASM Handbook, 9th ed., vol. 3.
[4] Bertinelli, Production of Low-Carbon Magnetic Steel for the LHC Superconducting Dipole and Quadrupole Magnets, 2006
[5] http://www.pennstainless.com/ [6] http://www.azom.com/
[7] Keppert, Pole sheets Data sheet, voestalpine Steel Division
[8] EDMS#1382378 + Izquierdo, Private communication

HSLA steels (3/6)

- HSLA = High-strength low-alloy
- Classified by yield strength:
  - Norm EN 10265 (EU): **700**-TG-179 = **700** MPa
  - Norm SAE (Society of Automotive Engineers): 9**80**X = **80** ksi = 552 MPa
- Low carbon content: 0.05-0.25 %
- Other elements up to 2%: mainly Mn, also Cu, Ni, Nb…
- Magnetic polarization inversely proportional to the yield strength
- Mainly obtained in sheets and strips (already annealed), but also in plates, shapes and bars
- Sheets from 2 to 12 mm thick
- Big press for punching required?
- Open questions: properties at cold?, cycling test?

Mechanical and magnetic properties: Tensile test/magnetic polarization

Standard grades pursuant to EN 10265:1995, corresponding to IEC 404-8-5 and ultra-high-strength special voestalpine grades

Steel grade	Testing direction	Yield strength R_{p02} [MPa]	Tensile strength R_m [MPa]	Elongation [%] min.		Magnetic polarization [Tesla] Minimum value at field intensity	
				A_{80}	A_5	5000 [A/m]	15000 [A/m]
	Standard grades pursuant to EN 10265:1995, corresponding to IEC 404-8-5						
250-TG-180	transverse	≥ 250	≥ 350	22	26	1.60	1.80
300-TG-180	transverse	≥ 300	≥ 400	20	24	1.60	1.80
350-TG-179	transverse	≥ 350	≥ 450	18	22	1.55	1.79
400-TG-179	transverse	≥ 400	≥ 500	16	19	1.55	1.79
450-TG-179	transverse	≥ 450	≥ 550	14	17	1.54	1.79
500-TG-179	transverse	≥ 500	≥ 600	12	14	1.53	1.79
550-TG-178	transverse	≥ 550	≥ 650	12	14	1.52	1.78
600-TG-178	transverse	≥ 600	≥ 700	10	12	1.50	1.78
650-TG-178	transverse	≥ 650	≥ 750	10	12	1.48	1.78
700-TG-178	transverse	≥ 700	≥ 800	10	12	1.46	1.78
	Ultra-high-strength special voestalpine grades						
750-VA-178	transverse	≥ 750	≥ 800	≥ 10	≥ 12	1.46	1.78
	longitudinal	≥ 730	≥ 750				
750-VA-175	longitudinal + transverse	≥ 750	≥ 800	≥ 9	≥ 11	1.46	1.75
800-VA-175	longitudinal + transverse	≥ 800	≥ 850	-	≥ 10	1.46	1.75
850-VA-175	longitudinal + transverse	≥ 850	≥ 900	-	≥ 10	1.46	1.75
900-VA-175	longitudinal + transverse	≥ 900	≥ 930	-	≥ 10	1.46	1.75

Measurement of fracture elongation A_{80} for thicknesses < 3 mm
A_5 for thicknesses < 3 mm

Steel: Magnetic properties (4/6)

Material	Coercivity [A/m]	Max. μr	Saturation [T]*
Low-carbon [3]	60-140	2200-5500	2.15
Magnetil [4]	80	~7000	2.19
Armco [8]	~200	3000-6000	~2.15
ST430 [3]	240-320	1100-1600	1.47
1010 [3]	80-160	~3800	2.10
HSLA [7]	~400	~3000	<2.0?
Silicon steels [3] 1% 2.5% 3%	 140-260 60-150 100-160	 1700-6000 1800-11000 7500-15000	 2.06 2.00 ~1.80

*$\lim(B-\mu_0 H)_{H \to \infty}$

Steel: Conclusion (5/6)

- Low-carbon steel usually used in SC magnets: Magnetil, Armco
  - Very high saturation fields: 2.0-2.1 T
  - But, limited yield strength: <200 MPa at RT
- Si steels:
  - Very high saturation fields: up to 2.0 T
  - Higher yield strength ~300 Mpa
  - But, cold rolled, then laminations < 1.5 mm
- ST430:
  - Higher yield strength ~300 Mpa
  - Low saturation field: ~1.5 T
  - **Should we explore this option in more detail?**

HSLA:

  - Very high saturation fields: up to 2.0 T
  - Very high (and large choice of) yield strength: 250-900 MPa
  - Small impact of strength on saturation field
  - **Should we explore this option in more detail? Which one?**

Steel: Test specification (6/6)

- Traction tests at room temperature and 4.2 K to determine the yield limit.
- Fracture tests at 4.2 K to determine the fracture toughness (K_{Ic}). The best reference we have now is 30 MPa*m$^{1/2}$, that translates in a maximum tensile stress in the yoke of 280 MPa at cold assuming that we can have cracks of 1 mm in the material
- Fatigue tests at 4 K
  - Cycling to 200 MPa to determine the number of cycles before rupture (it should be larger than 20.000 for HiLumi magnets)
  - Cycling to 300 MPa to determine the number of cycles before rupture (useful for 16 T magnets). If someone thinks that it would be very useful for the design to have S1(4K)>300 MPa, we can ask to perform this test at slightly larger load.

Cost model considerations (1/1)

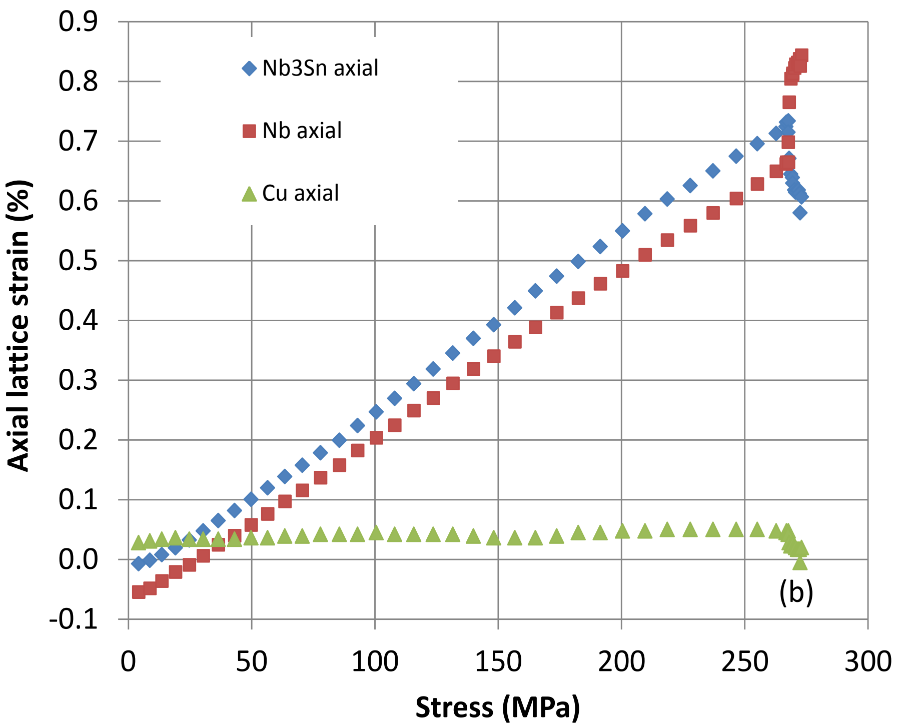
- Detection equipment and circuit protection is not part the EuroCirCol cost model
- Tolerances are very important for the cost of the parts. At the time for LHC performed Monte-Carlo simulations in 2D. What is your opinon to include this in the study?
- End spacers could be done from a material, which is easily machinable and does not have (excessive) grain growth during the heat treatment, is non-magnet and fulfils the mechanical/structural specifications (if it exists or can be created). Should we write a specification and start a study?
- Wedges, study of different materials to be started?

Tensile stress (1/3)

- The CCT design has seen some tensile stress, which influence does it have on the performance?

Axial tensile stress-strain relation of Nb_3Sn/Cu PIT wire at 4.2 K (2/3)

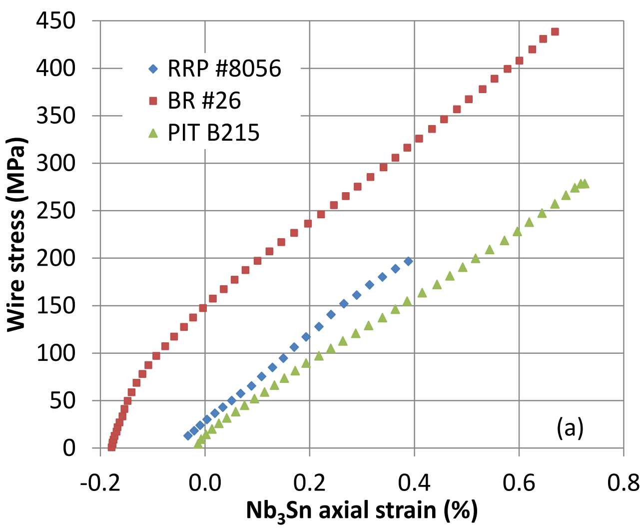
- At 4.2 K 100 MPa axial tensile stress on the PIT type Nb_3Sn wire causes an axial strain of about 0.25%.
- The reversible axial strain influence on I_c increases with increasing applied field. At 16 T more than 30% I_c reduction are possible, depending on the Nb_3Sn strain state in the unloaded conductor.
- The axial tensile strain irreversibity limit reported for RRP and PIT type Nb_3Sn wires is typically below 0.25% strain (at 4.2 K).



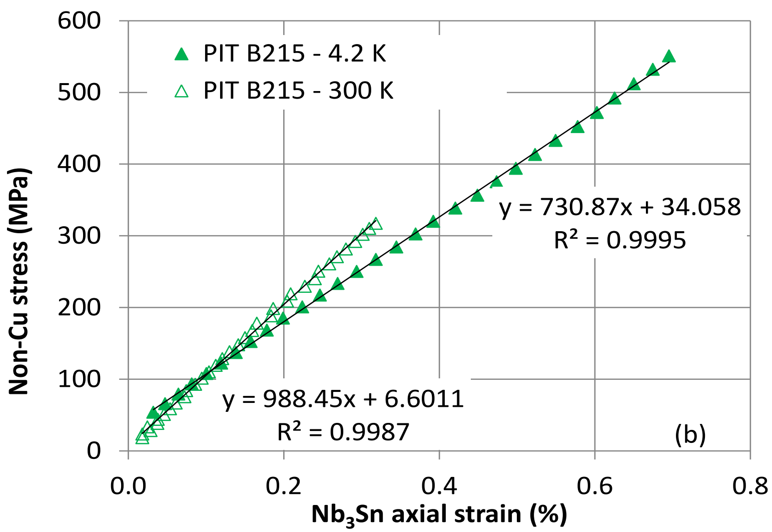
Lattice strain in the different constituents of a Nb_3Sn PIT wire measured simultaneously by X-ray diffraction as a function of wire stress at 4.2 K.
From C Scheuerlein et al, Supercond. Sci. Technol. **27** (2014) 044021

4.2 K uniaxial tensile stress-strain behaviour of PIT, RRP and Bronze Route wires (3/3)

- Similar stress-strain behaviour in RRP and PIT type wires.
- Strong Nb3Sn lattice softening during cooling to 4.2 K.



Stress in the BR, RRP and PIT wire as a function of Nb_3Sn axial strain at 4.2 K. Stress is tensile force normalised to the wire cross section.



Comparison of the stress-strain in the Nb_3Sn PIT wire at RT and at 4.2 K. Stress is normalised to the non-Cu wire cross section, assuming that the Cu does not carry substantial loads.

Conclusion

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