Comparison of mechanical concepts for Nb_3Sn high-field accelerator magnets

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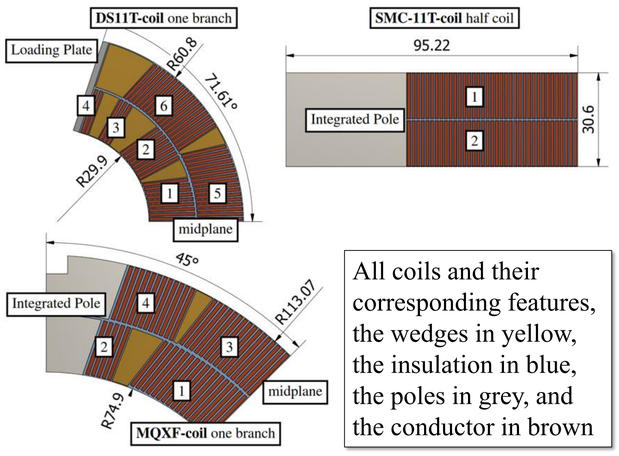


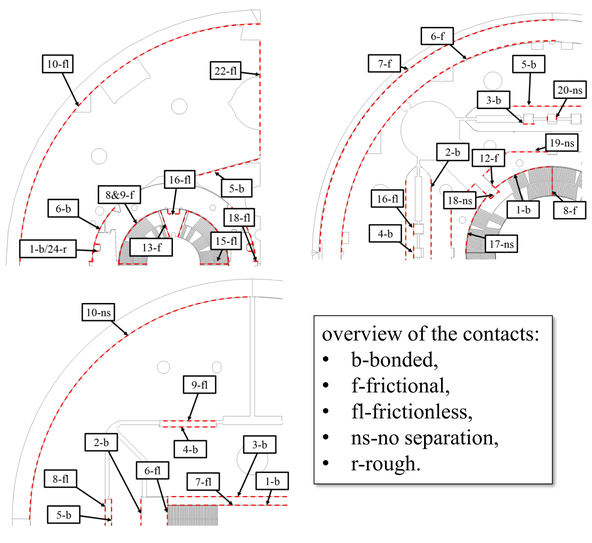
All coils and their corresponding features, the wedges in yellow, the insulation in blue, the poles in grey, and the conductor in brown

1. Introduction

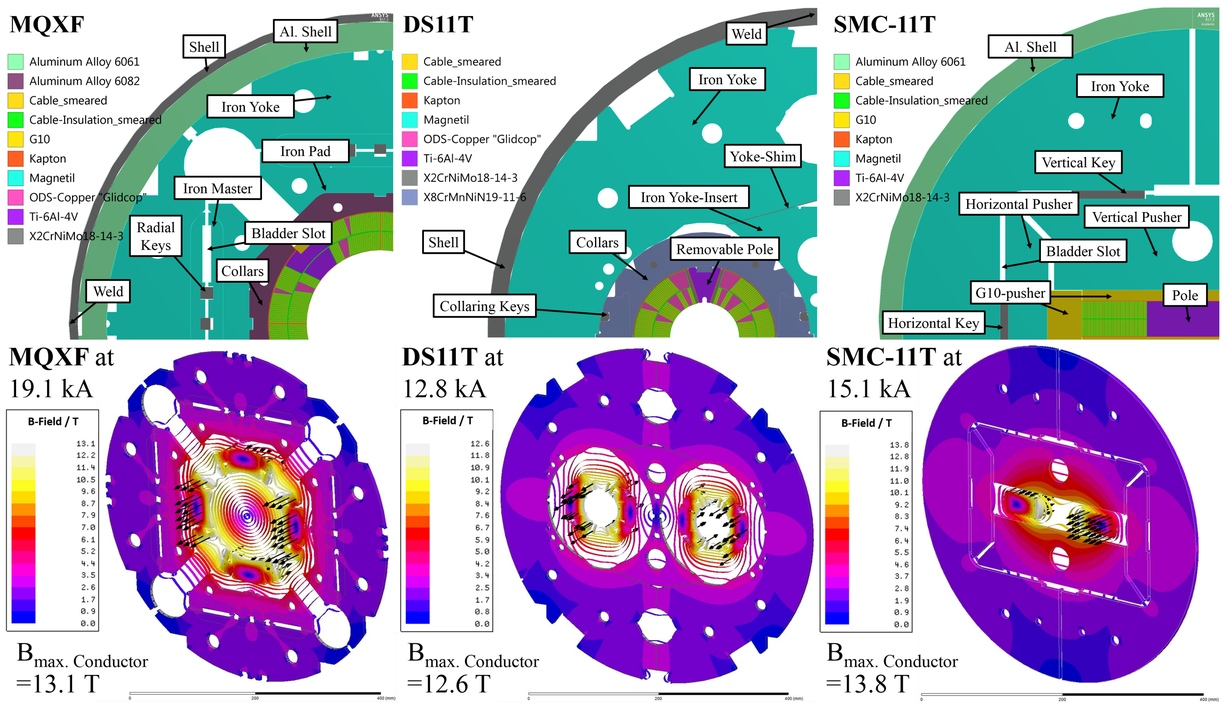
Several magnets using Nb3Sn as the conductor are currently being developed at CERN; these magnets are either slated for later upgrades of the LHC or for research purposes relating to future accelerators. The mechanical structure is one of the challenging aspects of superconducting high-field magnets. This paper compares the mechanical behaviour of three magnets by means of the finite element method (FEM). The free magnets are the DS11T cos-theta dipole, the MQXF cos2-theta quadrupole, and the SMC-11T block-coil dipole. The mechanical structure of the DS11T is "collar-based" and the latter two are "bladder and key," they rely on an aluminium shell, whose thermal shrinkage causes the build-up of pre-stress in the coils. The pre-stress of the DS11T is created at room temperature. The DS11T and MQXF will be installed in the accelerator ring for the HL-LHC. The SMC-11T is considered a research magnet to investigate the behaviour of superconducting coils under different loading concepts. The SMC can host two coils, but can also be adapted to host coils made from the same cable as the DS11T. Only the placement of one coil is possible in this configuration. All the calculations for the FEM were carried out by using the software ANSYS 17.2 and ANSYS® Electronics Desktop 2016.2.0. This paper is an excerpt of the thesis *Comparison of mechanical concepts for Nb3Sn high field accelerator magnets*, CERN-THESIS-2017-078.

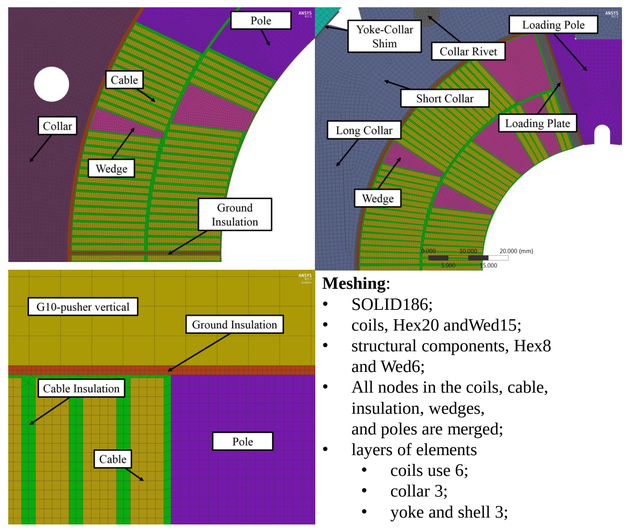
2. The Finite Element Model

All the calculations for this paper have been done with a 3D-FEM model, which is used to represent a 6mm thick cross-section of the magnet, to realistically depict the influence of the inter-leaving collars of the DS11T. The longitudinal boundary is plane strain and there is no thermal shrinkage in the longitudinal direction. The materials used for the cable have an elastic-plastic behaviour. A kinematic hardening mechanism is used to simulate the observed hardening behaviour of the conductor.

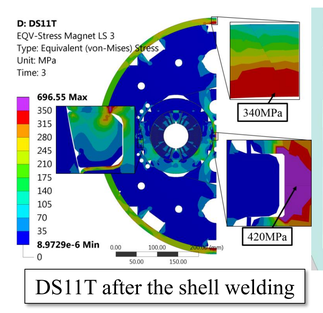


overview of the contacts:
- b-bonded,
- f-frictional,
- fl-frictionless,
- ns-no separation,
- r-rough.

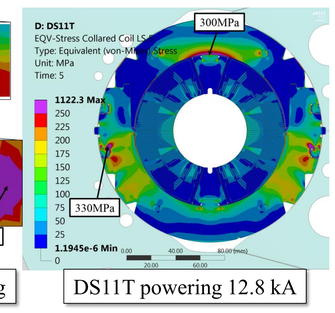




Meshing:
- SOLID186;
- coils, Hex20 andWed15;
- structural components, Hex8 and Wed6;
- All nodes in the coils, cable, insulation, wedges, and poles are merged;
- layers of elements
  - coils use 6;
  - collar 3;
  - yoke and shell 3;



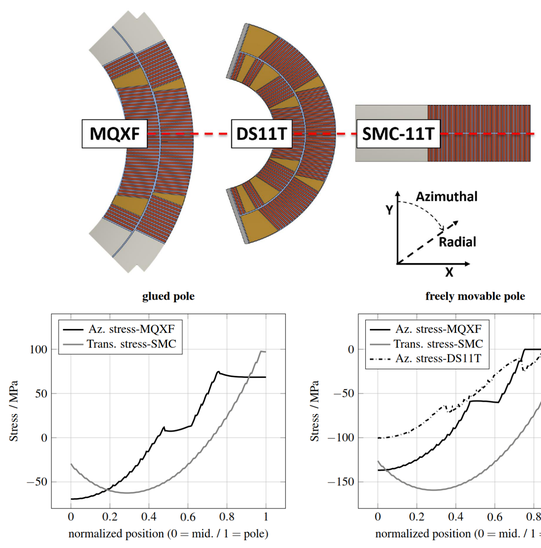
DS11T after the shell welding



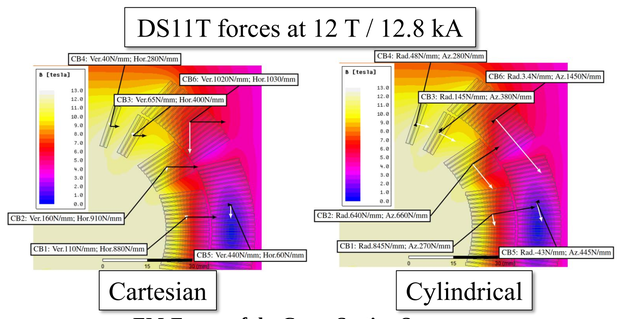
DS11T powering 12.8 kA

3. Electromagnetic Forces

As a reference for the analysis of the mechanical structure, the coils are subjected to their individual electromagnetic (EM) forces. Roughly 90% of the magnets load line at 1.9 K was selected as the corresponding current. The midplanes of the DS11T and the MQXF are parallel in the horizontal direction, X, while the winding axis of the SMC-11T is parallel in the vertical direction, Y. To better understand which forces were transmitted to the structure and which were contained in the coils, the absolute force vector was divided into its radial and azimuthal components. The radial forces for the MQXF and the DS11T, and the horizontal forces for the SMC-11T are transmitted to the mechanical structure.



DS11T forces at 12 T / 12.8 kA



EM-Forces of the Cross-Section Summary

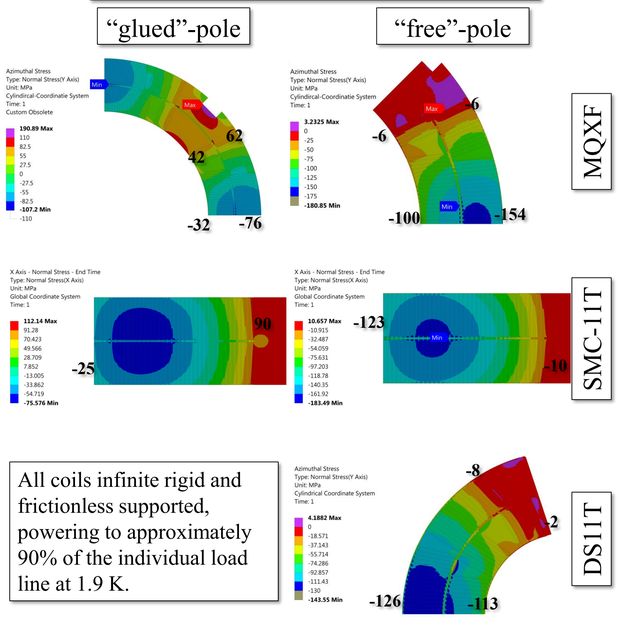
Force/ (N/mm)	Horizontal	Vertical	Radial	Azimuthal
MQXF	3120	-4536	**1266**	-5235
DS11T	3561	-1832	**1639**	-3484
SMC-11T	**1697**	-1825	-	-

For the DS11T and the MQXF, one half of coil was used, midplane horizontal. The data for the SMC-11T is shown for one-quarter of the coil. The forces in bold are the transmitted to the mechanical structure.

4. Induce Cable Stress by EM-Forces

The coils are supported by an infinitely rigid frictionless support, and then subjected to the EM force. For the MQXF and DS11T coils, the frictionless support will be on the outer diameter and the midplane, and the SMC-11T will be supported on all outer surfaces.

Average Cable Hoop-Stress EM-Forces



All coils infinite rigid and frictionless supported, powering to approximately 90% of the individual load line at 1.9 K.

Transverse cable stresses—EM-Force; glued pole / free pole

Stress / (N/mm²)	Inner layer pole	Inner layer midplane	Outer layer pole	Outer layer midplane
DS11T	-2	-113	-8	-126
MQXF	42 / -6	-32 / -100	62 / -6	-76 / -154
SMC-11T	90 / -10	-25 / -123	-	-

Perfectly supported coils; average for one cable

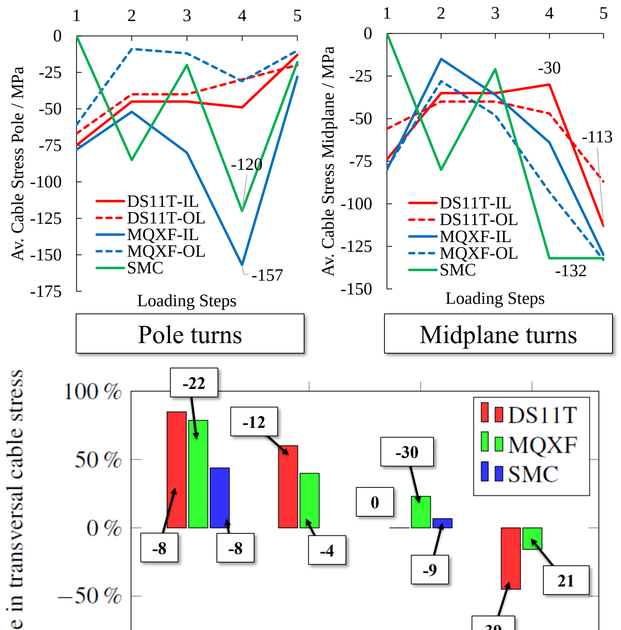
5. Comparison of the Mechanical Structures

All the models use five load steps. With the distinct features of the mechanical structures, the pre-stress of the coils can be adjusted. For the DS11T, shims between the poles can be adjusted, and the size of the keys can be changed for the MQXF and the SMC-11T. To set the "nominal case" for the pre-stress, all the structures were tuned to leave the pole turns at 10 MPa in compression during excitation of the coils. For the DS11T, a 0.2 mm thick shim between each pole and coil-quadrant was selected. The radial keys for the MQXF needed to be increased by 0.7 mm to achieve the goal. The shimming for SMC-11T was set to 0.2 mm on the horizontal key and 0.1 mm on the vertical key.

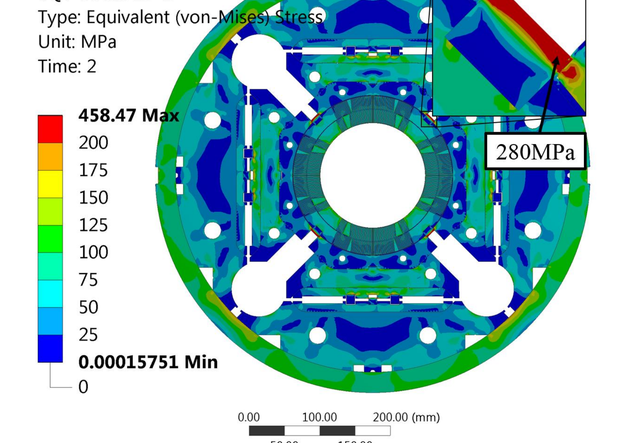
Load Steps used for the FEA

LS	DS11T	MQXF	SMC-11T
1	Collaring	Pressurization bladders	Pressurization vertical bladders
2	Spring-back collars	Keys contacts are initiated	Pressurization horizontal bladders
3	Shell welding	Shell welding	Pressure removed, keys in contact
4	Cooling down of all components to 1.9 K		
5	Powering 12.8 kA	Powering 19.1 kA	Powering 15.1 kA

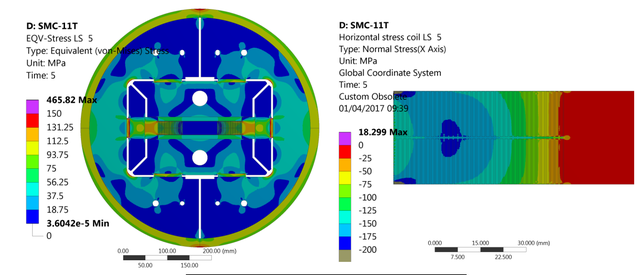
Average cable stresses during the assembly and powering.



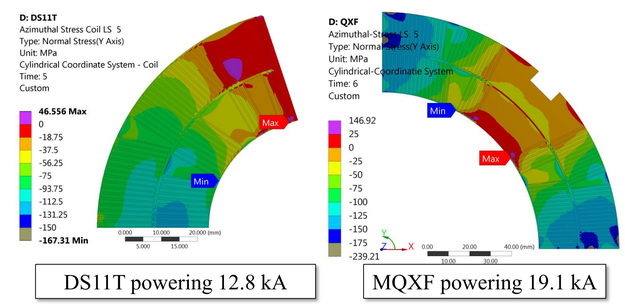
Change in average transversal cable stress, comparison between the single coil and the coils in the structure.
Negative values->higher compression in the structure



MQXF pressurization of the bladders



SMC-11T powering 15.1 kA



DS11T powering 12.8 kA

MQXF powering 19.1 kA

Material Properties

Material Name	E / GPa (295/4 K)	Poisson's Ratio	Sec. Coe. Ther. Exp.	Yield / MPa / (295/4 K)
Cable-axial $_{smeared}$ [6] [5]	124/112	0.35	1.06E-5	10/-[b]
Cable[d] $_{smeared}$ [6] [5]	114/92	0.35	1.06E-5	10/-[b]
Cable-insu. $_{smeared}$ [9]	12.9/19.7	0.35	6.50E-6	790/1260[c]
Kapton [12] [11]	2.5/8.96	0.34	1.51E-5	207/346
Magnetil [13]	205/210	0.30	7.22E-6	115/820
ODS-Copper [15] [2]	88/95	0.33	1.11E-5	332/-
Aluminium-6061 [2]	70/79	0.30	1.44E-5	340/-
Aluminium-6082 [2]	70/79	0.30	1.44E-5	320/450
Ti-6Al-4V [2] [16]	115/125	0.33	2.85E-6	868/-
X2CrNiMO18-14-3 [2]	196/210	0.30	9.97E-6	324/1360
X8CrMnNiN19-11-6 [14]	19./202	0.30	8.93E-6	415/1360

Secant coefficient of thermal expansion is for 295 to 4 K.
[a] tangent modulus = 18 GPa
[b] tangent modulus = 20 GPa
[c] in compression
[d] transverse and radial directions