Magnet end shaping of the FCC Main Quadrupole: optimization and validation

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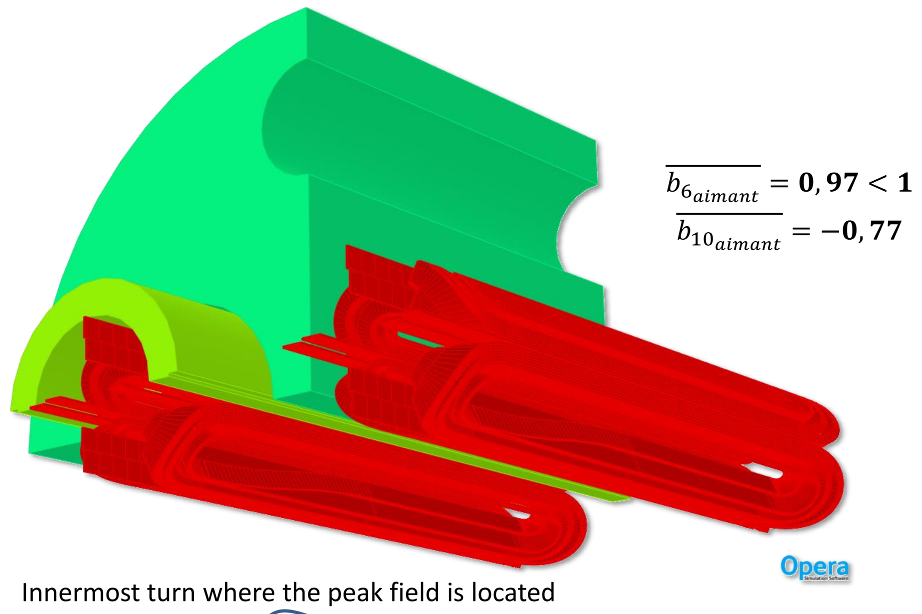
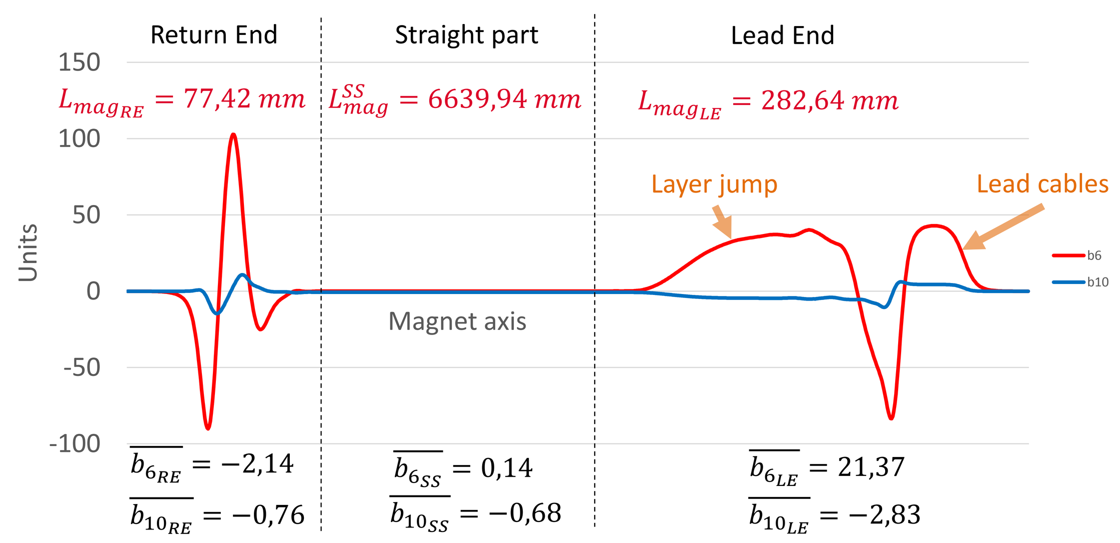
Introduction: For the Future Circular Collider (FCC), a 100 TeV post Large Hadron Collider machine, 750 main quadrupoles with a 360 T/m gradient over a magnetic length of 7 m are required. The poster deals with an **3D electromagnetic design** optimization of a **double aperture Nb_3Sn quadrupole** based on a **collared structure**. Preliminary winding trials are reported using off-the-shelf cables with a relatively close geometry. The baseline parameters, material properties, conductor performances are all aligned with the 16 T dipole magnets under development for the Future Circular Collider. This study is performed in the framework of a CERN-CEA collaboration agreement following the EuroCirCol project.

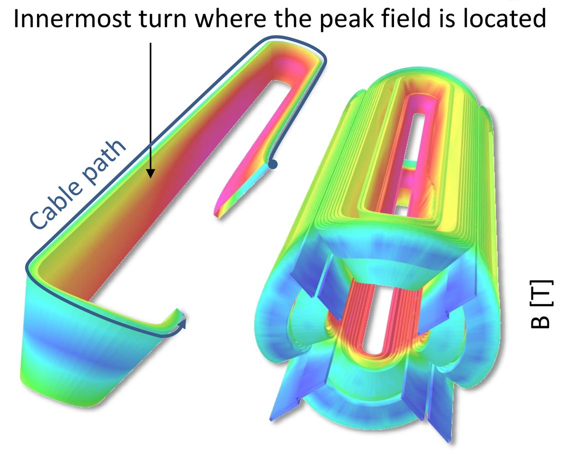
Cables

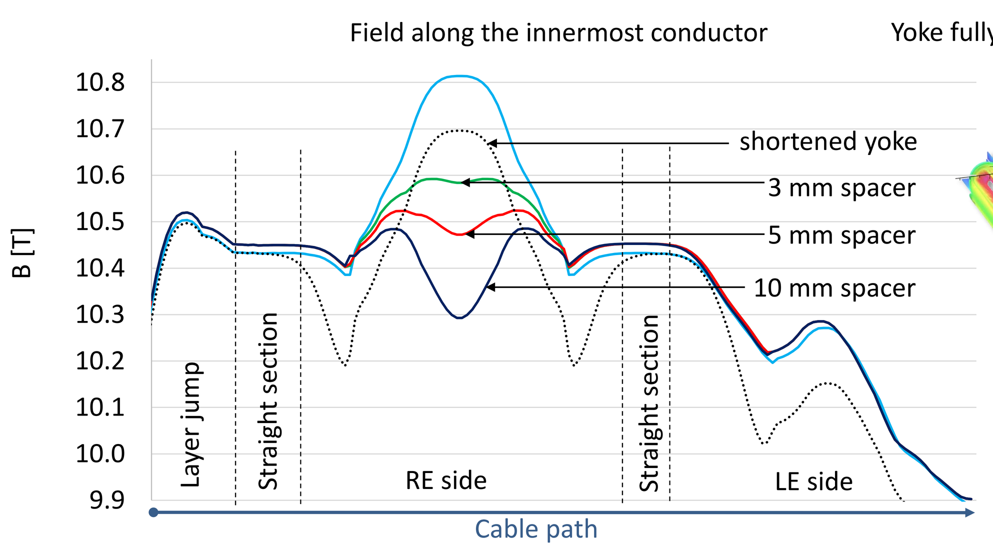
Cable Parameter	Units	FCC MQ	MQXF	LHC MQ
Material	-	**Nb_3Sn**	Nb_3Sn	Nb-Ti
Strand diameter	mm	**0.85**	0.85	0.825
Cu/NonCu	-	**1.65**	1.2 ± 0.1	1.65
Nb of strands	-	**35**	40	36
Cable bare width (before/after HT)	mm	**15.956/16.120**	18.15/18.363	15.1
Cable bare mid-thick.(before/after HT)	mm	**1.493/1.538***	1.525/1.594	1.48
Cable bare thinness (before/after HT)	mm	**1.438/1.481* (15.4%)**	1.462/1.530	1.362
Cable bare thickness (before/after HT)	mm	**1.549/1.596* (8.9%)**	1.588/1.658	1.598
Keystone	°	**0.40**	0.40	0.9
Insulation thickness per side (5 MPa)	µm	**150**	145 ± 5	142.5

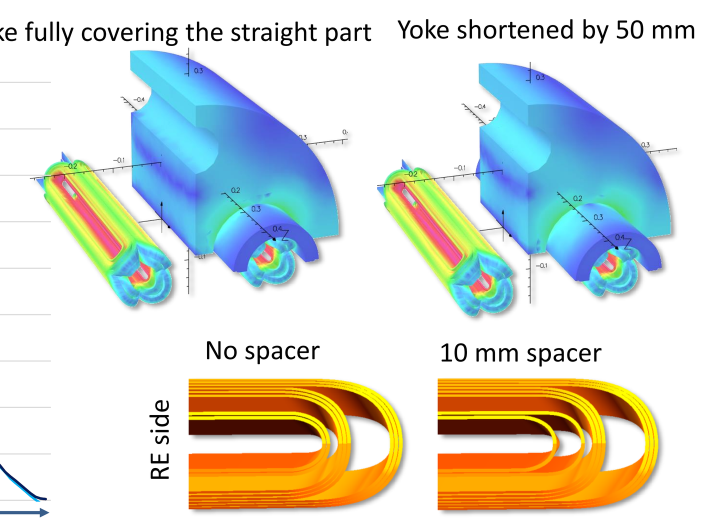
Electromagnetic analysis





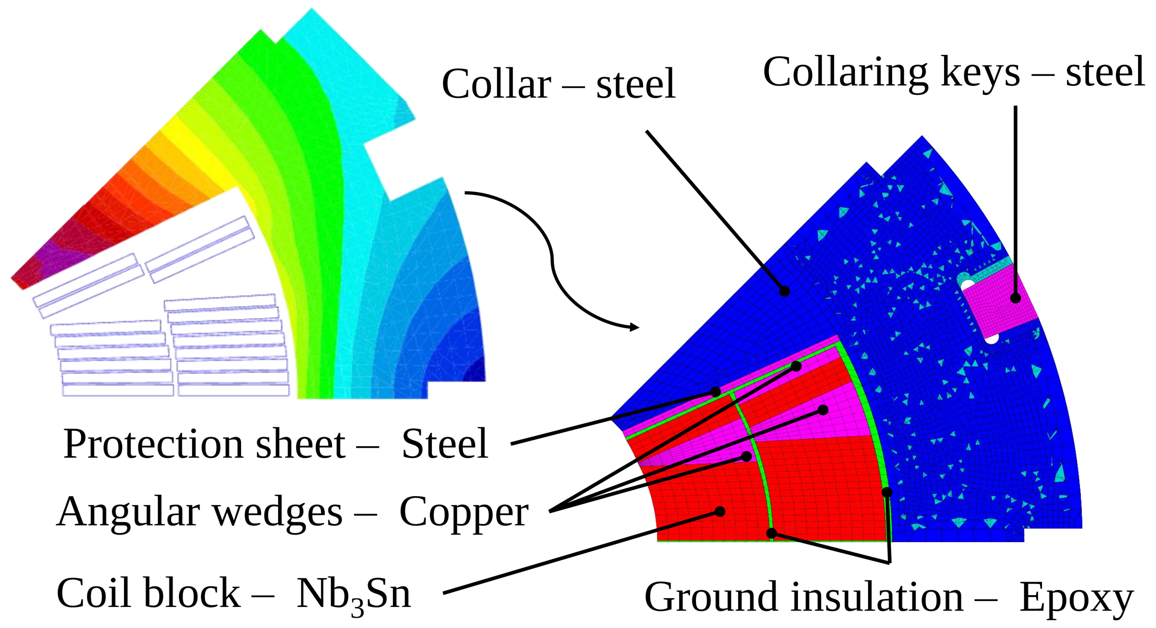






Magnet parameter	Units	FCC MQ	LHC MQ
Gradient	T/m	**367.4**	223
Nominal current	A	**22500**	11870
Peak field	T	**10.52**	7.0
Peak field / (Radius x Gradient)	-	**1.15**	1.12
Loadline margin	%	**20.0**	20.0
Temp magin	K	**4.6**	2.0
Inductance (2 ap.)	mH	**14.4**	11
Stored energy (2 ap.)	kJ	**3670**	800
Azimuthal force (per ½ coil)	MN	**12.3**	2.6
Radial force (per ½ coil)	MN	**5.5**	0.9
Fx (per ½ coil)	MN	**7.8**	1.5
Fy (per ½ coil)	MN	**11.4**	2.4
Midplane shim	µm	**330**	137
Hotspot (total delay)	K	**350 (30 ms)**	-
Nb of turns per layer	-	**8 + 10**	10 + 14
Total weight of conductor	tonnes	**272**	-
Magnetic length	m	**6.4**	3.15

Collar mechanical analysis



Double pancake glued
Sliding contact elsewhere without separation

Material	E [GPa] 293 K	E [GPa] 4.2 K	Pr	(L4.3K – L293K)/L293K
Nb_3Sn	30	33	0.3	3.9e-3⁺
Epoxy	5	8	0.34	6.0e-3
Steel (13RM19)	200**	210*	0.28*	2.7e-3**
Copper (DISCUP)	96***	96	0.3	3.3e-3

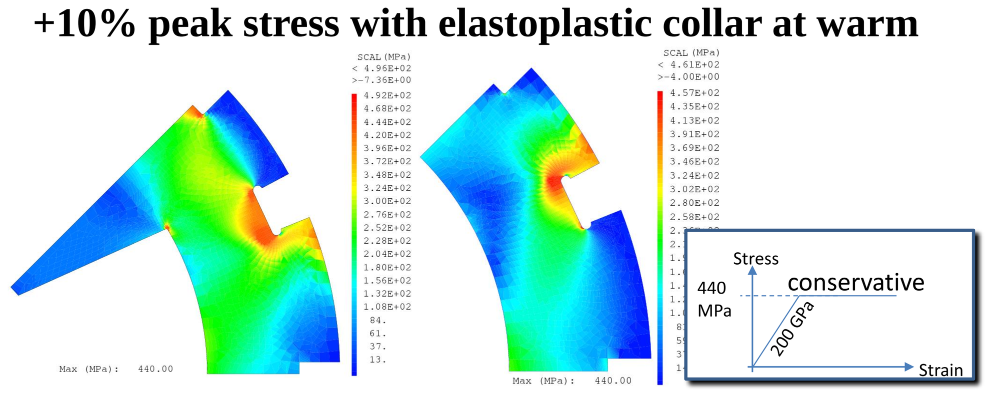
*Tommasini D. et al. https://indico.cern.ch/event/556692/contributions/2591664/ 3rd FCC week Berlin, 2017 + EuroCirCol meeting
**Lanza C., Perini D., Characteristics of the austenitic steels used in the LHC main dipoles, MT17, 24-28 September 2001, Geneva
***Scheuerlein et al, *Mechanical properties of the HL-LHC 11 T Nb3Sn magnet constituent materials*, IEEE TAS, 4003007, (2017)
⁺Vallone G. et al, Mechanical Performance of Short Models for MQXF, the Nb3Sn Low-βQuadrupole for the Hi-Lumi LHC, IEEE TAS

Nb_3Sn block coil azimuthal stress

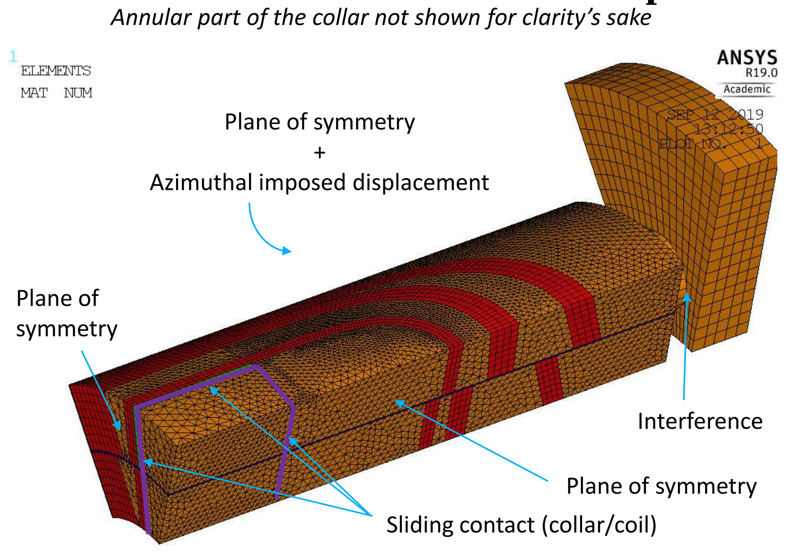
Collaring	Collaring - 10% creep*	Cold	Powering
peak average	peak average	peak average	peak average
-109 -91	-98 -82	-92 -72	-115 -69

*Felix Wolf "Strong creep behavior starting at 125 MPa" in "Effect of transverse stress applied during reaction heat treatment on the stiffness of Nb3Sn Rutherford cable stacks", ECC meeting, 22 May 2018

+10% peak stress with elastoplastic collar at warm

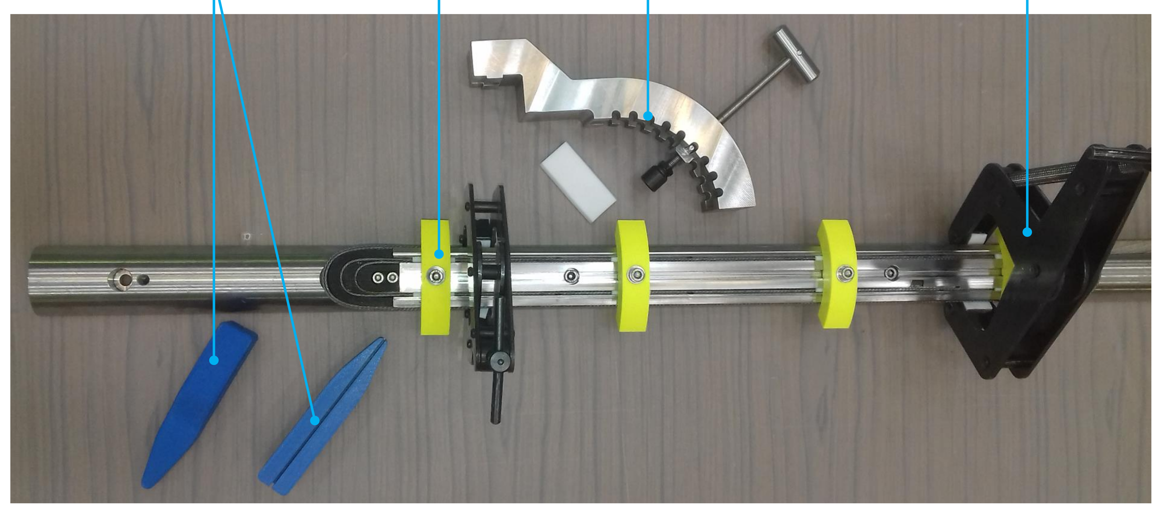


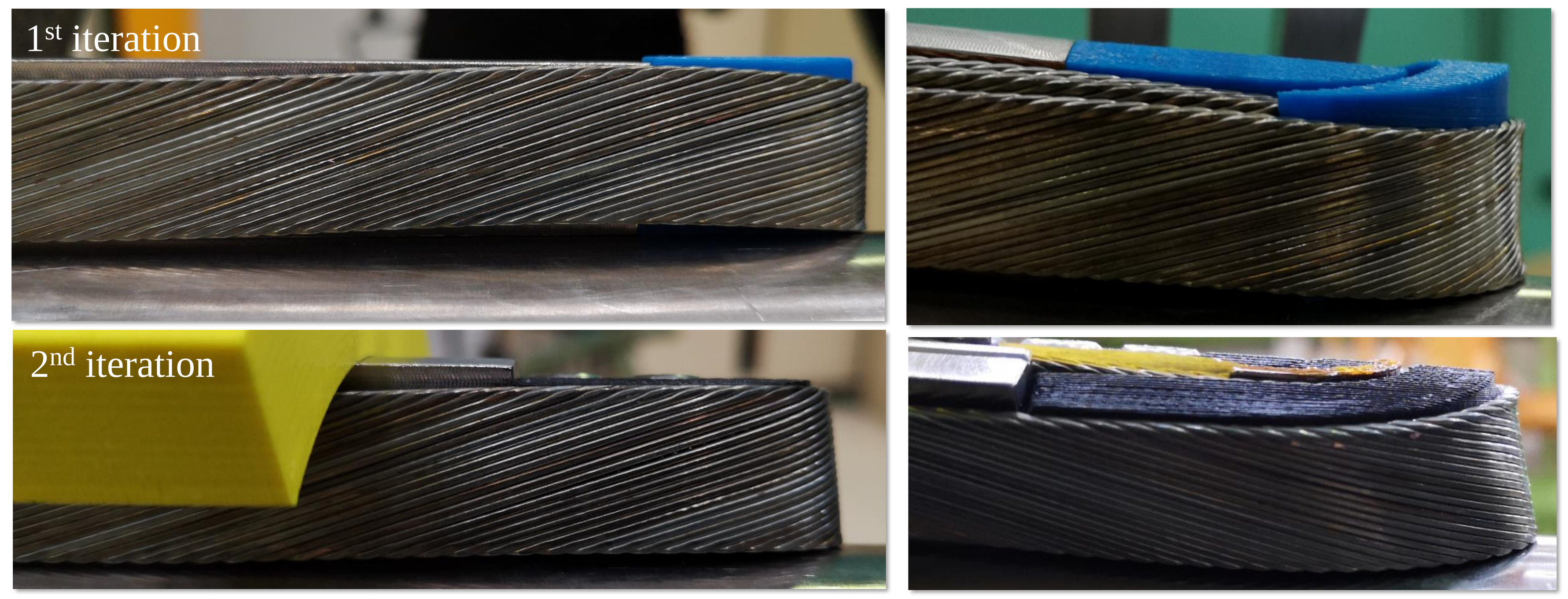
3D mechanical model under development
Annular part of the collar not shown for clarity's sake



Preliminary winding trials

2 iterations for designing the end spacers (blue 1st, black 2nd)
LHC MQ bare cable (Nb-Ti -> more compact / no-steel core)
Tooling: basic 500 mm central post (inner and outer layers)





Winding tension: 200 N straight part - 100 N coil ends – MQXF cable winding test to be done

Conclusion: A 3D electromagnetic design of a 360 T/m FCC MQ was performed with an analysis of the integrated harmonics and peak field. Preliminary 2D mechanical investigation showed bearable stress in the Nb_3Sn coils and will be further studied in a 3D FE model. Preliminary winding trials with a likely more stable cable underlined the difficulty to wind a 2 layer magnet configuration reaching 360 T/m.