Design of a Nb_3Sn 400 T/m quadrupole for the Future Circular Collider

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Introduction: For the Future Circular Collider (FCC), a 100 TeV post Large Hadron Collider machine, 750 main quadrupoles with a 381.2 T/m gradient over a magnetic length of 6 m are required. The poster deals with an **electromagnetic design** optimization of a **double aperture** Nb_3Sn quadrupole, going beyond the specifications (**400 T/m**) and a **structural design** of a **single aperture** configuration towards a prototype. The baseline parameters, material properties, conductor performances are all aligned with the 16 T dipoles under development for the FCC. In addition, the explored design makes use of the low-field (LF) cable of the dipole, as exercised before in the LHC. Such a choice represents an advantage, because the amount of conductor required for the FMQ (FCC Main Quadrupoles) represents only around 15% of the LF cable, so no extra cable has to be developed and produced.

Baseline parameters FCC dipoles

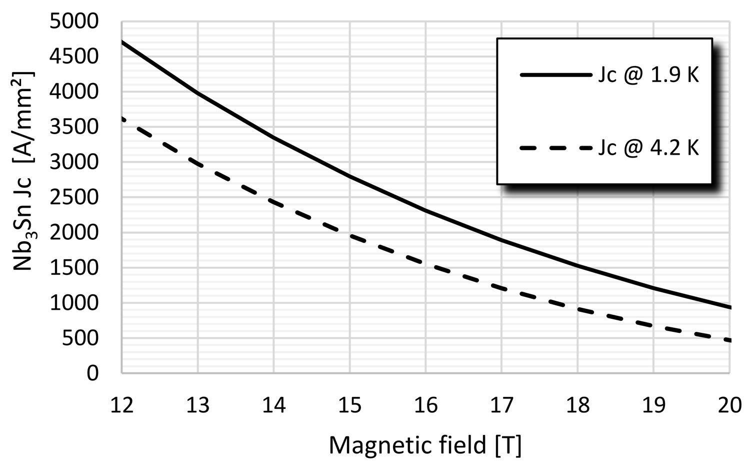
Parameter	Values	Unit
Operating temperature	1.9	K
Aperture diameter	50	mm
Beam-beam distance	204*	mm
Yoke outer diameter	600	mm
Margin on the load-line @ 1.9 K	>14	%
Critical current density @ 1.9 K, 16 T	2310	A/mm²
Copper/non-Copper ratio (cnc)	>0.8	adim
Number of strands per cable	<60	adim
Hot spot temperature (@ 105% I_{nom})	<350	K
Strand diameter	<1.2	mm
Stress on conductor at warm	<150	MPa
Stress on conductor at cold (@ 105% I_{nom})	<200	MPa
Voltage to ground (magnet only)	<1.2	kV

*In the present FMQ study the beam-beam distance is 250 mm.

Baseline parameters in August 2017.

Nb_3Sn critical current & cable dimensions

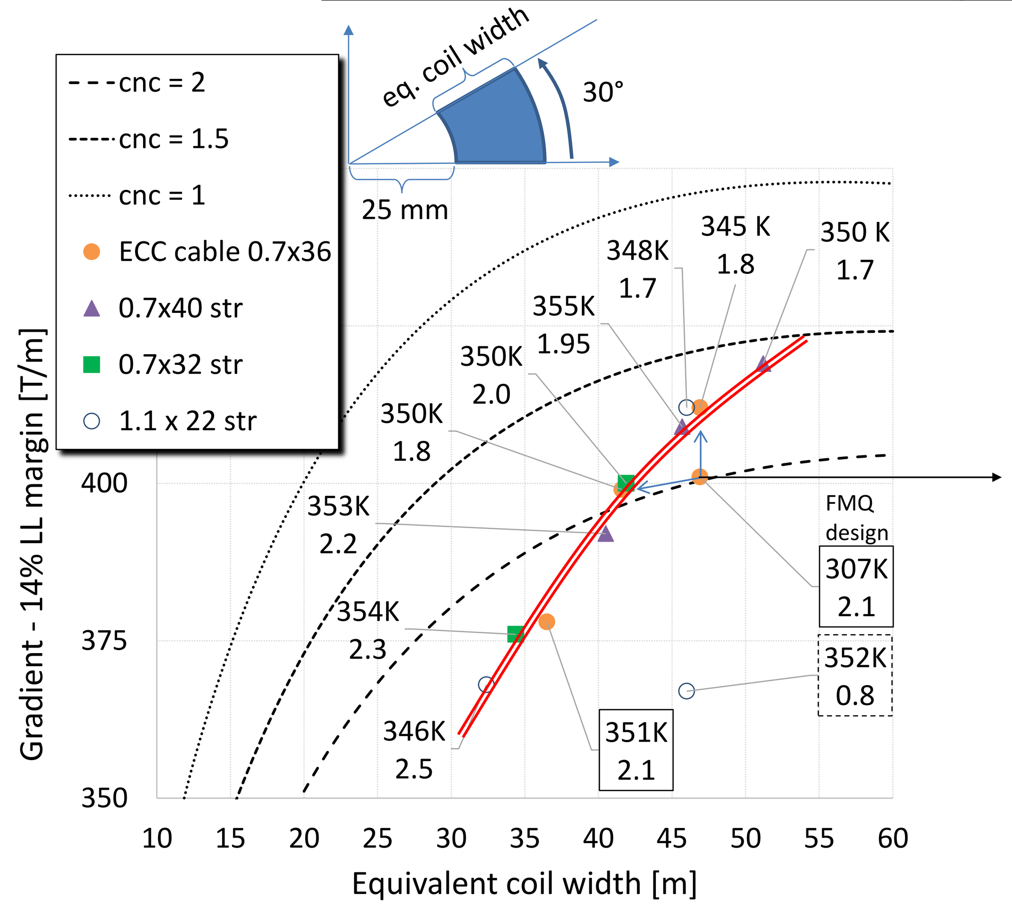
Parameter	HF	LF	Unit
Strand diameter	1.1	0.7	mm
Number of strands	22	39	adim
Bare cable width	13.2	14.25	mm
Bare cable thickness	1.95	1.26	mm
Keystoned angle	0.5	0.5	°
Copper/non-Copper ratio	0.8	2.1	adim
Insulation thickness	0.15	0.15	mm



$$\begin{cases} J_c = \dfrac{C(t)}{B} b^{0.5}(1-b)^2 \\ B_{c2}(T) = B_{c20}(1-t^{1.52}) \\ C(t) = C_0(1-t^{1.52})^{\alpha}(1-t^2)^{\alpha} \end{cases}$$

where $t = T/T_{c0}$ and $b = B/B_{c2}(t)$ with B the magnetic flux density on the conductors. T_{c0} = 16 K, B_{c20} = 29.38 T, α = 0.96, C_0 = 275880 AT/mm² are fitting parameters computed from the analysis of measurements on the conductor. The cabling degradation is assumed to be 3%.

Exploration of designs and selection



Parameter	Values	Unit
Nominal current	12285	A
Peak field	12.12	T
Gradient	401	T/m
Loadline margin	14.0	%
Inductance (2 apertures)	17.9	mH/m
Stored energy (2 apertures)	1397	kJ/m
Azimuthal force (per ½ coil)	3530*	kN/m
Radial force (per ½ coil)	1580	kN/m
Number of turns HF cable per layer	3+12+16+19 = 56	adim
Area of conductor (2 apertures)	124.2	cm²
Total weight**	~475	tons

*0.55+0.8+1.1+1.1 MN/m per layer
**given as an indication for 750 quadrupoles, 5.7 m long each, and a conductor density of 8700 kg/m³.
**FCC dipoles: ~7500 tons

Single aperture mechanical analysis – Ansys – Pole contact and coil stress

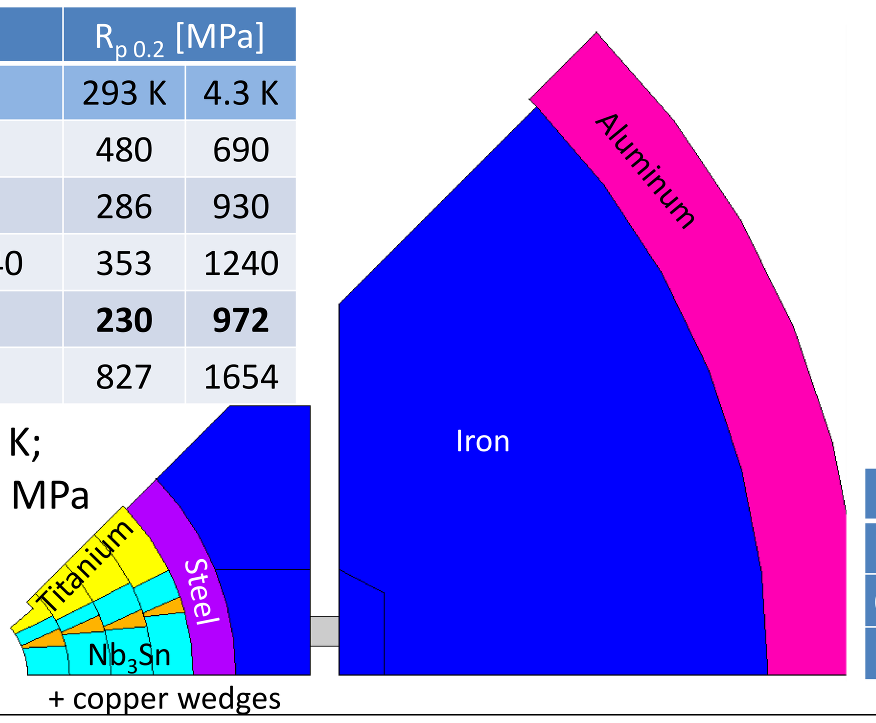
Bladder&Key structure

U.S. LARP

Material	E [GPa]		pr	$(L_{4.3K}-L_{293K})/L_{293K}$
	293 K	4.3 K	293K / 4.3K	293 K -> 4.3K
Nb_3Sn	EX = **25** EY = **30** GXY = 21	EX = **27.5** EY = **33** GXY = 21	0.3	X = 3.36e-3 Y = 3.08e-3
StSt	193	210	0.28	2.84e-3
Iron	213	224	0.28	1.97e-3
Al7075	70	79	0.34	4.2e-3
Ti6Al4V	**115**	**126.5**	0.3	1.74e-3

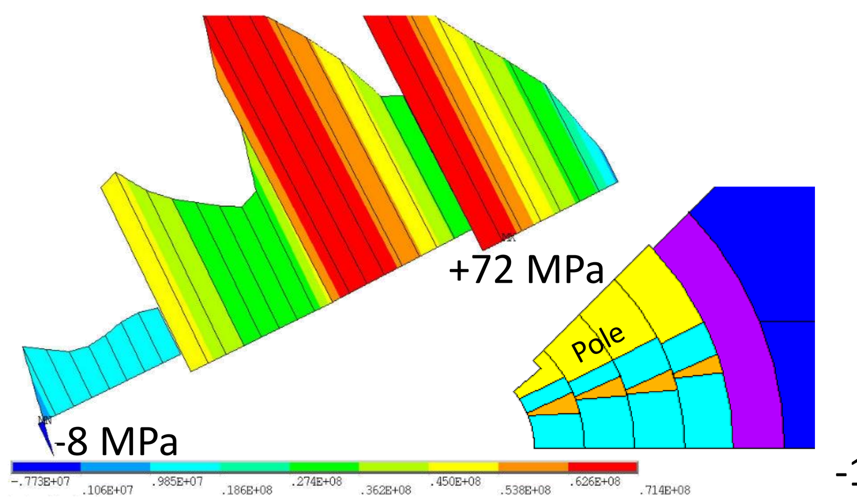
Material	$R_{p\,0.2}$ [MPa]	
	293 K	4.3 K
Al 7075	480	690
SS 316 LN	286	930
NITRONIC 40	353	1240
ARMCO*	**230**	**972**
Ti 6Al 4V	827	1654

*Iron @ 4.2 K; stress < **350** MPa in tension (brittle)

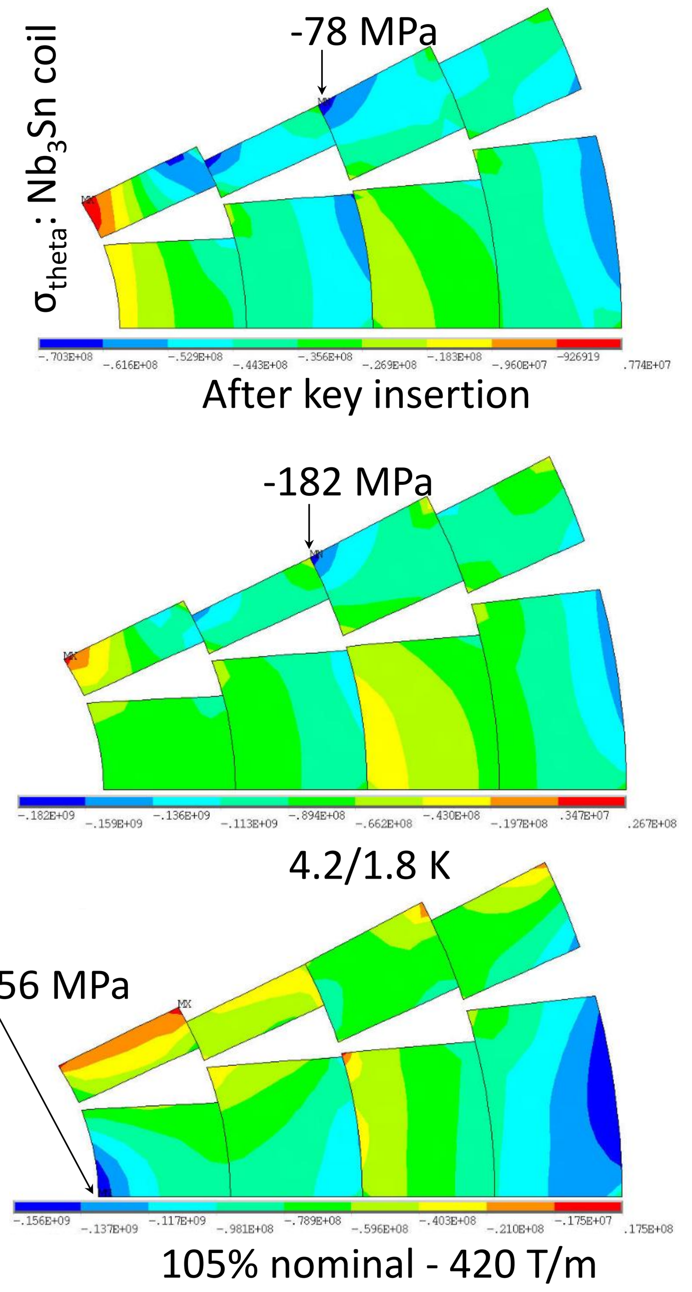


- 32 mm thick shell
- 500 µm ← horizontal interference
- Ryoke = 275 mm
- Contacts/symmetry:
  - sliding; 0.2 friction
  - glued: coils with pole and the first 2 layers and the last 2 layers

Contact at 105 % of nominal

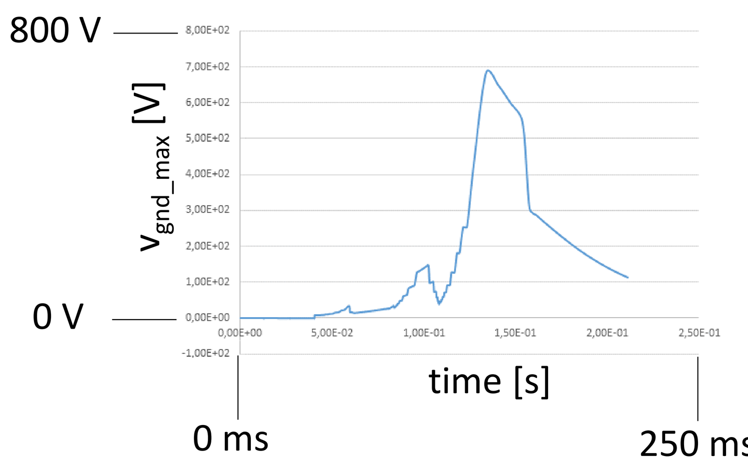


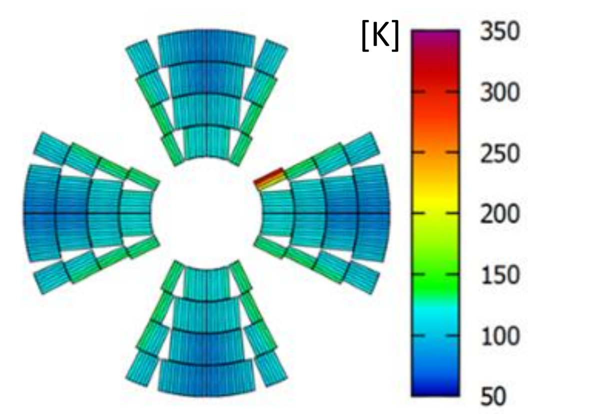
stress in [MPa]	θ-stress	von Mises
Key inserted	-70	68
Cool-down	-182	174
Powering @105% of Inom	-156	156



Protection analysis

Voltage to ground and *hotspot temperature* throughout a quench





Quantities	Values	Unit
Detection + validation time	20	ms
Resistive transition delay	20	ms
Voltage threshold	100	mV
Hotspot temperature	313	K
Voltage to ground	700	V

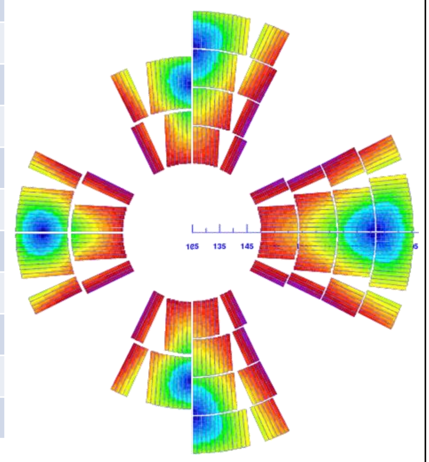
Preliminary results to fine-tune along with heater geometry or Coupling-Loss Induced Quench (CLIQ) system.

Other route… 2 layers?

Quantity	3rdFCC_v15	Unit
gradient	360	T/m
strand diameter	0.7	mm
nb of strands	51	N/A
width	18.63	mm
average thickness	1.181 – 1.343	mm
Cu/nonCu	2.1	N/A
I_{nom}	19480	A
B_{peak}	10.5	T
LL margin (1.9 K)	19.5	%
Inductance diff. (2 ap)	3.1	mH/m
Stored energy (2 ap)	617	kJ/m
Nb of turns	23 = 6 + 3 + 10 + 4	-
F_/_ & F // (per ½-coil)	1.99* & 0.99	MN/m
Hotspot	320	K
Midplane shim	0.35	mm
I/Ic max	0.54	-
length	**6.3**	m
Conductor area (2 ap)	**72.3**	cm²
750 x length x 8.7 weight	**306** *(dip ~7000)*	tons

*0.8 + 1.2 MN/m per layer [614 mm yoke OD]

Spec:
same strand as ECC
2 layers
20% margin
current < 20 kA
204 mm b-b distance
< 700 mm outer yoke



Conclusion: Using a cable identical to the FCC dipole could lead to a quadrupole performance of 400 T/m, not far from an optimum without developing a dedicated strand and cable. Indeed, the reduction of performance is only around 3% in terms of gradient, or differently translated, around 10% in terms of conductor quantity (integrated gradient). Electromagnetics, mechanics and protection look promising.