Quadrupole magnets for the FCC triplets

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FCC Week 2018
11 April 2018

IRQ magnet requirements (from D. Schoerling)

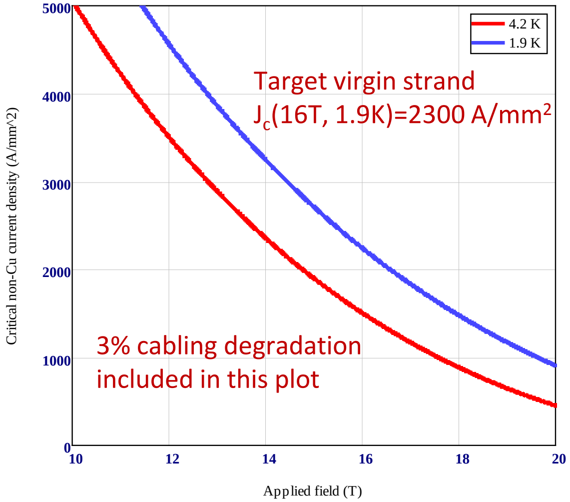
Magnet	Number	Strength	Length	Aperture
Q1 low lumi	4/IP	270 T/m	10.0 m	64 mm
Q2 low lumi	4/IP	270 T/m	15.0 m	64 mm
Q3 low lumi	4/IP	270 T/m	10.0 m	64 mm
Q1 high lumi	4/IP	130 T/m	14.3 m	164 mm
Q2 high lumi	8/IP	105 T/m	12.5 m	210 mm
Q3 high lumi	4/IP	105 T/m	14.3 m	210 mm

- 6 magnet types and 3 distinct coil cross-sections: LL-Q1/Q2/Q3, HL-Q1, HL-Q2/Q3.
- Cable J_c specified for FCC dipoles (next slide).
- Operating temperature 1.9 K.
- Nominal current < 20 kA.

Cable parameters

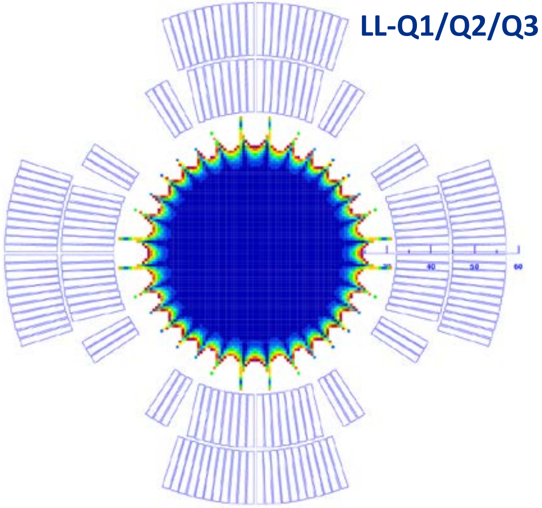
Parameter	Unit	LL	HL
Strand diameter	mm	0.800	1.000
Cu/nonCu ratio		1.13	
Number of strands		28	
Bare cable width	mm	12.38	15.10
Bare cable mid-thickness	mm	1.495	1.869
Insulation thickness per side	mm	0.15	

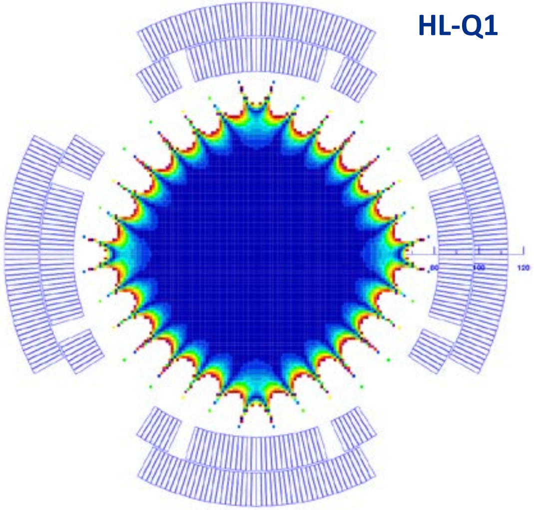
Specified in EuroCirCol-P1-WP5

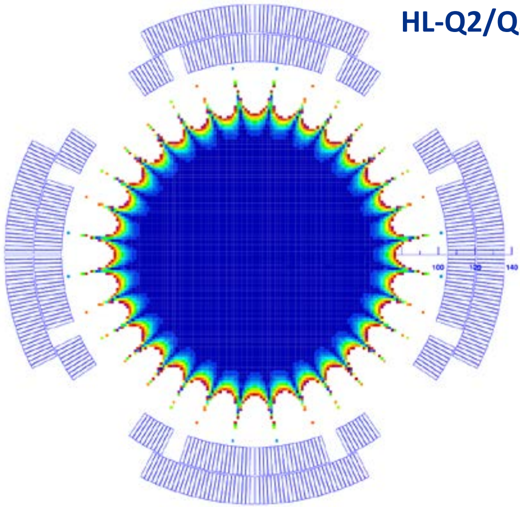


- A general consideration is that a bigger strand is better from the viewpoint of a magnet design. For a fixed coil thickness and number of layers (determined by the aperture and the required gradient) a bigger strand means:
  - a lower number of turns (fabrication labor) and a lower inductance (quench temperature);
  - a more efficient design (fraction of superconductor is higher for the same insulation thickness);
  - but a higher current (current leads start to be a problem at some point).
- 1 mm strand is at about the sweet spot for the HL designs. Also the cable dimensions are similar to what is presently used for the 15-16 T dipoles developed within the US MDP program and for the past 12 T HFDA models fabricated and tested at FNAL – a lot of practical experience with this kind of cable.
- Strand diameter has to be reduced to 0.8 mm for the LL designs to meet the maximum current requirement.

Coil designs and the geometrical field quality

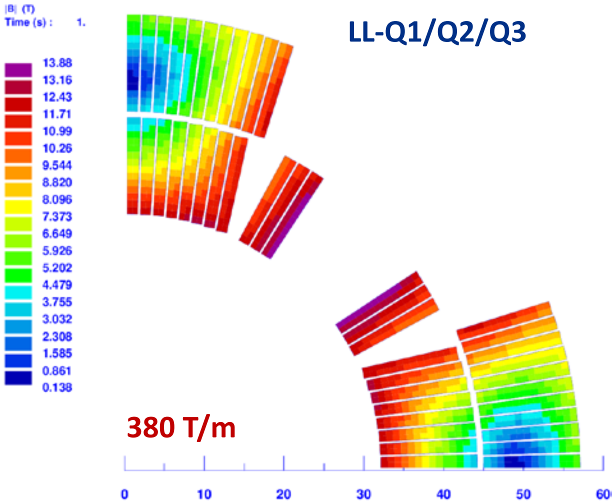

LL-Q1/Q2/Q3


HL-Q1

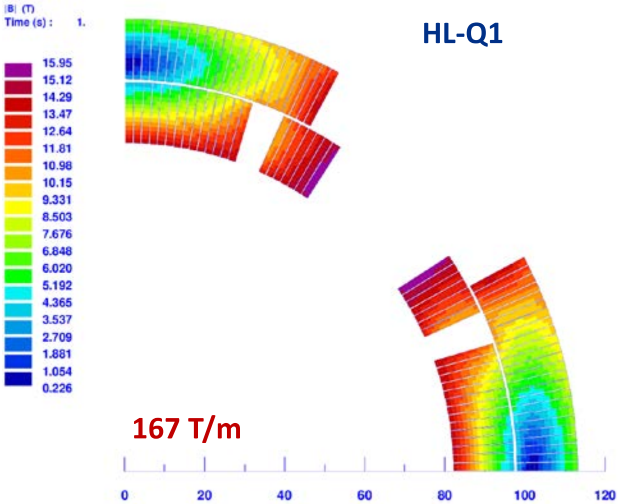

HL-Q2/Q3

Parameter	Unit	LL-Q1/Q2/Q3	HL-Q1	HL-Q2/Q3
Aperture	mm	64	164	210
R_{ref}	mm	21	55	70
b_6	10^{-4}	0.0003	0.0032	0.0002
b_{10}		-0.0017	0.0165	0.0020
b_{14}		-0.0811	0.9223	0.1117

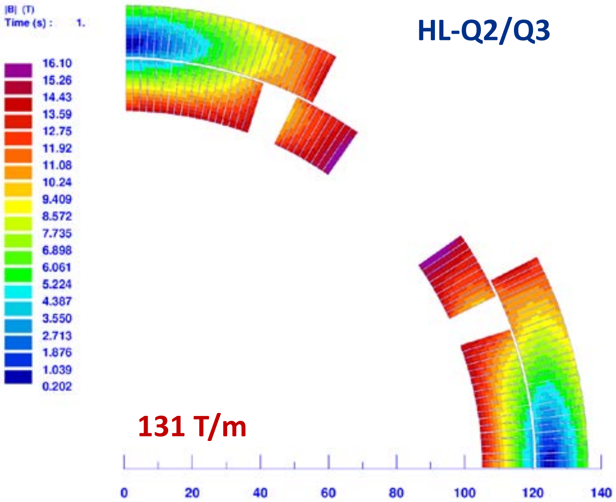
Coil fields at SSL (1.9K)


LL-Q1/Q2/Q3

380 T/m


HL-Q1

167 T/m

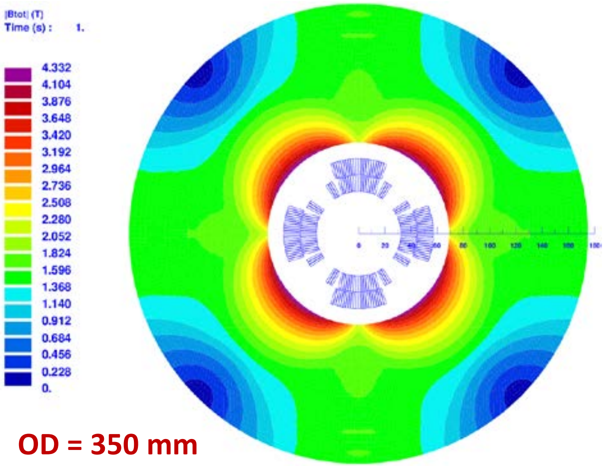

HL-Q2/Q3

131 T/m

- Two-layer coils meet the nominal gradient requirements with sufficient margins.
- One spacer/octant in the inner layer – sufficient for the field quality.
- Full cable keystoning in the outer layers of the HL designs.
- The coil peak field in LL design is 14 T:
  - a hybrid design with NbTi conductor in the outer layer is possible.
- The peak coil field in HL designs is 16 T - requires Nb_3Sn in all the layers.

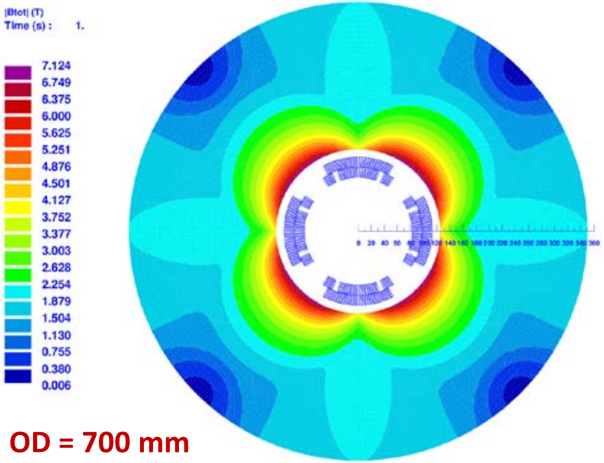
Iron yoke (fields at the nominal gradients)

LL-Q1/Q2/Q3



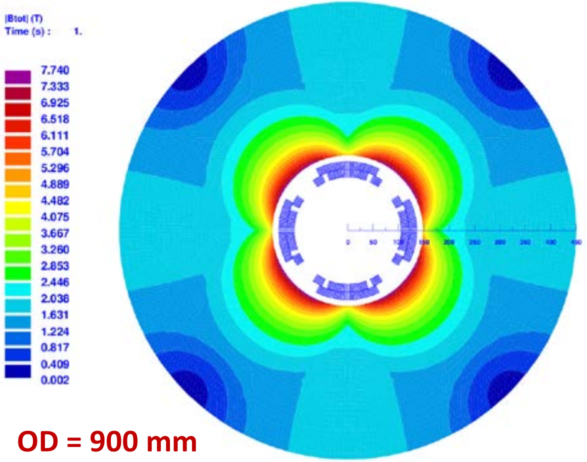
OD = 350 mm

HL-Q1



OD = 700 mm

HL-Q2/Q3



OD = 900 mm

- General constraints:
  - Yoke OD < 1 m (FCC requirement);
  - Peak field at the yoke outer surface < 2 T (at the nominal gradient) to minimize the fringe fields.

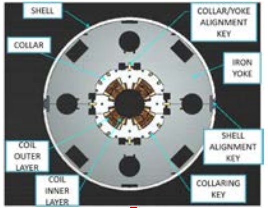
Magnet parameters

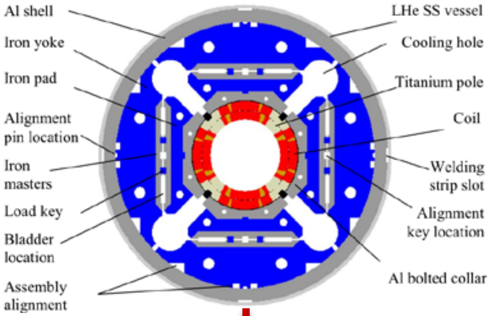
Parameter	Unit	LL-Q1/Q2/Q3	HL-Q1	HL-Q2/Q3
Aperture	mm	64	164	210
Iron yoke OD	mm	350	700	900
Nominal gradient, G_{nom}	T/m	270	130	105
Maximum gradient (SSL at 1.9 K), G_{max}	T/m	380	167	131
Fraction of SSL at G_{nom}		0.71	0.78	0.80
Peak coil field at G_{nom}/G_{max}	T	9.9/13.9	12.4/16.0	12.9/16.1
Current at G_{nom}/G_{max}	kA	15.2/21.9	17.7/23.4	17.7/22.7
Inductance at G_{nom}/G_{max}	mH/m	1.89/1.83	8.77/8.44	13.60/13.14
Stored energy at G_{nom}/G_{max}	MJ/m	0.22/0.44	1.37/2.31	2.13/3.39
F_x per octant at G_{nom}/G_{max}	MN/m	0.99/1.86	2.94/4.62	3.71/5.55
F_y per octant at G_{nom}/G_{max}	MN/m	-1.22/-2.49	-3.55/-6.04	-4.48/-7.18
Azimuthal midplane stress in IL at G_{nom}/G_{max}	MPa	65/97	138/233	185/295
Azimuthal midplane stress in OL at G_{nom}/G_{max}	MPa	49/131	135/225	159/251

Comparison to other magnets

LHC MQXB(A) quads:

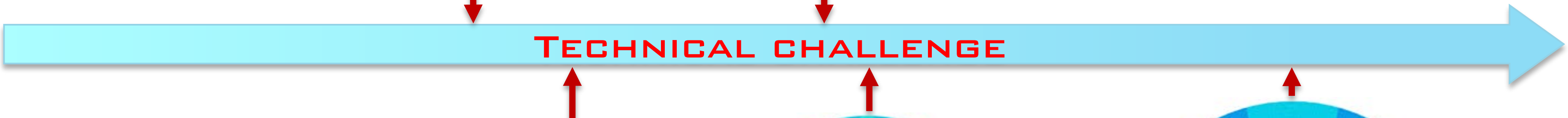
- 70 mm aperture
- 215 T/m nominal
- 230 T/m tested
- G_{nom}/G_{test} 0.93





LARP/HL-LHC quadrupole:

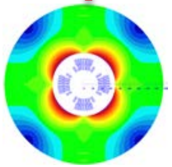
- 150 mm aperture
- 133 T/m nominal gradient
- 150 T/m tested



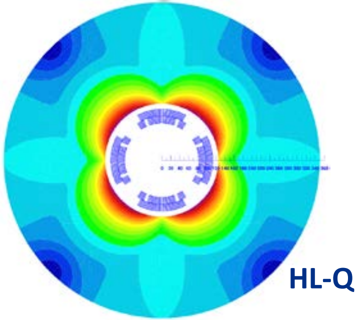
Technical challenge

NbTi option for LL:

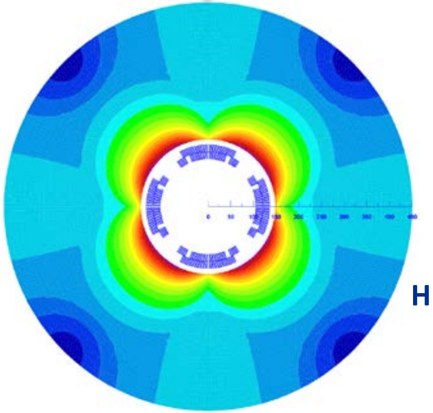
- Aperture 70 mm → 64 mm
- Gradient 230 T/m → 252 T/m
- J_c(5T,4.2K) 2750 A/mm^2 → 3300 A/mm^2
- Gradient 252 T/m → 302 T/m
- G_{nom}/G_{test} 0.9



LL-Q1/Q2/Q3



HL-Q1



HL-Q2/Q3

Same gradient as in the HL-LHC quad, 10% larger bore

Summary

- The LL magnet requirements are within reach of the NbTi technology. With the best available NbTi strand, it becomes a feasible (and the most cost-effective) option. In case of the Nb_3Sn design (or a hybrid Nb_3Sn/NbTi), it is possible to increase the nominal gradient by 10-20% and to proportionally reduce the magnetic length.
- The HL-Q1 magnet parameters are at the present limit of the Nb_3Sn technology. Slightly more challenging than 150 mm HL-LHC quadrupoles. The design feasibility has to be proven by the conductor and the magnet R&D campaigns, which can largely benefit from the LARP/HL-LHC experience.
- The HL-Q2/Q3 parameters are very challenging. A substantial R&D is required to prove the feasibility:
  - Azimuthal stress is over the acceptable limit already at the nominal gradient. The equivalent stress would be even higher. Stress management is necessary. A 4-layer design may be needed because of the reduced efficiency due to the internal support structure. Alternatively, using of the more strain-tolerant materials (Nb_3Al) can be considered, but because of the lower critical current density the number of layers would also go up.
  - The stored energy is an order of magnitude higher than for the LL magnets. For Q3, the total stored energy is over 30 MJ at the nominal gradient. The quench protection needs to be carefully studied.