Magnetic Design Update of Large Aperture Beam Separation Dipole for the HL-LHC Upgrade

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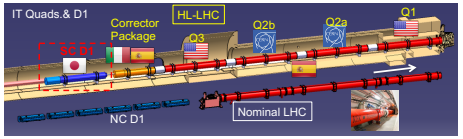
HL-LHC upgrade

- Peak luminosity: 5 × 10^{34} $cm^{-2}s^{-1}$ (a factor of five of nominal LHC)
- Integrated luminosity: 3000 fb^{-1} (a factor of ten of nominal LHC)

Layout around interaction points, ATLAS and CMS



KEK is in charge of development of **beam separation dipole (D1)**

Aperture increase in IT Quads:70mm→150mm

➡ Large bore also for the new D1

Stronger kick to accommodate shorter distance between D1 and D2

Field integral : 26 Tm → 35 Tm

Overview of D1

Design parameters

	2 m model	Production
Field integral	9.4 T·m	35 T·m
Coil aperture	150 mm	
Nominal dipole field	5.57 T	
Coil peak field	6.45 T in the straight section	
	6.58 T at coil end	
Load line ratio	75.6% in the straight section	
	76.7% at coil end	
Field quality	<10^{-4} w.r.t B_1 at R_{ref}=50 mm	
Nominal current	12.05 kA	
Operation temperature	1.9 K	
Magnetic length	1.68 m	6.26 m
Coil mechanical length	2.00 m	6.58 m
Magnet mechanical length	2.15 m	6.73 m

Design guideline

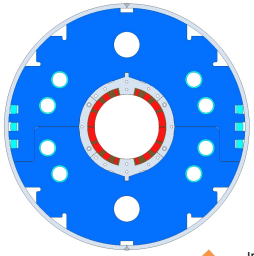
- Single layer coil
- Nb-Ti/Cu cable with APICAL and PIXEO insulations (MB outer cable)
- Collared yoke structure
- Design features for better cooling
  - Void space
  - Packing factor of collar and yoke < 100%

Technical challenges

- Tight constraint of field quality under high level of iron saturation
- High radiation dose of 25 MGy
- Precise prediction of coil deformation for controlling pre-stress

Update of magnet cross-section

1st model

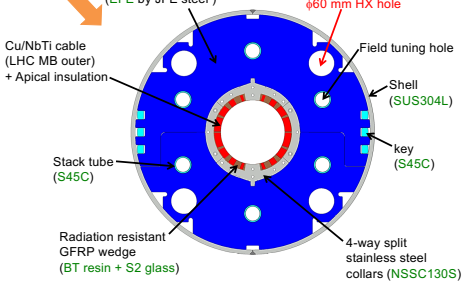


Objective of this study

Request from CERN for changing heat exchanger holes to be in line with the inner triplets

Magnetic design update for the 2nd model magnet of D1 base on ROXIE calculation

2nd model



Optimization of 2D cross-section

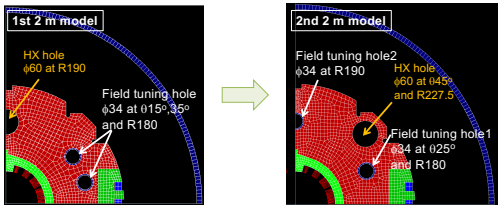
Multipole expansion

$$B_y + iB_x = 10^{-4} B_{ref} \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

b_n, a_n: Normal and skew multipole coefficient
R_{ref}: Main dipole field
Reference radius: 50 mm

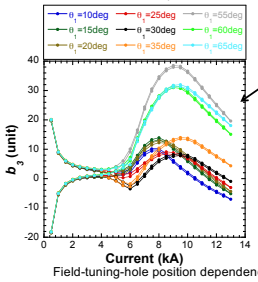
Iron shaping

Change in heat exchanger holes



Optimization of field tuning holes

Field tuning hole conditions (number of holes, a hole diameter, R and θ positions) were varied to minimize iron saturation effect on b_3.



Number of field tuning holes: 3 per yoke
Diameter of holes = ϕ34
One hole at θ_2=90°, R=190 is fixed.
Another HX hole is moved at θ_1=10-65° on R=180.

Field tuning holes after optimization
- Number of holes: 3 per yoke
- Diameter of holes: ϕ34 mm
- Hole positions
  - θ_1=25°, R_1=180 mm
  - θ_2=90°, R_2=190 mm

Field-tuning-hole position dependence of iron saturation effect

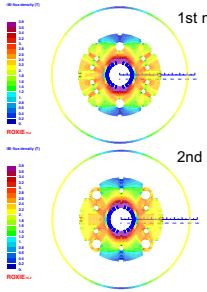
Field quality at nominal current after coil block rearrangement

Coil block arrangement was re-optimized for the new iron cross-section and calculated field quality.

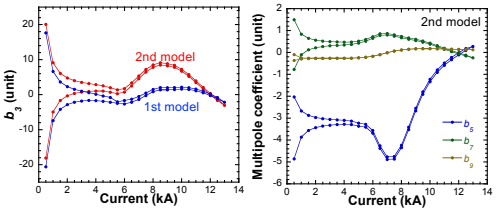
→ Same number of coil blocks, number of turns, only slight change in cable angle

	1st model Ver3.0.0	2nd model Ver4.0.1
Nominal current (kA)	12.0	12.047
Main field (T)	5.573	5.569
b3 (unit)	-0.059	-0.028
b5 (unit)	-0.097	-0.045
b7 (unit)	-0.111	-0.054
b9 (unit)	0.284	0.139
b11 (unit)	0.360	0.176
b13 (unit)	-0.663	-0.695
b15 (unit)	-1.115	-1.157
b17 (unit)	-0.788	-0.815
b19 (unit)	0.399	0.402

Nominal current in the modified model was determined to generate the main dipole field of 5.57 T.



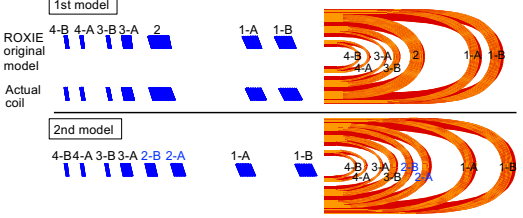
Variation of b_n with current



Optimization of coil end shape by 3D field calculation

Coil end shape was optimized for 7 m production magnet and the same coil end was applied to the 2nd model.

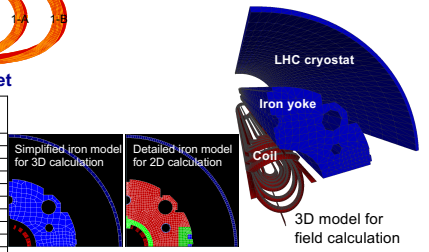
Coil end design



- More inclined cable angle in the 1st model than ROXIE original model
  → Measured cable angle is reflected to the design parameters.
- Subdivision of CB2 (13 turns → 6 + 7 turns)
- Longitudinal positions of CB1A, 1B, 2A and 2B were adjusted to minimize integrated b_3, b_5, b_7 and b_9 at I_{nom} over 7 m magnet

Field integral at the nominal current in 7 m magnet

	RE (unit)	SS (unit)	LE (unit)	Total (unit)	Target value (unit)	Difference (unit)
z	-4000~-2870	-2870~2720	2720~4000	-4000~4000		
BL (Tm)	1.422	31.344	2.262	35.027		
b3 (unit)	-3.607	8.805	-2.132	3.066	3.057	0.009
b5 (unit)	-0.281	0.048	0.298	0.065	-0.228	0.292
b7 (unit)	-0.287	0.016	-0.058	-0.330	0.067	-0.397
b9 (unit)	-0.269	0.091	-0.167	-0.345	0.109	-0.454
b11 (unit)	-0.119	0.167	-0.086	-0.038		
b13 (unit)	-0.055	-0.620	-0.054	-0.729		
b15 (unit)	-0.035	-1.030	-0.060	-1.124		
b17 (unit)	-0.011	-0.726	-0.027	-0.765		
b19 (unit)	0.006	0.359	0.015	0.380		
a1 (unit)	0.001	0.148	-5.539	-5.391		
a3 (unit)	0.000	0.039	1.808	1.847		



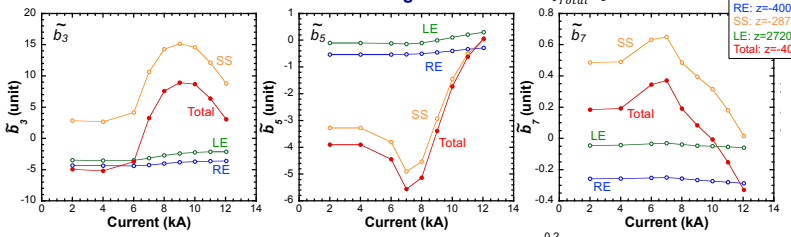
3D model for field calculation

The 2D calculation results with the simplified iron model was set as a target.

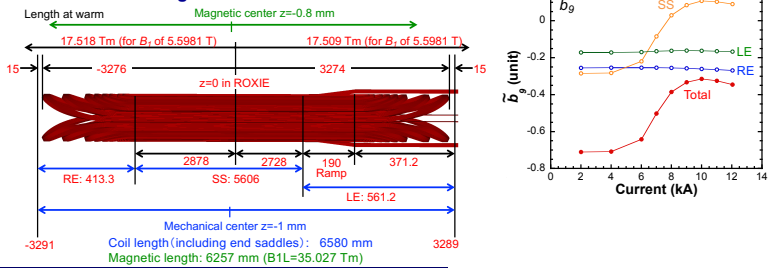
Contribution of SS and coil ends to field integral

$$\tilde{b}_n = \frac{\int_i B_n dz}{\int_{Total} B_1 dz} \times 10^4$$ i=SS, RE, LE, Total

RE: z=-4000 ~ -2870 mm
SS: z=-2870 ~ 2720 mm
LE: z=2720 ~ 4000 mm
Total: z=-4000 ~ 4000 mm



Coil mechanical length



Summary

- Magnetic design of D1 magnet was updated for new iron yoke cross-section with four heat exchanger holes.
- In 2D calculation, almost all normal multipoles were able to be controlled within 1 unit.
- Field integrals of b_3 – b_9 were adjusted within 0.5 unit with respect to the target values for 7 m magnet by optimizing longitudinal position of coil end blocks.
- Fabrication of the second model magnet will be started in 2017.

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