Development of superconducting magnets for LHC luminosity upgrade (2) – Conceptual design of a large aperture dipole magnet for beam separation

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Abstract

Upgrade of the low-beta insertion system for the ATLAS and CMS experiments is proposed in the HL-LHC (High Luminosity LHC upgrade) project. It includes the final beam focusing quadrupoles, beam separation and recombination dipoles, and larger aperture matching section quadrupoles. KEK is in charge of conceptual design of the large aperture separation dipole D1. Latest design parameters are a main field of ~ 5 T at 1.9 K with Nb-Ti superconducting technology, a coil aperture of 160 mm, and a cos-theta 1-layer coil with LHC dipole cable. Since the new D1 is expected to be operated in very high-radiation environment, radiation resistance and cooling scheme are being carefully considered. The collaring-yoke structure is adopted to provide the mechanical support for the single layer Nb-Ti coil. We summarize the design study of this magnet, including (i) the very large iron saturation effect on field quality due to the large aperture and limited size of the iron yoke, (ii) the stray field at the outer surface of the iron cryostat, (iii) the stress management from room temperature assembly to final operation, and (iv) the high-level of heat deposition in the coil due to radiation.

INTRODUCTION

HL-LHC (High Luminosity-Large Hadron Collider) is the luminosity upgrade project for the LHC. The main objective of this project is to implement a hardware configuration and a set of beam parameters that will allow to reach a peak luminosity of 5×10^{34} $cm^{-2}s^{-1}$ and a total integrated luminosity of 3000 fb^{-1} per year, which is ten times more than the integrated luminosity of the first 10 years of the LHC lifetime [1-2]. Upgrade of the low-beta insertion system for the ATLAS and CMS experiments is one of the main tasks of the HL-LHC project. It involves replacing the magnets in the lattice from the interaction point to the beginning of the matching section (Q4), with larger aperture ones to allow reaching a smaller β^*. KEK is in charge of design of the new separation dipole. The new D1 magnet, replacing the current room-temperature 1.28 T dipole modules, will be superconductive, radiation-hard and have a nominal field of ~ 5 T with an aperture diameter of 160 mm. The integrated field is increased from 26 T m to 40 T m.

DESIGN PARAMETERS AND CROSS SECTION OF THE MAGNET

A one-layer and four-block coil layout is adopted in the latest design of the new D1 magnet. The Nb-Ti LHC dipole cable (outer layer) [2] is the baseline conductor for the coil winding. The aperture diameter is 160 mm. The coil width (cable width) is 15 mm. The thickness of the collar-spacer between coil and iron yoke is 20 mm; then we get the inner diameter of the iron yoke is ~ 230 mm. The outer diameter of the iron yoke is 550 mm, the same size as the main dipole magnets of LHC. The magnet will be located at the center of the iron cryostat, which has an outer diameter of 914 mm and thickness of 12 mm, also the same size as the cryostats for LHC main dipole magnets.

The electromagnetic field has been modeled with ROXIE [3]. Due to the position of the magnet is right after the interaction point and therefore will be heavily irradiated, we take a conservative margin of 30% on the load line at 2 K. With the cross section shown in Fig. 1, the nominal current is 10. 5 kA; the main field in the aperture is ~ 5 T. To achieve an integrated field of 40 T m, the magnetic length is 8 m. The peak field in coil is 5.9 T. Most part of the iron yoke is highly saturated due to the large aperture of the magnet. Table 1 shows main parameters of the magnet and LHC dipole cable.

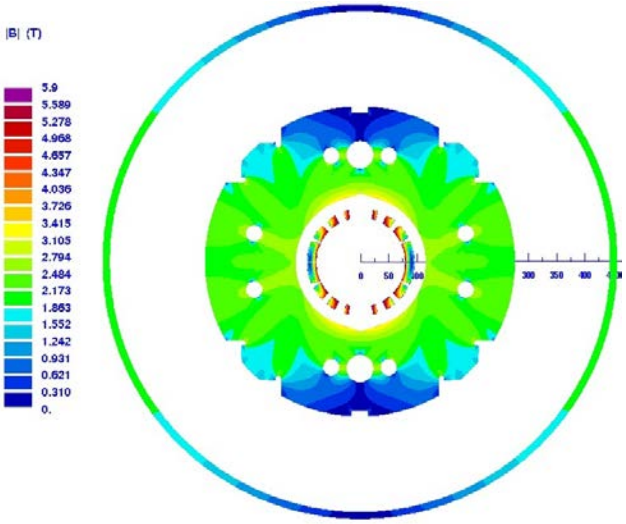

Fig. 1: Magnetic field distribution of the new D1 magnet at nominal current.

Table 1: Design Parameters of the New D1 Magnet

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Item	Value
Bore diameter	160 mm
Nominal field (dipole)	5.04 T
Magnetic length	8 m
Operating current	10.5 kA
Injection current	0.675 kA
Field homogeneity	< 0.01% (R_{ref} = 50 mm)
Peak field in the coil	5.9 T
Load line ratio	70% @1.9 K
Inductance (low / nominal field)	6.54 / 5.97 mH/m
Stored energy	307 kJ/m
No. of layers/blocks	1/4
Peak field/central field	1.17
Lorenz force X/Y (in 1st quadrant)	1.32 / 0.54 MN/m
Outer dia. of iron yoke	550 mm
Inner dia. of iron yoke	232 mm
Strand diameter	0.825
Cu/Non-Cu ratio	1.95
Cable dimension / Insulation	15.1* 1.48mm^2 / 0.16 mm (radial) 0.145 mm (azimuthal)
No. of strands	36
Keystone angle	0.9 °
Superconductor current density	1632 A/mm^2

FIELD QUALITY OPTIMIZATION FROM INJECTION TO NOMINAL CURRENT

At nominal current, the field quality in the aperture can be well optimized by adjusting the position angles and inclination angles of coil blocks, but due to the saturation effect of iron and magnetization effect of superconductors (especially in low field region), field quality strongly depends on the operating current of the magnet [4]. If we choose to optimize the coil layout at nominal current, the field quality at injection will be not optimized, due to magnetization and saturation components. The magnetization effect is related to the filament diameter and critical current density of superconductors; we can do nothing to control it after the type of superconductor and the operating current of the magnet are fixed. However, for the effect of iron saturation, by optimizing the size and shape of the iron yoke, we can minimize its influence on field quality. An easy way is to increase the collar thickness between coil and iron yoke. If we increase the collar thickness of the new D1 magnet from 15 mm to 20 mm, the b_3 variation (from injection to nominal current) can be reduced from 90 units to 70 units (including the effect of filament magnetization in low field region), as shown in Fig. 2. A drawback of this way for our new D1 magnet is that the iron yoke becomes thinner because of a fixed outer diameter of the yoke; then the stray field outside of the magnet will be enhanced.

Instead of simply increasing the inner diameter of the iron yoke, by adding a notch at 90 degree of the inner surface of the iron yoke, where the iron is highly saturated, we can balance the iron saturation effect on field quality in certain level. By adjusting the size of the notch, different b_3 variations along operating current can be observed. We tried different angles (11 degree and 15 degree) and different vertical coordinates of the top points (120 mm, 125 mm, 130 mm) of the notch, the variation range of b_3 is reduced from 70 units to 60 units.

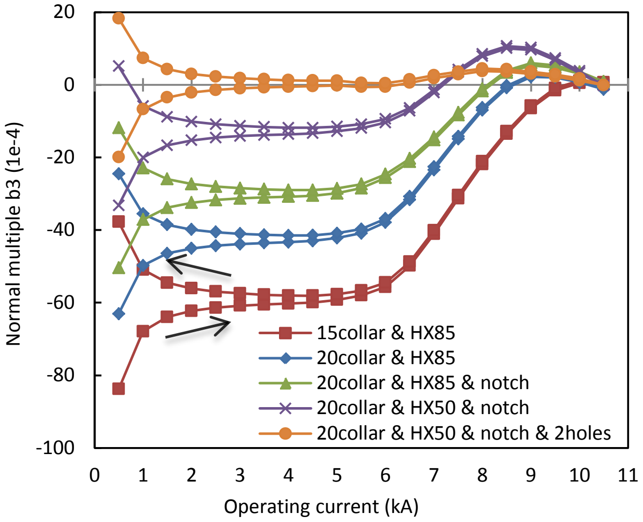

Fig. 2: The effect of iron saturation and filament magnetization on b_3 from injection to nominal current. (arrows indicate the ramp direction of the current).

The size of Heat Exchanger (HX) hole is also capable of changing the b_3 variation from injection to nominal current. Obviously only if the hole area is large enough that the saturation area of the iron yoke is occupied, the b_3 variation will become different with the case that no any HX hole in the yoke. We fix the vertical coordinate of the central point to 200 mm; and reduce the diameter of HX hole from 85 mm to 50 mm, the variation range of b_3 is reduced from original ~ 60 units to ~ 45 units.

By adding additional two small holes with a diameter of 30 mm in the iron yoke, we can further reduce the variation range of the b_3. We tried different position angles of the two holes from 15 degree to 75 degree; the b_3 variation can be further reduced to 40 units, which is dominantly caused by the effect of filament magnetization; and also the slope around nominal current is satisfying, as shown in Fig. 2. Fig. 3 and Table 3 shows ¼ cross-section of the optimized coil layout and iron yoke for the best case in Fig. 2; Fig. 4 shows variation of the other multiple coefficients (b_5, b_7,…b_{13}) from injection to nominal current for this case.

Table 3: Coil Layout Parameters of the Best Case in Fig.2

Coil Blocks	Radius (mm)	Phi (degree)	Alpha (degree)	No. of conductors
1	80	0.770	0.000	20
2	80	26.674	33.787	14
3	80	50.423	49.895	9
4	80	71.000	76.000	4

* Phi – position angle; Alpha – Inclination angle.

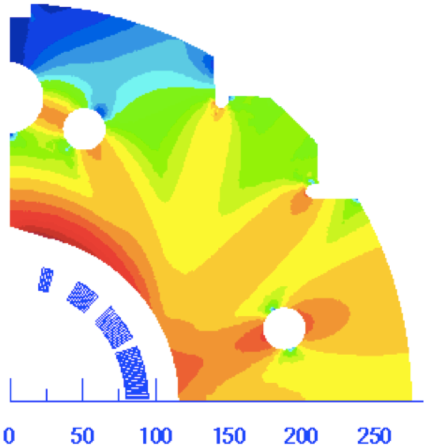

Fig. 3: Optimized coil layout and yoke shape & hole pattern for the best case in Fig. 2.

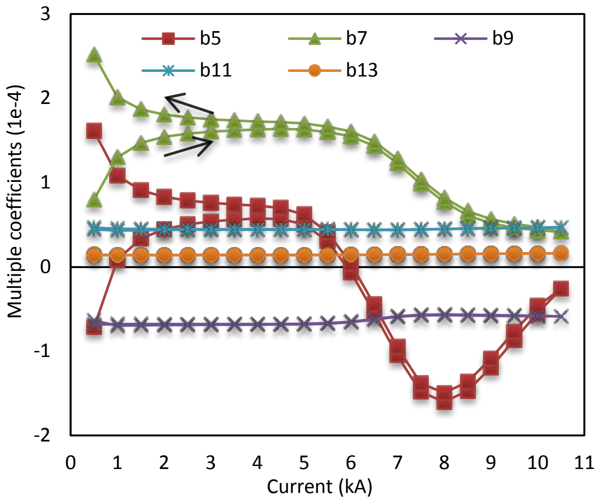

Fig. 4: The effect of iron saturation and filament magnetization on other multiple coefficients (b_5, b_7,…b_{13}) from injection to nominal current for the best case in Fig. 2 (arrows indicate the ramp direction of the current).

STRAY FIELD

Although the new D1 magnet has a large aperture of 160 mm, the current design assumes the outer diameter of the iron yoke is 550 mm, the same size as the iron yoke for LHC main dipole magnets. The iron cryostat is also the same size as the current LHC cryostat: the outer diameter is 914 mm and the thickness is 12 mm. The maximum stray field at the outer surface of the iron cryostat is about 35 mT, as shown in Fig. 5. A simple method to reduce the stray field is to increase the thickness (outer diameter) of the iron yoke. Fig. 5 also shows the variation of the stray field with different outer diameters of the iron yoke. If we need to reduce the stray field to less than 10 mT at the outer surface of the cryostat, the required outer diameter of the iron yoke is 630 mm.

MECHANICAL SUPPORT STRUCTURE

The Lorentz force of the 1-layer coil in the 1st quadrant is 1.4 MN/m in X direction and -0.5 MN/m in Y direction at nominal current; the corresponding stress on the mid-plane of the coil is about 80 MPa. The collaring-yoke type mechanical structure, which has been adopted for the development of MQXA magnet and JPARC SCFM magnet at KEK [5, 6], is a suitable choice to support this 1-layer coil. Fig. 6 shows the cross section of the collaring-yoke structure for the new D1 magnet. During room temperature assembly of the magnet, the coil is firstly pre-assembled by using metal collar-spacers with a very low stress (less than 10 MPa); then the horizontally split iron yoke is assembled. The structure is loaded, pressing on the shoulder of the yoke, till closing the initial gap between the top yoke and bottom yoke: the coil is fully pre-stressed at this step; after keys are inserted into slots of the iron yoke to lock the whole structure, the load on the shoulder is released. The final step of the room temperature assembly is welding SS316L shell at the outer surface of the iron yoke, which applies certain additional stress to the iron yoke because of the shell shrinkage during welding.

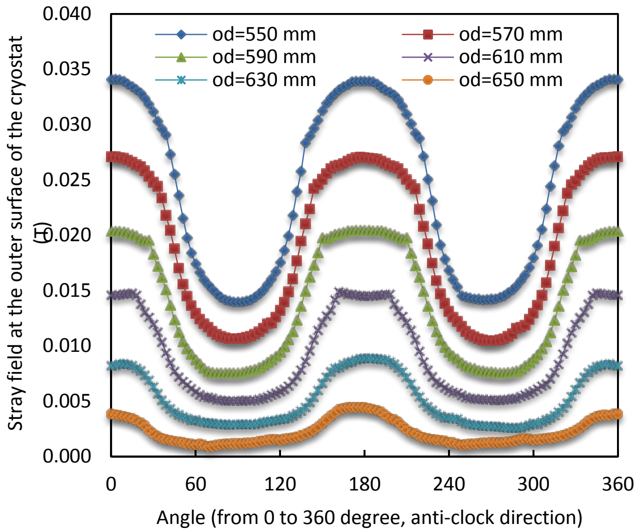

Fig. 5: Stray field at the outer surface of the iron cryostat and at nominal current with different outer diameters of the iron yoke.

A 2D 2-layer mechanical simulation model was developed in ANSYS to simulate the stress distribution of the magnet from room temperature assembly to low temperature excitation, as shown in Fig. 6. Each layer contains half of the yoke (top or bottom), and the two layers are overlapped at the region indicated by yellow line. In this region 0.5 unit thickness is set for each layer, instead of the 1 unit thickness for all the other regions; this represents the real assembly condition of the collaring-yoke structure: one spacer yoke and one fixing yoke are bonded together, the thickness of the region in the yellow line should be half of the other regions. This characteristic is the key point of the 2D two-layer simulation model; it can provide us accurate estimation of the stress distribution around the key-slot region, where the peak stress of the whole yoke is located. By setting up contact pairs between key-side and corresponding slot-side, the two layers are connected together in the simulation model. The friction coefficient of 0.2 is applied for all internal interfaces of the simulation model. Shear stress in keys is not included.

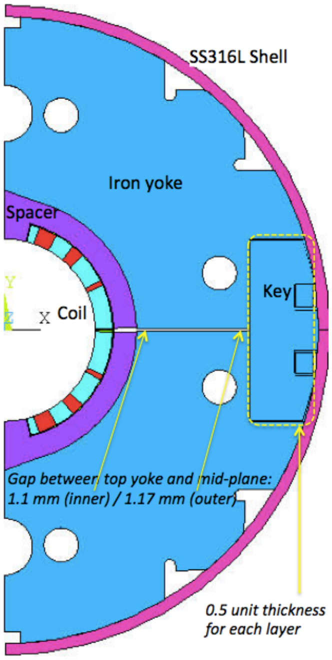

Fig. 6: 2D 2-layer mechanical simulation model for the new D1 magnet

There are totally 6 steps for mechanical simulation, corresponding to the real assembly procedures and cool-down & excitation: collaring; yoking (load application); yoking (key insertion); shell welding; cool-down to 2 K and excitation with 110% of the nominal current. During collaring, certain force is applied to the end of the collar-spacer, to generate ~ 5 MPa pre-stress in the coil; during yoking with load, ~ 1.9 MN/m force (for one quadrant) is applied on the shoulder of the iron yoke to close the initial gap between top and bottom halves of the yoke; the gap thickness between top yoke and mid-plane is 1.1 mm at inner boundary and 1.17 mm at outer boundary, as shown in Fig. 6; during yoking with key, the key is inserted into the slot to lock the top and bottom halves of the iron yoke, and the force on the yoke shoulder is released; during shell welding, stress generated by shell shrinkage is included; During excitation, Lorentz fore at 110% of the nominal current is applied to the model, corresponding to ~ 20% safety margin for the mechanical support at nominal current. Fig. 7 shows the average coil stress in mid-plane and pole region at each step. The coil stress in mid-plane is ~ 85 MPa after room temperature assembly; ~ 60 MPa after the magnet is cooled down to 2 K (due to different thermal expansion coefficients of the magnet components); ~ 80 MPa after excitation with 110% of nominal current. The coil stress in pole region becomes almost zero after excitation.

The peak stress in iron yoke is about 300 MPa in the current design, due to the stress concentration at the corner of the key-slot, as shown in Fig. 8; however, the yield strength of iron is about 220 MPa. In order to reduce the peak stress to less than 220 MPa, at least one more slot should be added to the yoke besides the two in the current design.

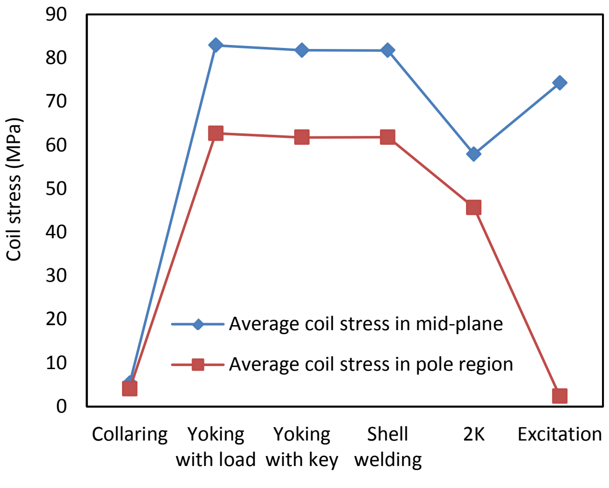

Fig. 7: Average coil stress in mid-plane and pole region at each step.

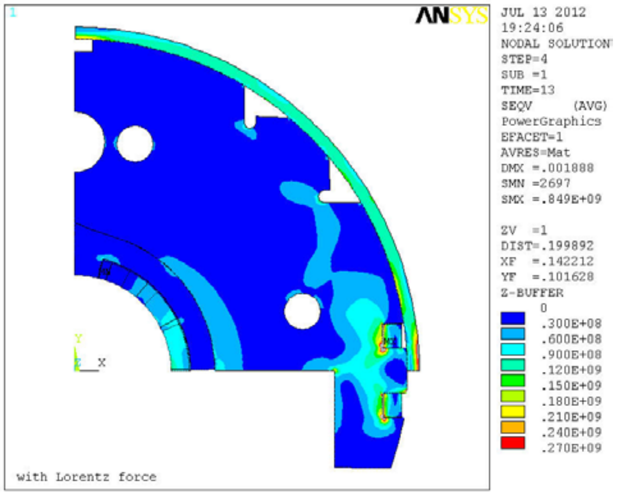

Fig. 8: Stress distribution of the magnet after excitation with 110% of the nominal current.

SUMMARY

The design of the new D1 magnet for HL-LHC upgrade is ongoing. A single layer & 4-block coil wound with LHC dipole cable (outer) is adopted to generate ~ 5 T dipole field in a 160 mm – diameter aperture. The load line margin is 30% at 1.9 K. The outer diameter of the iron yoke is 550 mm; the magnet will be located at the center of an iron cryostat, which has an outer diameter of 914 mm and thickness of 12 mm. The magnetic length is 7 m to reach an integrated field of 35 T m. The field quality is carefully optimized both at injection and nominal current by modifying shape and hole patterns of the iron yoke. At nominal current, all the high order multiples are less than one unit with reference radius of 50 mm. At injection, filament magnetization is the dominant effect givg 20 units in b_3 and less than 1 unit from b_5 to b_{13}.

The maximum stray field at the outer surface of the iron cryostat is 35 mT at nominal current with a 570 mm diameter of the cold mass.it is reduced to less than 10 mT for an outer diameter of the iron yoke is 630 mm.

The collaring-yoke type mechanical structure is adopted to support this single layer coil. During room temperature assembly, ~ 1.9 MN/m load (for one quadrant) is required on the shoulder of the iron yoke to close the initial gap between top and bottom halves of the yoke; the coil stress in the mid-plane is ~ 85 MPa after room temperature assembly; ~ 60 MPa after cool down to 2 K; ~ 80 MPa after excitation with 110% of nominal current. The peak stress in the iron yoke is about 300 MPa due to the stress concentration at the corner of the key-slot; in order to reduce the peak stress to less than 220 MPa, at least one more slot should be added to the yoke besides the two in the current design.

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