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Conceptual Design of a Large-aperture Dipole Magnet for HL-LHC Upgrade

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Abstract

The development of a large-aperture (120-180 mm) dipole magnet is proposed in the framework of the CERN-KEK cooperation program. The application target is the D1 magnet (separation dipoles) replacement for the HL-LHC (High Luminosity - Large Hadron Collider) upgrade. The Cos-theta type coil cross section and the shell-based structure are adopted in the conceptual design of this magnet. The nominal field is estimated to be 6-10 T at 1.9 K with a 30-mm-width coil arranged in two layers. The candidates of superconductor are Nb_3Al, Nb_3Sn and Nb-Ti. We present the analytical estimation of the key parameters of this magnet, and the magnetic & mechanical simulation results of the actual design, including the field quality in the aperture, the stray field of the magnet, and the stress distribution in the coil.

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***Index Terms*— Superconducting accelerator magnets, Large-aperture, Cos-theta type coil, Shell-based structure.**

I. INTRODUCTION

HL-LHC (High Luminosity-Large Hadron Collider) is an upgrade project of the current LHC. The main objective is to implement a hardware configuration and a set of beam parameters that will allow the LHC to reach a peak luminosity of 5×10^{34} $cm^{-2}s^{-1}$ and an integrated luminosity of 250 fb^{-1} per year, which is more than ten times the integrated luminosity reach of the first 10 years of the LHC lifetime [1]. The conventional room-temperature magnet modules D1 (separation dipoles) are considered to be replaced by large-aperture radiation-hard superconducting magnets. The nominal field of the current D1 magnet is 1.28 T [2]. The new superconducting D1 magnet will increase the nominal field to 6-10 T with an aperture diameter of 120-180 mm. The possible candidates of superconductor are A15 type superconductors (Nb_3Al or Nb_3Sn) and Nb-Ti. The higher T_c of A15 conductors is expected to provide more enthalpy margin than Nb-Ti to against the heat deposition by irradiation.

In this paper we present a preliminary analysis of the design: we first address the margin issue, and we then estimate the expected nominal field for the three conductors for apertures ranging from 120 to 180 mm. We then study the two extreme cases for the Nb_3Al conductor. Due to the strain sensitivity of the A15 conductors, instead of the collar structure we propose to adopt the shell-based mechanical structure for the new D1 magnet [3] – this allows avoiding the large required pre-stress during the room-temperature assembly of the magnet. An estimate of the loads and stress during assembly and powering is done, and issues related to the field quality are addressed. The outer diameter of the magnet should not be much larger than the current D1 magnet, because of the limited space in the tunnel. This makes fringe field a critical aspect of the design.

II. ANALYTICAL ESTIMATION OF THE MAGNETIC FIELD

The critical current density (J_c) of the superconductors Nb_3Al, Nb_3Sn and Nb-Ti can be fit by using simple functions in Table I [4, 5]. The fitting error is within 5% on a wide domain. The Nb_3Al J_c is fitted by using the average of the measured J_c of K1 and K3 strands as described in [5], the worst one and the best one respectively among several measured samples. Fig. 1 shows the fit lines of these superconductors. The J_c of Nb_3Al and Nb-Ti are close below 10 T at 1.9 K, both are around one third of that of Nb_3Sn; beyond 13 T, the J_c of Nb-Ti goes down to zero and the J_c of Nb_3Al is about half of that of Nb_3Sn.

The central magnetic field of a Nb_3Al or Nb_3Sn dipole magnet at the short sample limit B_{ss} can be expressed as a function of the aperture radius r, the equivalent coil width w_{eq}, the critical current density of the superconductor and the geometry parameters of the cable and of the coil without iron. This function is based on a simple sector coil model [4]

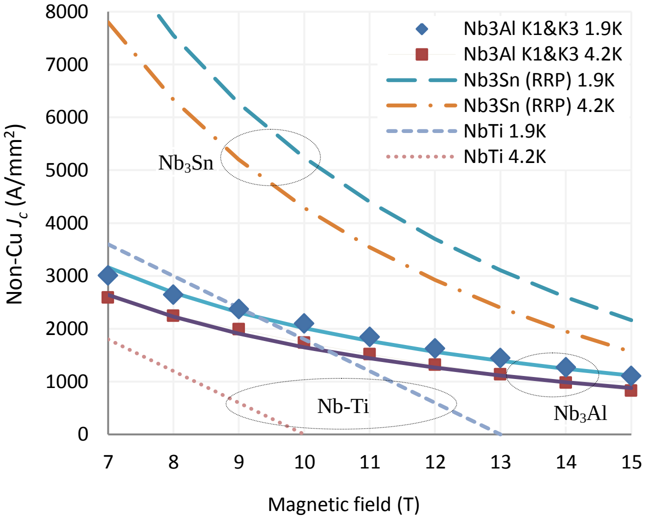

Fig 1: J_c fit of the superconductors by using the functions in Table 1.

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TABLE I: FITTING FUNCTION OF THE SUPERCONDUCTORS

Superconductor	Fitting function	b	c	Error
Nb_3Al @ 4.2K	$j_c = c\left(\frac{b}{B} - 1\right)$	35	6.6E+08	5% for 7-15 T
Nb_3Al @ 1.9K		40	6.7E+08	
Nb_3Sn @ 4.2K		21	3.9E+09	5% for 5-17 T [4]
Nb_3Sn @ 1.9K		23.1	4.0E+09	
NbTi @ 4.2K	$j_c = c(b - B)$	10	6.0E+08	5% for 5-10 T [4]
NbTi @ 1.9K		13	6.0E+08	5% for 6-13 T [4]

$$B_{ss} \approx \frac{kc\gamma_0 w_{eq}}{2}\left(\sqrt{\frac{4b}{kc\gamma_0(w_{eq}+ar)}+1}-1\right) \qquad (1)$$

Where k is the filling factor of the coil pack: $k = k_{w\text{-}c}k_{c\text{-}i}/(1+v_{cu\text{-}sc})$; $k_{w\text{-}c}$ is the area ratio of strands to conductor (cable), $k_{c\text{-}i}$ is the area ratio of bare conductor to insulated conductor, and $v_{cu\text{-}sc}$ is the Cu/Non-Cu ratio of the strand; c and b are parameters of J_c fit in Table 1, $\gamma_0 * w_{eq}$ is the central field per unit of current density, a is a constant number in the following function: $\lambda = 1 + ar/w_{eq}$; where λ is the ratio of the peak field to the central field.

The above expression is valid for the short sample field: a critical aspect is the margin on the loadline, which usually ranges between 20% and 30% in most accelerator magnets. Due to the position of the magnet, which is the first dipole after the interaction point and is therefore heavily irradiated, we take a conservative margin of 33%, i.e. it works at B_{op}=0.67 B_{ss}.

Assuming a filling factor of k=0.34, a=0.04, we get the dependence of central magnetic field B_{op} on coil width for Nb_3Sn and Nb_3Al superconductors, as shown in Fig. 2. For Nb-Ti superconductor, we have a similar equation with (1) [4], the corresponding result is also included in Fig. 2.

The second choice we make is the coil thickness. We choose a rather large coil thickness to decrease the current density and therefore the stresses, which are large in the case of large aperture dipoles. For this reason we propose 30 mm arranged in two layers of 15 mm each, as in the LHC main dipoles. An aperture variation from 60 to 90 mm (radius) gives little impact on the operational field. In Fig. 2, the 4.2 K case is also shown.

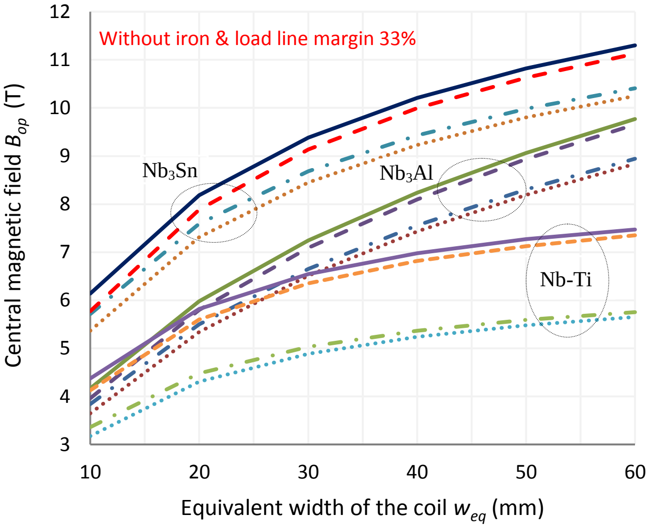

Fig. 2: The dependence of B_{ss} on w_{eq} for aperture radius of 60 mm and 90 mm, with iron and load line ratio 67%. Solid line – r=60 mm @ 1.9 K; dashed line – r=90 mm @ 1.9 K; dashed + dotted line – r=60 mm @ 4.2 K; dotted line – r=90 mm @ 4.2 K;

III. STUDY OF TWO CASES: 120 AND 180 MM APERTURE

A. Main electromagnetic parameters

We studied the two extreme cases for the Nb_3Al conductor by using ROXIE [6] and ANSYS. The coil layout is optimized at the nominal operating current. The target is to reduce the multiple coefficients from b_3 to b_{11} less than 1 unit (10^{-4} relative to the main field) at 2/3 of the aperture radius. The proposed cross-section of the magnet for the 180 mm case is shown in Fig. 3. Five coil blocks are distributed in two layers in each quadrant of cross-section, and the same superconducting cable is adopted for the inner and outer layers (no grading, since it would increase stresses). The outer diameter of the iron yoke is assumed to be 550 mm, i.e., the same size with the current LHC dipole magnets. The thickness of the aluminum shell is ~50 mm. A ~20 mm aluminum-bronze spacer is placed between the iron yoke and coil packs. Totally six holes are arranged in the iron yoke: the two central holes are for the helium flow and the other four are occupied by the aluminum rods. The location of these holes is optimized to reduce the effect of iron saturation on the field quality in the aperture.

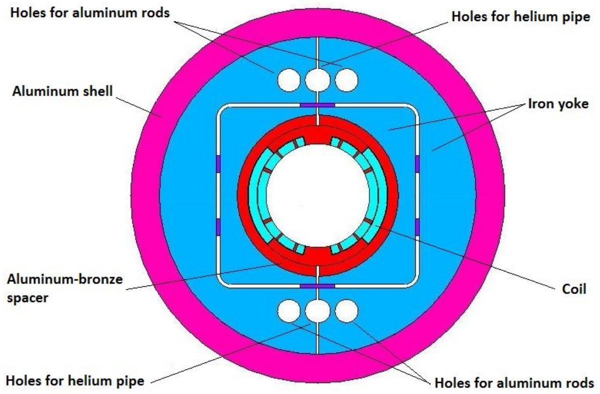

Fig. 3: The cross-section of the D1 magnet with the aperture radius of 90 mm.

The parameters of the magnet, cable and strand are listed in Table II, assuming the load line margin is 33% at 1.9 K for Nb_3Al superconductor, the nominal dipole field of the D1 magnet is 7.6 T, and the operating current is 11.9 kA. The peak field of the coil is 8.5 T, located at the top block of the inner layer; for the outer layer, the peak field is 6.8 T, corresponding to a margin of 41%; as shown in Fig. 4. The parameters with the aperture radius of 60 mm and the coil width of 30 mm are also listed in Table II.

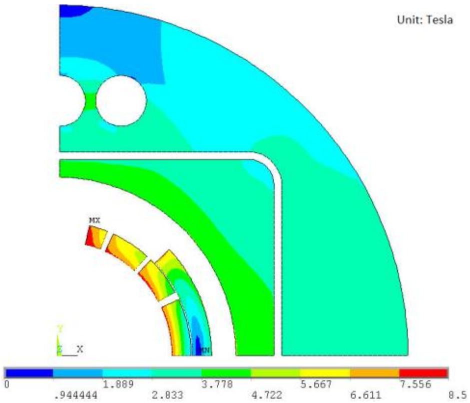

Fig. 4: The magnetic field distribution in the coil and iron yoke (unit: T).

TABLE II: KEY PARAMETERS OF THE MAGNET WITH Nb_3Al SUPERCONDUCTOR

Item	**Value**	
Aperture radius	90 mm	60 mm
Nominal field (dipole)	7.64 T	8.01 T
Operating current	11.9 kA	11.7 kA
Peak field in the coil	8.46 T	8.55 T
Operational temperature	1.9 K	1.9 K
Load line margin	33%	33%
Inductance	16.5 mH/m	8.3 mH/m
Stored energy	1017 kJ/m	512 kJ/m
No. of layers/blocks	2/5	2/5
Peak field/central field	1.11	1.07
Diameter of iron yoke	550 mm	550 mm
Strand diameter	1 mm	1 mm
Cu/Non-Cu ratio	1.0	1.0
Cable dimension	15×1.85 mm^2	15×1.85 mm^2
No. of strands	30	30
Keystone angle	1.15 °	1.37°

B. Iron saturation

The peak field in the iron yoke is 4.6 T at the nominal operating current, as shown in Fig. 4. Most parts of the iron are saturated at the nominal current. Iron saturation causes the variation of sextuple and decapole coefficients along with the increasing of the operating current, as shown in Fig. 5. Since the coil layout is optimized at the nominal current, the sextuple coefficient rises to 35 units at 10% of the nominal current and the decapole coefficient rises to 9 units at 40% of the nominal current. As a comparison with the current design, Fig. 5 also shows the results of two modifications of the iron yoke: remove the spacer between the coil and iron yoke, and remove both the spacer and the holes in the yoke. Without spacer, the maximum value of the sextuple coefficient rises from 35 to 60 units; and without spacer and holes, it rises further to 75 units. The influence of iron saturation on the other multiple coefficients (b_7, b_9 …) is less than 1 unit.

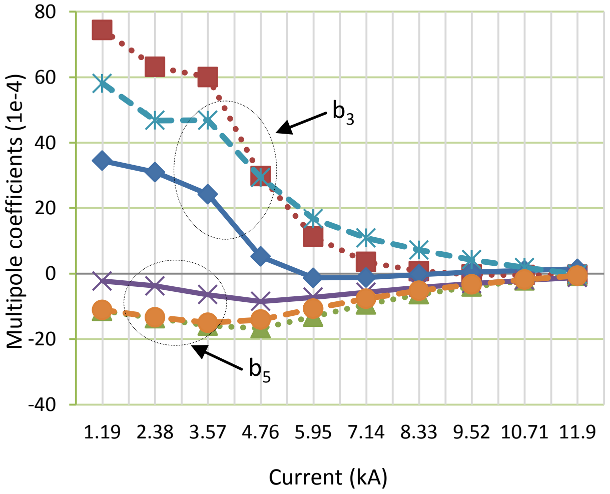

Fig. 5: The effect of iron saturation on field quality in the aperture. Solid line: with spacer and holes in the iron yoke; dashed line: no spacer between the coil and iron yoke; dotted line: remove holes from the iron yoke and no spacer.

C. Filament magnetization

Persistent magnetization currents in the superconductor are the source of severe field distortions at low excitation of superconducting accelerator magnets. It is proportional to the filament diameter and the critical current density of the superconductor [7].

The persistent magnetization currents generate all multipoles which are allowed by coil symmetry, and the multipole fields have opposite signs for increasing and decreasing main field. Fig. 6 shows the dependence of sextuple coefficient on the operating current for the current design, with the filament diameter of 50 µm and 20 µm. The contribution from the effect of iron saturation is also included. In both cases, the variation of b_3 from the injection to the nominal current is around 30 units. The influence of persistent currents on the other multiple coefficients (b_5, b_7 …) is less than 1 unit. Simulations are needed to check if these large multipoles are tolerable at injection or if a corrective strategy should be envisaged.

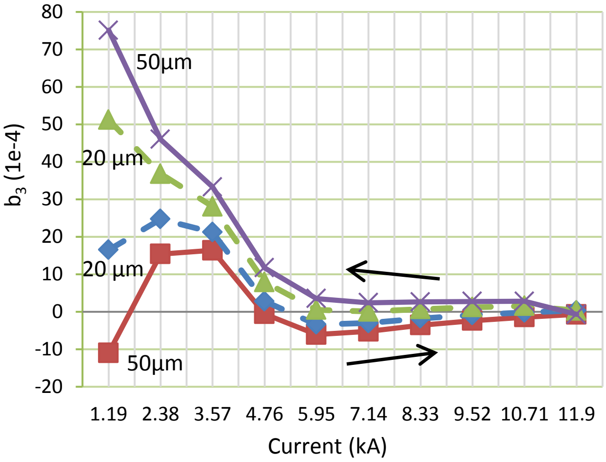

Fig. 6: The effect of magnetization on b_3. The ramp direction of the current is indicated by arrows. Solid line: $b_{coil} + b_{iron} + b_{magn}$ with the filament diameter of 50 µm. Dashed line: $b_{coil} + b_{iron} + b_{magn}$ with the filament diameter of 20 µm.

D. Stray field of the magnet

Although the new D1 magnet has a large aperture, the current design assumes a limited diameter of the iron yoke to be 550 mm. The stray field measured at the outer surface of the magnet is 0.2 T for aperture radius of 60 mm and 0.5 T for aperture radius of 90 mm. A simple method to reduce the stray field is to increase the thickness of the iron yoke. Fig. 7 shows the variation of the stray field with different sizes of iron yoke. If we want to reduce the stray field to less than 0.05 T at the outer surface of the magnet, the required diameter of the iron yoke is 1 m for aperture radius of 90 mm and 0.7 m for aperture radius of 60 mm.

Including the influence of the iron vacuum chamber, Fig. 8 shows the stray field distribution of the magnet in the cryostat, with the aperture radius of 90 mm and the yoke diameter of 550 mm. The level of the stray field inside the cryostat is 0.2 - 0.5 T. If the magnet is not centered in the cryostat, this relatively strong stray field will generate certain magnetic force between the magnet and the cryostat, and distort the precise field in the aperture. At the outer surface of the cryostat, the stray field is still higher than 0.2 T.

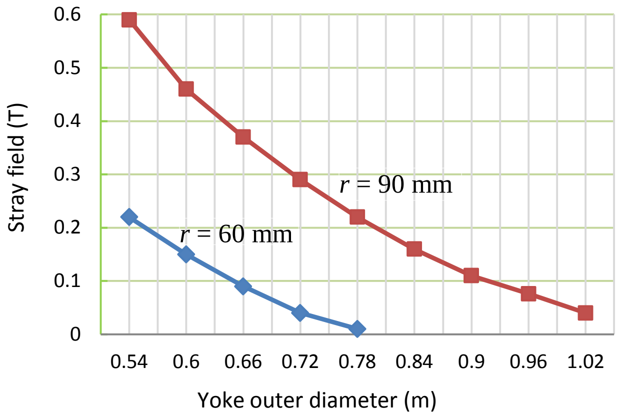

Fig. 7: Stray field of the D1 magnet with different sizes of the iron yoke for aperture radius of 90 mm and 60 mm. Measuring point: 50 mm from the outer surface of the iron yoke

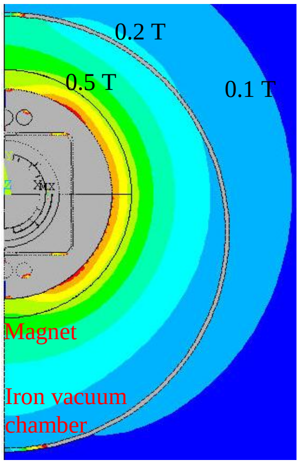

Fig. 8: Stray field distribution of the magnet in the cryostat with the aperture radius of 90 mm and the yoke diameter of 550 mm.

IV. Mechanical Support Structure of the Magnet

The shell-based structure is adopted for the new D1 magnet, to reduce the required pre-stress in the coil during the room temperature assembly. There is an aluminum-bronze spacer between the iron yoke and coil pack. Both the spacer and the iron yoke are divided in vertical direction, to focus the force transferred from the aluminum shell to the coil packs. The positions of stainless-steel keys and the thickness of pads (inner parts of the iron yoke) are carefully optimized to prevent generating any bending force in the coil.

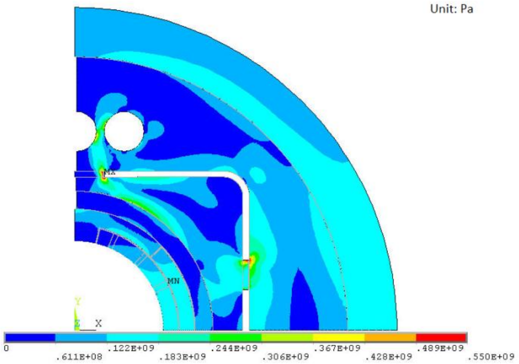

Fig. 9: Stress distribution of the magnet after excitation (r = 90 mm).

With the aperture radius of 90 mm, the sum of the Lorenz force is 3.4 MN/m in horizontal direction and 1.8 MN/m in vertical direction. The maximum stress in the coil during the room temperature assembly is below 90 MPa (the corresponding bladder operation pressure is below 50 MPa); after cool-down to 1.9 K it rises to over 170 MPa; and after excitation it is around 170 MPa, as shown in Fig. 9. For the aperture radius of 60 mm, the corresponding maximum stress is around 140 MPa. These values are well below the tolerable limit of 200 MPa.

V. SUMMARY

The conceptual design of the new D1 magnet for HL-LHC upgrade is ongoing. The aperture diameter of this magnet is 120-180 mm. Assuming a 30-mm-width coil, an operational temperature of 1.9 K, and a 33% margin on the loadline, the central magnetic field is around 8 T. The magnet length is 5 m to reach the integrated field of 40 T m.

With a limited yoke diameter of 550 mm, a stray field of over 0.5 T is generated at the outer surface of the magnet for the aperture diameter of 180 mm. This is a relevant issue since we cannot increase the iron yoke size due to space constraints in the tunnel. Filament magnetization gives relevant sextupole components (several tens of units) at injection and simulations should prove if this is acceptable for the beam dynamics.

Instead of the traditional collar structure, the shell-based mechanical structure is adopted for the new D1 magnet, due to the large aperture and the corresponding large Lorenz force in the coil. The maximum stress in the coil after excitation is 170 MPa for the aperture diameter of 180 mm, or 140 MPa for the aperture diameter of 120 mm.

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