HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Milestone Report

CONCEPTUAL DESIGN OF NB3AL AND NB-TI SEPARATION DIPOLES

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HILUMI LHC

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MILESTONE REPORT

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Abstract:

In this document we report the latest conceptual design of beam separation dipole magnets, D1, for the IR magnet system at IP1 and IP5 for the HL-LHC upgrade. The main design requirements of D1 are an aperture of 150 mm and a field integral of 35 Tm. Some design options at different operating points have been studied. Preliminary summary is that the design option at the operating point of 75 % would be the baseline for the new D1.

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Executive summary

The conceptual design study of the new D1 with the aperture of 150 mm for the HL-LHC upgrade has been pursued. The study is still ongoing, but preliminary summary is that the design option at the operating point of 75 % would be the baseline for the new D1.

1. INTRODUCTION

For HL-LHC machine, current normal conducting dipole magnets for beam separation (D1) in the low beta insertion regions at IP1 and IP5 will need to be replaced by new superconducting ones which should have a larger beam aperture and a higher field integral. KEK has been in charge of conducting conceptual design study of the new D1 superconducting magnet. As described in the previous report [1], the coil bore diameter was set to be 160 mm, which was 10 mm larger than one for inner triplet quadrupole magnet with Nb_3Sn technology. This additional space was reserved for putting extra shielding for the radiation and the heat deposition in the new D1 coil with NbTi conductors having lower critical temperature. Furthermore, the operating point along the load line was set to be the modest value of 70 %.

However, latest radiation simulation results for HL-LHC machine revealed that the new D1 should be operated under more relaxed conditions thanks to thick tungsten shielding in the beam pipe: a radiation dose of a few tens MGy, relevant for the lifetime and a heat deposition around 1 mW/cm^3 [2], relevant for local cooling conditions. After these results, the coil bore was finally reduced down to150 mm in May 2013, the same value as the inner triplet quadrupoles.

In this report, we summarize the latest conceptual design of the new D1 magnet with the 150 mm coil bore. The detailed report can be found in [3].

2. DESIGN CONCEPT OF THE NEW D1

Main requirements for the new D1 are the field integral of 35 Tm and the large coil bore of 150 mm. Nominal dipole field can be 5-6 T, but the whole magnet length should be 7 m or shorter in order to perform the cold test in a superfluid helium bath at the KEK's vertical test stand in the production phase. Operational fields beyond 7 T are not considered, since they bring additional design challenges not worth for gaining 1 m space in a non-critical region. Moreover, control of iron saturation effects on the field quality and suppression of the stray field outside the cryostat would become critical issues.

The design guideline of the new D1 can be listed as follows;

- Use of leftover of the LHC Nb-Ti superconducting cable for the MB outer layer with the same polyimide insulation scheme,
- Operational temperature of 1.9 K by superfluid helium cooling,
- A single layer coil for better cooling capability,
- Enhancement of the amount of iron yoke in the cross section accomplished by "a collared yoke structure" like RHIC magnets and LHC MQXA quadrupoles [4],
- A yoke outer diameter of 550 mm, same as J-PARC SCFM [5], enabling reuse of the assembly jigs and relevant facilities at KEK,
- Use of radiation resistant materials for the coil parts: wedges, end spacers.

3. MAGNETIC DESIGN

3.1. OPTIMIZATION OF 2D CROSS SECTION

Two design options (Option A and B) with the same LHC outer cable but different load line ratios have been studied for the new D1 with 150 mm coil bore. The main design parameters are listed in Table I. The nominal dipole fields for the design Option A and B are 5.22 T at 11 kA and 5.97 T at 13.0 kA, respectively.

Table I: Design parameters of the D1 beam separation dipole magnet for the HL-LHC

Parameters	Option A	Option B
Field integral	35 Tm	35 Tm
Coil bore diameter	150 mm	
Cable type	Nb-Ti LHC MB outer cable	
Number of turns in quadrant	44 (4+8+13+19)	
Nominal field (dipole)	5.22 T	5.97 T
Nominal current at collision	11.0 kA	13.0 kA
Injection current	~ 0.7 kA	~ 0.84 kA
Magnetic length	6.7 m	5.9 m
Field homogeneity at R_{ref} of 50 mm	< 0.01 %	
Peak field in 2D coil	6.0 T	6.9 T
Load line margin in 2D coil	31%	20%
Inductance (injection / collision field)	5.7 / 5.2 mH/m	5.7 / 5.1 mH/m
Stored energy	294 kJ/m	391 kJ/m
Lorenz force X/Y (1st quadrant)	1.3/0.5 MN/m	1.7/0.7 MN/m
Outer dia. of iron yoke	550 mm	
Inner dia. of iron yoke	222 mm	
Strand diameter	0.825 mm	
Cu/Non-Cu ratio	1.95	
Cable dimension /insulation	$15.1 * 1.48\ mm^2$ / 0.160 mm (radial) & 0.145 (azimuthal)	
No. of strands	36	
Keystone angle	0.9 °	
Superconductor J_c	1710 A/mm^2	1954 A/mm^2
Cable length per coil	~620 m	~550 m

Due to the large aperture and the limited outer diameter of the iron yoke, the iron saturation significantly influences the transfer function and the field quality. In the design optimization of the 2D cross section, the coil position and the shape of the iron yoke excluding the outer interfaces are carefully adjusted so that allowed higher order multipole components b_3 to b_{13} can be suppressed within an acceptable range along the energization and that the best field quality can be eventually achieved at the nominal current. Figure 1 shows the cross sections of the Option A and B in Table I. The two iron yoke cross sections are slightly different, because they have been optimized at different nominal currents: 11.0 kA with the 70% load line ratio for Option A, and 13.0 kA with the 80% load line ratio for Option B. Both iron yokes have two small notches, two 50-mm-diameter heat exchanger holes and the other eight small holes to balance the iron saturation effect. Both cross sections keep total void area of 150 cm^2 at least that may be necessary for the longitudinal conduction cooling by the external heat exchanger as an alternative option. Figure 2 shows the b_3 variation from the beam injection to the nominal current for the Option A and B. Figure 3 similarly shows the other higher order multipole variations for the Option A and B. One can see that the multipole component variations are successfully controlled along the energization by the 2D cross section optimization. The maximum stray fields at the nominal currents at the outer surface of the iron cryostat are 35 mT and 60 mT for the Option A and B, respectively.

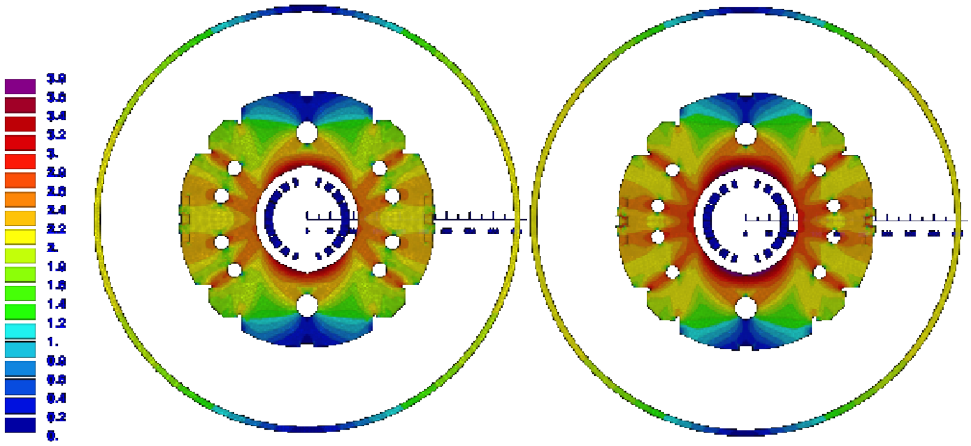

Fig. 1 Cross sections of the new D1 for the Option A (left) and B (right). Field distributions in the iron yokes and cryostats are displayed.

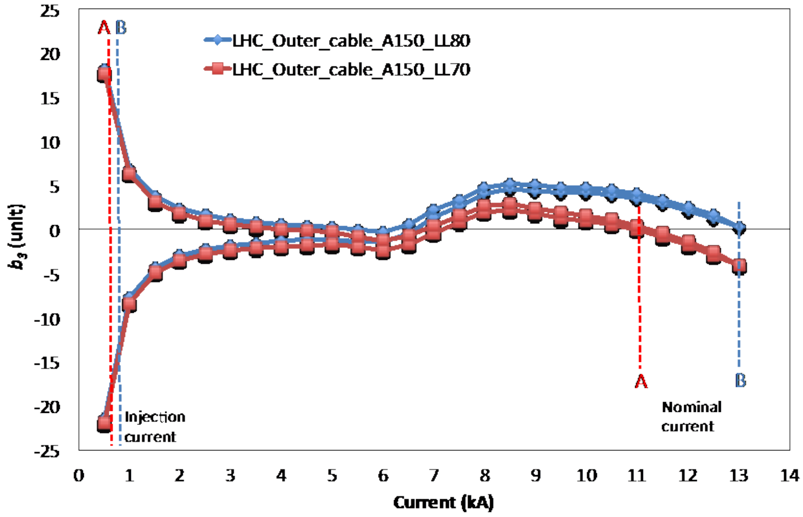

Fig. 2 Variations of b_3 for the Option A and B as a function of current.

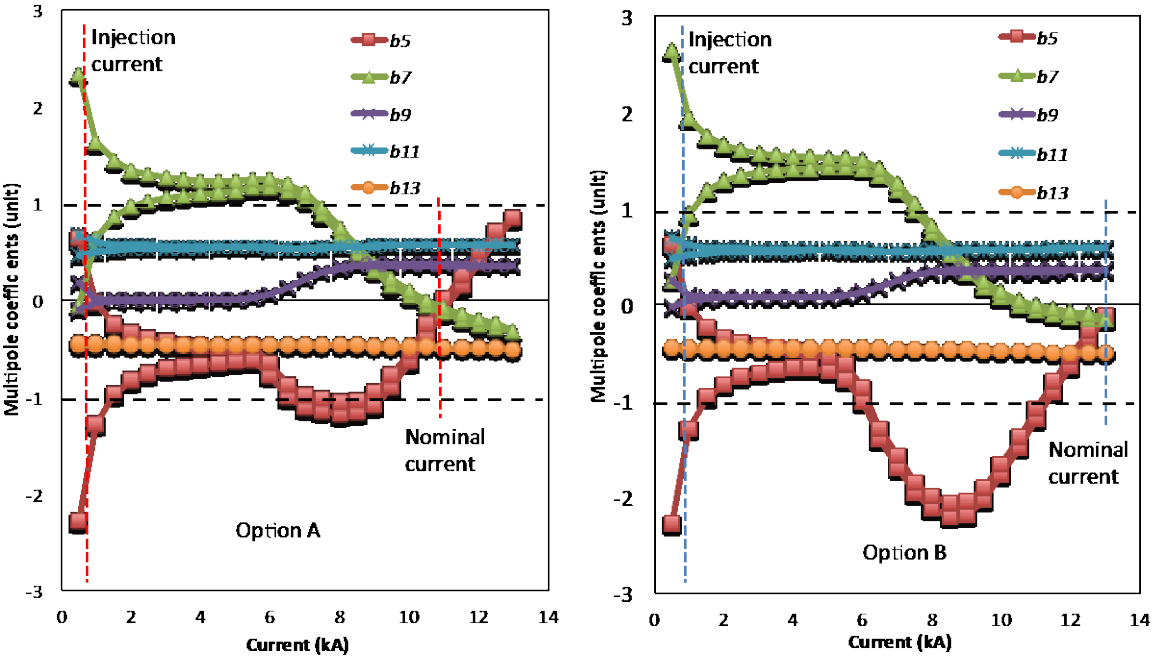

Fig. 3 Variations of allowed higher order multipole components (b_5 to b_{13}) for Option A (left) and B (right) as a function of current.

3.2. COIL END DESIGN

The design and optimization of the coil ends for the new D1 have been carried out by using ROXIE. A full 3D model of the new 6.7 m long magnet with the Option A cross section is built for the ROXIE calculation and is displayed in Fig. 4. The model includes the whole top and bottom coils, the iron yoke and the cryostat. The coil ends are optimized at the nominal current. The following design objectives have been considered in the optimization process;

- Minimizing field integrals of the higher order multipoles along the magnet length,
- Reducing peak field in the coil end,

- Acceptable size of end spacers and reasonable subdivision of coil end blocks while keeping coil ends to be compact.

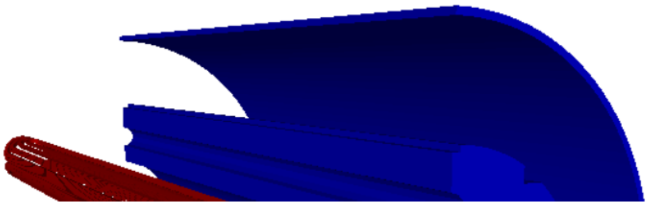

Fig. 4 A full 3D model of the new D1 for ROXIE calculation.

Field integrals of multipole component for the 6.7 m long magnet with the optimized coil ends are listed in Table II. The skew component can be seen in the lead end because the two identical coil windings will be used as the top and bottom coils and the coil cross section in the lead end is no longer dipole symmetry. It should be noted that the coil ends strongly influence the field quality in the straight section even in the 6.7 m long magnet. For example, b_3 at the center of the straight section of the 6.7 m long coil is about 4 unit though the one in the 2D model is tuned to be almost zero. Nevertheless, all allowed multipole components are still below 3 unit for the whole length, and further minor tuning will be possible: the multipole components in the 2D model can be initially adjusted to certain values so that the field integral along the whole length together with the coil ends can be compensated eventually.

The mechanical magnet length for the full-scale D1 magnet for Option A can be estimated by using the results listed in Table II. The straight section of the 6.7 m long magnet, where the nominal dipole field of 5.2 T is generated, should be elongated by 0.208 m. This extension will provide another 1.08 Tm, and the total field integral can reach 35 Tm. The total magnet length, but without longitudinal support structure and the lead splice box, is about 6.9 m. The whole magnet length will be finally at least 7.3 m and this would be unacceptable for the vertical cold test at KEK. This means that the nominal field should be increased in order to reduce the magnet length.

Table II: Field integrals of multipole components for the 6.7 m long D1 magnet with the cross section for Option A (Unit: Tm)

Field Integral	Return End (-3500 mm < z < -1500 mm)	Straight Section (-1500 mm < z < 1500 mm)	Lead End (1500 mm < z < 3500 mm)	Total
B1	9.1802	15.5631	9.1814	33.9247
B3	-0.0004	0.0059	0.0003	0.0058

B5	-0.0058	-0.0002	-0.0042	-0.0103
B7	-0.0017	-0.0004	-0.0014	-0.0034
A1	0.0000	0.0001	-0.005	-0.005
A3	0.0000	0.0000	0.002	0.002

Figure 5 shows the peak field of each coil block in the return end for Option A. Without subdividing the coil blocks, the peak field in the return end is 6.4 T and is located in the coil block 3. By subdividing the coil block 3 into two smaller end blocks, the peak field can be reduced to less than 6.2 T and the location is shifted to the coil block 4. Further reduction of the peak field can be made by additional subdivision or replacement of the iron yoke at the ends by non-magnetic steel.

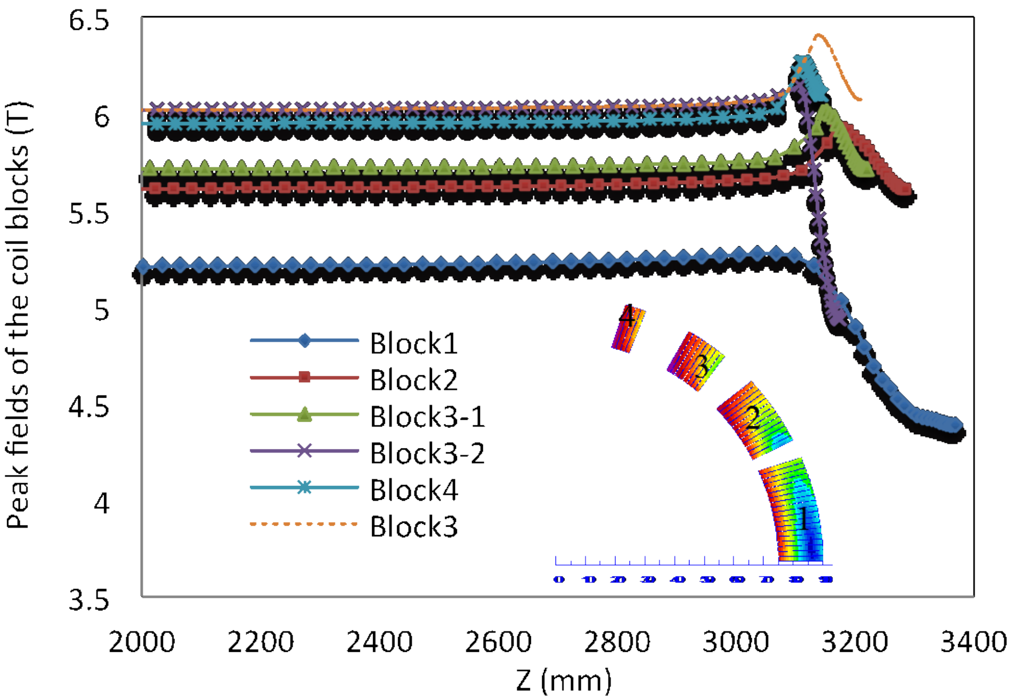

Fig. 5 Peak field of each coil block in the return end for Option A

4. MECHANICAL DESIGN

The concept of “a collared yoke structure” [4] has been adopted for the new D1. A pair of top and bottom yokes is locked by horizontal keys and the appropriate preload on the coil is provided. Of course, the iron yoke serves as the flux return and the mechanical support for the electromagnetic force. The yoke inner interface has important functions to form and align the coils and the non-magnetic spacer collars: influencing the field quality.

A 2D ANSYS FEM simulation model has been developed to analyze the stress status of the coil and the other components at each assembly step, after cool-down and during operation [6]. The mechanical analysis has been made aiming at the design target of 110 % nominal current. The stress distributions at the magnet assembly, where the local stress around the key slot of the yoke is maximum, for Option A (operating point of 70 % in 2D coil) and B (80 %) in Table I, are shown Fig. 6. During the yoking process at room temperature, the required forces (for one quadrant) to close the initial gap between the top and bottom yokes are 2 MN/m for Option A and 2.5 MN/m for Option B (one side, double for full cross section). The local stress around the key slot for Option A after key insertion is 200 MPa or below in the most region. Since yield strength of the low-carbon steel for the iron yoke is specified around 200-250 MPa, the situation for Option A is acceptable. However, the local stress in the same area for Option B exceeds 200 MPa in places and it would be unfavorable.

Figure 7 shows the simulation results of the coil stress for Option A and B at each step. The average stresses in the median plane after excitation are ~85 MPa for Option A and ~100 MPa for Option B while the compressive stresses of 10 MPa at the pole at least still remain for both cases. Nevertheless, the peak stresses in the coils are much higher and located around the inner corner in mid-plane: ~140 MPa for Option A and ~180 MPa for Option B. From the viewpoint of the mechanical endurance of the polyimide insulation of the cable, Option B seems not to be preferable.

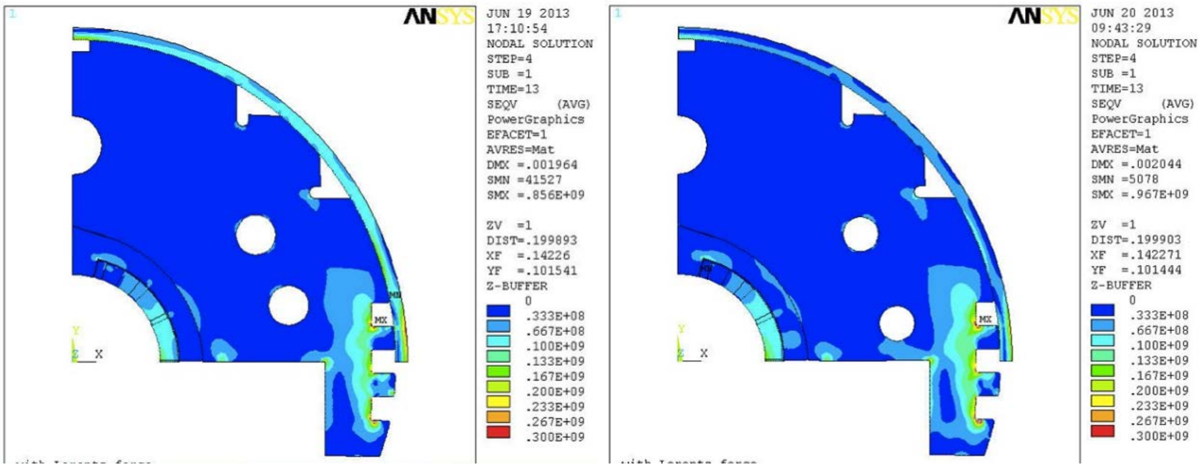

Fig. 6 ANSYS FEM results for stress distributions at magnet assembly for Option A (left) and B (right)

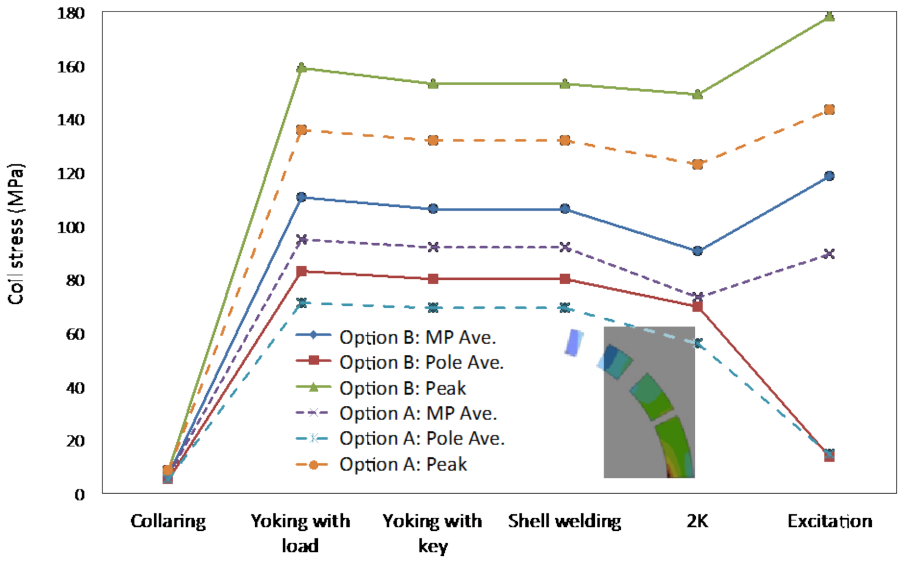

Fig. 7 Coil stress for Option A and B at each step of magnet assembly, cooling-down, and excitation.

5. DISCUSSION AND SUMMARY

Conceptual design study of the new D1 magnet for the HL-LHC machine has been made in accordance with the latest design requirements including the field integral of 35 Tm and the coil bore diameter of 150 mm. Optimizations of the 2D cross sections with respect to the field quality are successful for the two design options (Option A and B) differing the operating points at 70% and 80%, respectively. The coil end design is made for Option A. It is demonstrated that field integrals of higher order multipoles over the length and the coil end peak field can be controlled. But the whole magnet length of 7.3 m for Option A is too large for the vertical cryostat at KEK. In terms of mechanical design, on contrary, Option A is comfortable while Option B seems to have no margin.

Considering these results, it is proposed to carry out another design study of Option C at the different operating point between Option A and B, like 75 % in 2D coil. Table III lists the preliminary design parameters of Option C. The nominal field can be increased to 5.59 T which can shorten the magnetic length by 0.4 m in comparison with Option A and the whole magnet length could be approximated to be 6.9 m. The same iron cross section of Option A adopted for Option C, as shown in Fig. 8. Similar behaviors on variations of allowed multipole components have been observed. Stray fields on the surface of the cryostat are shown in Fig. 9.

The design study on Option C is still underway and the detail will be reported in the next milestone report. However, preliminary summary is that Option C at the operating point of 75 % would be the design baseline for the new D1.

Table I: Main design parameters of Option C for the new D1

Parameters	Option C

Field integral	35 Tm
Coil bore diameter	150 mm
Cable type	NbTi LHC MB outer cable
Number of turns in quadrant	44 (4+8+13+19)
Nominal field (dipole)	5.59 T
Nominal current at collision	12 kA
Injection current	~ 0.77 kA
Magnetic length	6.3 m
Peak field in 2D coil	6.5 T
Load line margin in 2D coil	25 %
Inductance (low/nominal field)	5.7 / 5.1 mH/m
Stored energy	340 kJ/m
Lorenz force X/Y (1st quadrant)	1.5/0.6 MN/m
Cable length per coil	~590 m

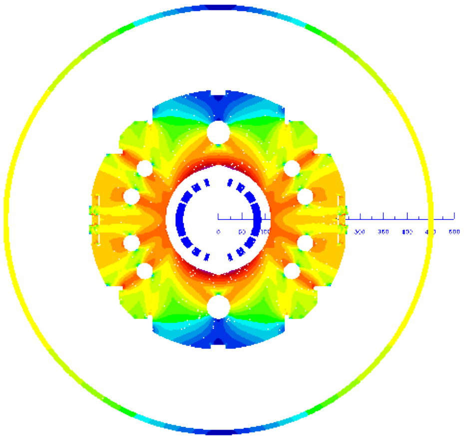

Fig. 8 Cross section of the new D1 for Option C

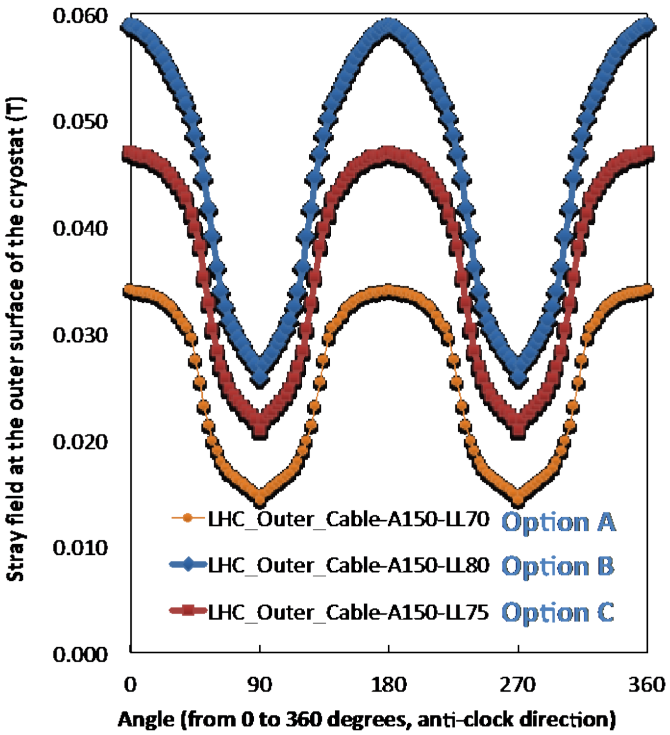

Fig. 8 Stray fields outside the cryostat for Options A, B and C.

6. REFERENCES

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ANNEX: GLOSSARY

Acronym	**Definition**
LHC	Large Hadron Collider
HL-LHC	High Luminosity LHC
IR	Interaction Regions
LARP	LHC Accelerator Research Program
BINP	Budker Institute of Nuclear Physics
LS1	Long Shutdown I taking place in 2013 and 2014
LS2	Long Shutdown II taking place from 1.5 year when the machine will receive an integrated luminosity of 150 fb^{-1}
LS3	Long Shutdown III taking place for 2 years when the machine will receive an integrated luminosity of 350 fb^{-1} . during this shut down the largest number of equipment for the HL-LHC will be installed
R3	Right of point 3
L3	Left of point 3
R7	Right of point 7
L7	Left of point 7