Preliminary electromagnetic design and cost estimate of C-shape dipole magnet required for DIRAC experiment

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1. INTRODUCTION

The C-shape dipole magnet required for the DIRAC experiment. The magnet core made of low carbon steel. The coil is wound from solid copper wire and is air cooled by natural convection. This report describes the preliminary electromagnetic design and cost estimate of the magnet.

2. REQUIREMENTS AND CONSTRAINTS

The magnet parameters, such as aperture, integrated magnetic field and required field quality are determined by the beam optics considerations. The full magnet aperture should be 60 mm. The magnet should provide the integrated field strength of 0.01 T×m, defined as an integral of vertical field component B_y at transverse position X=Y=0, along longitudinal z-axis in the range from -50 mm to 50 mm, where the magnet centre is taken as z=0 mm. The integrated field homogeneity $\Delta\int B_y dz/\int B_y(0,0,z)dz$ has to be better than ± 2% inside the Good Field Region (GFR) of 20 mm x 30 mm. Table 1 summarizes the magnet requirements.

Table 1: Requirements for the C-shape dipole

Parameter	Units	
Overall length	mm	not specified
Overall width × height	mm × mm	not specified
Yoke length	mm	< 60
Vertical full aperture	mm	60
Distance between the coil and pole edges	mm	> 180
Integrated field strength $\int B_y dz$ along z-axis from -50 mm to +50 mm	T×m	0.01
Good Field Region(GFR) Hor. × Vert.	mm × mm	20 × 30
Integrated field quality $\Delta\int B_y dz/\int B_y(0,0,z)dz$ inside GFR	%	< ± 2
Operation mode		DC
Coil cooling		Air, natural convection

3. MAGNET DESIGN

3.1 MAGNET PARAMETERS

The proposed design is an electromagnetic C-shape dipole with a mechanical aperture of 60 mm. The required integrated field of 0.01 T×m is provided by 144 turns with the current of 43 A. A preliminary mechanical layout is shown in Figure 2. The overall dimensions of the magnet are 453.6 mm (width) x 320 mm (height) x 150.2 mm (length). The total magnet mass is 64 kg. The support is not included in the above mentioned dimensions. The main magnet parameters are summarized in the Annex (Table 3). The preliminary mechanical layout of the magnet is shown in Figure 1.

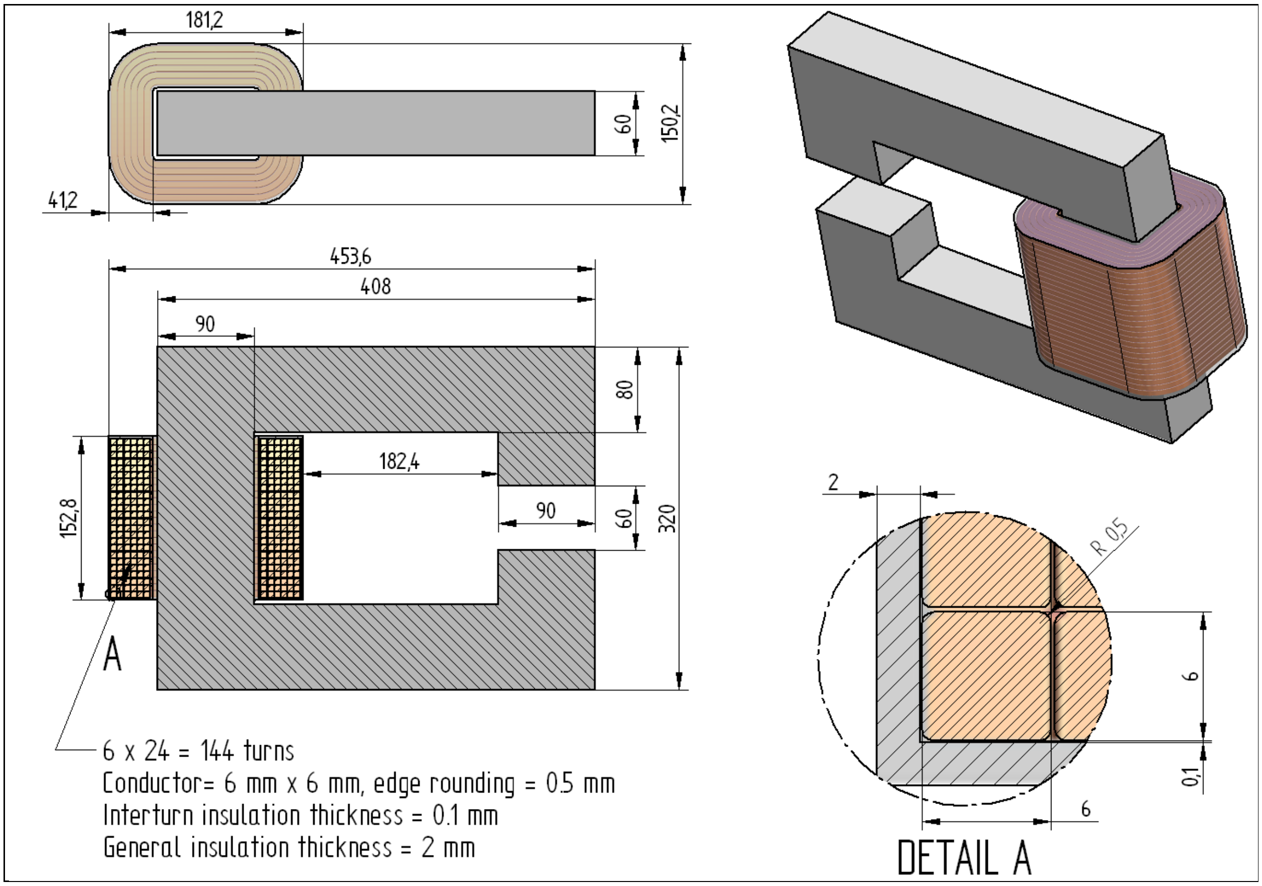

Figure 1: Magnet preliminary layout

3.2 MAGNET YOKE LAYOUT

The magnet circuit consists of 3 pieces made of low carbon solid steel blocks which permit installation of the coil around the yoke. The overall dimensions of the magnet yoke are 408 mm (width) × 320 mm (height) × 60 mm (length) and the yoke mass is 42 kg. The recommended steel type is AISI 1010. The B(H) curve of the proposed steel is given in the Annex (Figure 6 and Table 4).

3.3 COIL DESIGN

The coil consists of 144 turns (6 layers of 24 turns). The coil will be wound from one continuous piece of square enamelled solid copper wire with a cross-section of 6 mm x 6 mm. The conductor wire shall be made from copper of high conductivity (type OF). The wire shall be insulated with a temperature resistant coating like Thermex®, Duroflex® (both trade names of vonRoll/ISOLA) or an equivalent product of at least 0.05 mm thickness. The coil shall be impregnated with radiation resistant epoxy resin to withstand a total integrated radiation dose of 5×10^{7} Gy. For the parameter calculations, a resistivity of 1.72 μΩ·cm at 20ºC is assumed. The calculated resistance at room temperature is 34 mΩ.

4. MAGNETIC FIELD CALCULATIONS

Since the magnets are short and have a large aperture, the fringe field in the direction of the beam axis (z-axis) is significant. In this case, the 2D field calculations give only the preliminary results and need to be verified by the 3D modelling. Thus, 3D model the magnet was constructed and used for analysis of the integrated field characteristics. The B(H) curve of the proposed material, mentioned above, was used for the simulations.

4.1 3D CALCULATIONS

The calculation was done by Opera-3D/TOSCA program. Due to symmetry only 1/4 of the magnet geometry was modeled. The boundary conditions were chosen in a way that the flux lines were perpendicular to the horizontal middle plane and parallel to the symmetry axis and the limiting edge of the model. The coils are modeled as square region with a total applied current density equal to the ampere-turns of the coil divided by the total cross section of the coil.

Figure 2 gives an excitation curve of the magnet. It shows that the required integrated field strength of 0.01 T × m can be achieved at excitation current of 43 A, that corresponds to a central field $B_y(0,0,0)$ of 0.117 T. In order to avoid the saturation effects, the iron yoke cross-section was optimized such that the magnetic flux density in the magnet core is less than 1.5 T for the nominal current of 43 A. Figure 3 shows the OPERA-3D model with the field distribution on the surface of magnet at 43 A of excitation current. The vertical field distributions along the z-axis are shown in Figure 4. The integrated vertical field error stays below ± 1% inside the GFR defined above as a rectangular region with X= ± 10 mm and Y= ± 15 mm, see Figure 5. Further field quality improvements are possible by introducing pole shims and suitable chamfers of the pole ends.

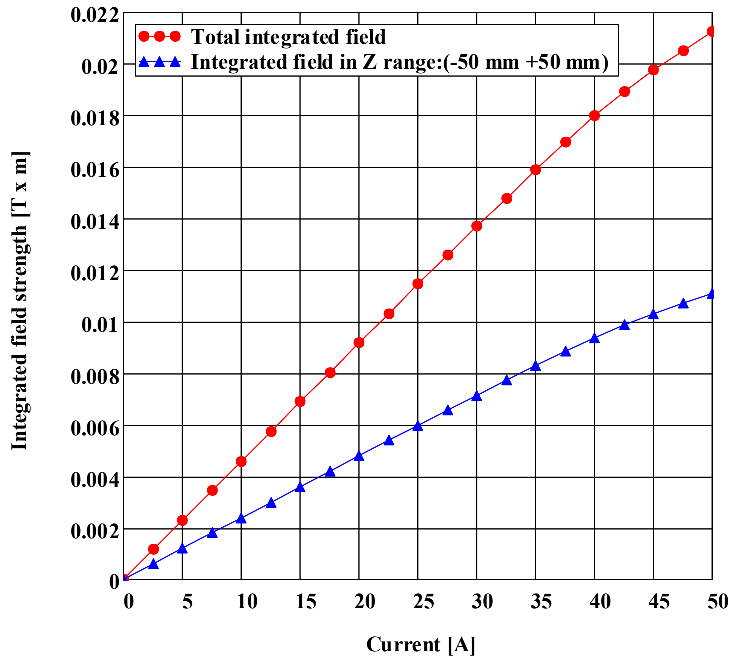

Figure 2: Excitation curve of the magnet.

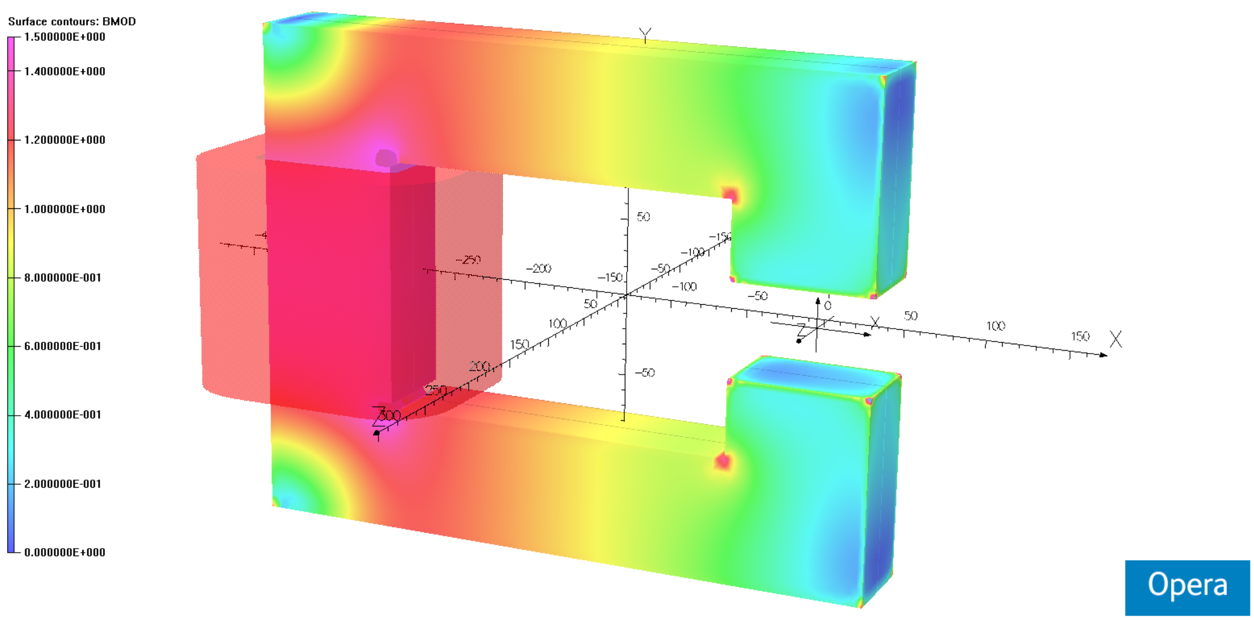

Figure 3: Field distribution on the iron yoke surface at 43 A

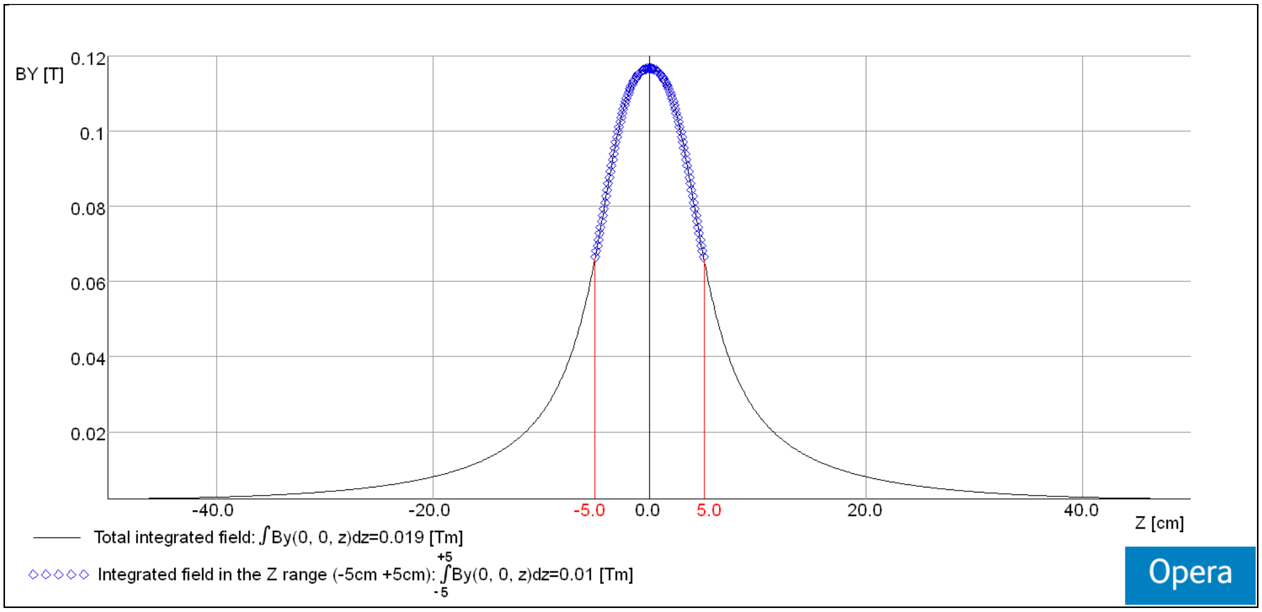

Figure 4: Vertical field distribution along Z axis at 43 A

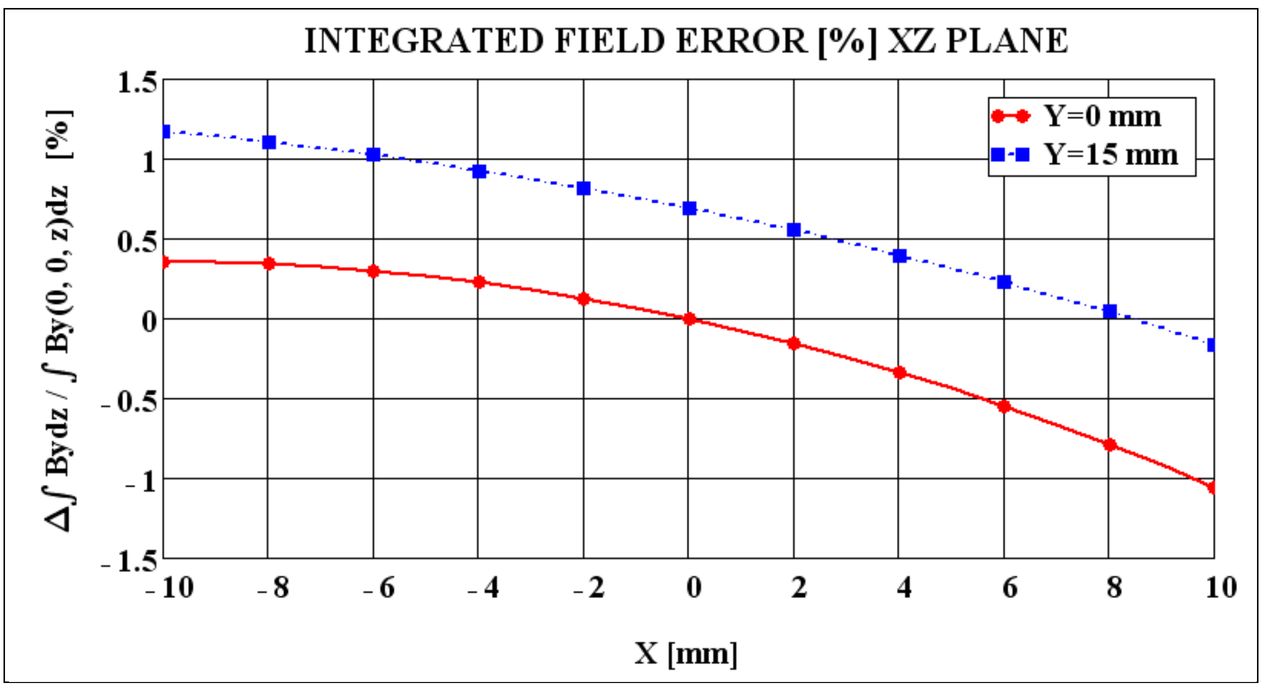

Figure 5: Integrated field error [%] at 43 A

5. COST ESTIMATE

Magnet parameters such as yoke, used steel and coil mass, served as an input for the cost estimate. This amount includes the raw materials and components, tooling, manufacturing and assembling. Running costs and cost for power converter are not included. The estimated costs are based on analytical formulas and experience from magnet projects in the recent past. The results of the cost estimate are shown in the Table 2.

Table 2: Magnet cost estimate

Magnet type	**Dipole, C-shape**
Number of magnets	1
TOOLING	
Total Tooling COSTS(winding/molding tools) [kCHF]	5
YOKE	
Yoke mass/magnet [kg]	42
Used steel/magnet [kg]	62
TOTAL Yoke costs (Material+Manufacturing) [kCHF]	4.5
COIL	
Coil mass/magnet [kg]	21
Total Coil costs (Material+Manufacturing) [kCHF]	4.3
Magnet Assembly [kCHF]	1.5
TOTAL	
Total Costs [kCHF]	15.3

6. CONCLUSIONS

Preliminary design of the C-shape electromagnetic dipole required for the DIRAC experiment has been completed and is used to establish a relevant cost estimate. The required integrated field strength of 0.01 T×m and integrated field quality of ± 2% inside good field region appear to be feasible. The cost of this magnet has been estimated at about 15.3 kCHF. In order to reduce costs, magnet overall dimensions and to simplify a mechanical structure, an alternative solution based on permanent magnet can be considered. A drawback of this solution is a demagnetization of the permanent magnet material due to neutron radiation.

7. ANNEX

7.1 MAGNET MAIN PARAMETERS

Table 3: Magnet main parameters

Parameters	UNITS	
Magnet type		Dipole, C-shape
Full aperture (Hor/Vert)	[mm]	90/60
Good field region (Hor/Vert)	[mm]	10/15
Effective length	[mm]	~164
Field strength at Z=0 mm	[T]	0.117
Total integrated field	[T × m]	0.019
Integrated field in the z range of (-50mm ÷ +50mm)	[T × m]	0.010
Total magnet mass	[kg]	64
YOKE		
Yoke length	[mm]	60
Yoke cross section area	[m^2]	0.089
Yoke mass	[kg]	42
COIL		
Conductor type		OF copper, solid, square
Conductor height × width	[mm]×[mm]	6 × 6
Edge rounding radius	[mm]	0.5
Interturn insulation thickness	[mm]	0.1
General insulation thickness	[mm]	2
Conductor mass per 1 m	[kg/m]	0.321
Number of turns per coil		6×24=144
Number of pancakes per coil		1
Average turn length	[m]	0.454
Total conductor length	[m]	0.454×144=65.4
Total conductor mass	[kg]	21
Total coil mass including insulation	[kg]	22
Electrical parameters		
Ampere turns	[A]	6’200
Current	[A]	43
Current density	[A/mm^2]	1.2
Total resistance	[mOhm]	34
Total inductance	[mH]	26.2
Voltage	[V]	1.5
Power	[W]	63
COOLING		
Air, natural convection		

7.2 AISI 1010 MAGNETIC PROPERTIES

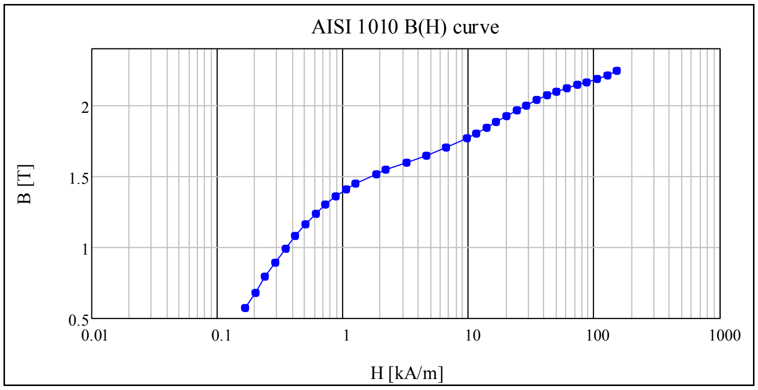

Figure 6: AISI 1010 B(H) curve

Table 4: B(H) data of the proposed steel type AISI 1010

B [T]	H [kA/m]
0	0
0.576	0.166
0.68	0.199
0.792	0.24
0.895	0.289
0.992	0.347
1.082	0.418
1.164	0.502
1.237	0.604
1.302	0.726
1.359	0.872
1.407	1.049
1.449	1.261
1.517	1.823
1.545	2.192
1.595	3.167
1.646	4.579
1.702	6.619
1.768	9.568
1.805	11.499
1.843	13.831
1.883	16.624
1.924	19.99
1.964	24.032
2.002	28.893
2.038	34.736
2.071	41.762
2.1	50.209
2.125	60.375
2.146	72.575
2.165	87.257
2.187	104.907
2.214	126.122
2.246	151.595