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SUPERCONDUCTIVE DIPOLAR ELECTROMAGNETS FOR PARTICLE ACCELERATORS TWO CONSTRUCTIVE MODELS

BY

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Abstract. This paper presents the 2-D numerical analysis conducted on two different configurations of superconductive windings made of high temperature superconductor (HTS) wire, designed to generate an intense dipolar magnetic field (~3T) of high uniformity (~0.1%), the 3-D numerical evaluations of the magnetic field and the pending mechanical stress in the superconductive windings. Numerical simulations reveal advantages and disadvantages of each particular design, which allows the selection of the configuration that best fits the design goals. The geometry of these electromagnets are cylindrical respective planar such that the accelerated particles could pass through the generated magnetic field zone. The superconducting windings will be made with 2nd generation of YBCO tape.

Key words: superconductive winding; dipolar electromagnet; finite element method; high intensity magnetic field; high uniformity magnetic field; numerical simulation.

1. Introduction

This paper presents numerical modeling and simulation results concerning the design phase of a superconductive dipolar electromagnet prototype, which is rated to generate an intense (~3 T) and uniform (~0.1%)

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magnetic field into a cylindrical region, the so-called “warm channel” of the electromagnet, along its whole length, where the flux of accelerated particles is “bent” from the initial direction. This deviation is to occur when the charged particles pass through the intense and uniform magnetic field zone (Takahashi *et al*., 2012). This type of superconductive electromagnet is used in modern particle accelerators of high energy (Dobrin *et al*., 2014; Dobrin *et al*., 2011). The design is concerned with the latest industrial produced superconducting materials: 2nd generation High Temperature Superconductors of YBCO type for the winding, with transition temperature of 92 K.

In sizing the electromagnet, we used also numerical modeling based on the Galerkin finite element method (http://www.comsol.com/) to compute the magnetic field and to simulate the working conditions of the dipolar electromagnet.

This paper presents two different winding designs for electromagnets for dipolar fields, and it highlights the advantages and shortcomings for each of them. Numerical modeling is used to analyze two winding configurations: “Cos θ” type, called in what follows “cosine windings” (Morega *et al*., 2015), and “racetrack” type.

The cosine winding electromagnet needs specially shaped coils to avoid the central zone of the electromagnet, which must remain available to a central channel. The parallel coils winding for the second magnet is a double pancake coil of racetrack shape. Both of them are “coil dominated” electromagnets with iron clad outside the coils that acts as a shield that contributes to the homogeneity of the generated magnetic field.

2. The Dipolar Cos θ Electromagnet

The magnetic field in the bore of the dipolar cosine electromagnet has to comply with the following requests:

a) the value of the magnetic flux density inside the air gap should be 2-3 T;

b) the yoke should be fabricated using minimum amount of iron;

c) the magnetic flux density uniformity in the air gap should be better than ~0.1%.

First we analyzed a cosine windings electromagnet (Fig. 1) using a 2D model. The main parameters are given in Table 1. Biot-Savart-Laplace theorem (Mocanu, 1982; Russenschuck, 2010) yields the following equations for the magnetic field harmonics generated by N conductors placed in four dials:

$$\begin{aligned} B_1 &= -2\frac{\mu_0 J}{\pi} w\sin(\theta_1),\ n=1, \\ B_3 &= 2\frac{\mu_0 J R^2}{3\pi}\left(\frac{1}{r+w}-\frac{1}{r}\right)\sin(3\theta_1),\ n=3, \\ B_5 &= 2\frac{\mu_0 J R^4}{15\pi}\left(\frac{1}{(r+w)^3}-\frac{1}{r^3}\right)\sin(5\theta_1),\ n=5. \end{aligned} \tag{1}$$

TABLE 1
The Main Parameters of the Dipolar cos θ Electromagnet

Parameter	Value
Aperture radius, [mm]	15
Air gap, [mm]	5
Iron yoke thickness, [mm]	30
Wire diameter, [mm]	0.2
Total number of turns	265
Current, [A]	290
Current density, [A/m$^{2]}$	7.25×10^9
θ_0, θ_1, θ_2, θ_3	59, 49, 26, 10

From (1), choosing θ_1 = 60º cancels B_3, and choosing either θ_1 = 36º or θ_1 = 72º cancels B_5.

Since the angles do not coincide, we cannot discard both B_3 and B_5 with one sector only, so we consider the case with two sectors, defined by four angles, θ_0, θ_1, θ_2, and θ_3, Fig. 1. The optimal values for θ angles are (Bruér, 2008):

$$(\theta_3,\theta_2,\theta_1,\theta_0)=(59.4°,49.6°,26.6°,10°). \quad (2)$$

The mathematical model for the stationary magnetic field is made of
Amper's law

$$\mathrm{curl}\,\mathbf{H}=\mathbf{J}, \quad (3)$$

Magnetic flux law

$$\mathrm{div}\,\mathbf{B}=0, \quad (4)$$

Constitutive law **B**(**H**)

$$-\mathrm{div}(\nu\,\mathrm{grad}\,\mathbf{A})=\mathbf{J} \quad (5)$$

$$\boldsymbol{B}=\mu_0\mu_{\boldsymbol{r}}\boldsymbol{H}, \quad (6)$$

where $\nu=\mu^{-1}$ [m/H] is the magnetic reluctance, **H** [A/m] is the magnetic field strength, **J** [A/m^2] is the current density, **B** [T] is magnetic flux density, **A** [T·m] is the magnetic vector potential, μ_0 [H/m] is magnetic permeability of vacuum and μ_r is relative magnetic permeability. The boundary condition that closes the model (3)-(6) is magnetic insulation, $\mathbf{n}\times\mathbf{A}=0$.

The degree of non-uniformity of the magnetic field is

$$f_{om}[\%]=\frac{B_{\max}-B_{\min}}{B_{\max}}\times 100\,. \quad (7)$$

In this case, f_{om} = 0.96%. The total number of turns here is N = 265, distributed as Fig. 2 shows. The spectrum of the magnetic field obtained through numerical simulation is shown in Fig. 3.

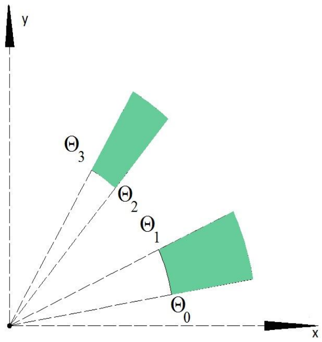

Fig. 1 – Cross-sectional view of a dipolar coil with two sectors.

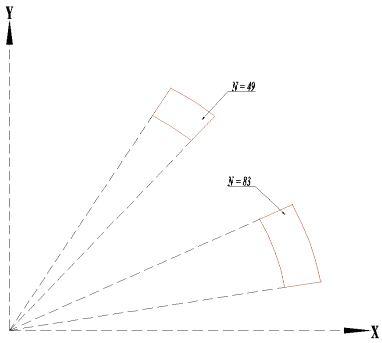

Fig. 2 – The amperturns for the cosine windings configuration.

The dipolar magnetic field inside the central channel of the electromagnet reaches 2.51 T for a current of 290 A.

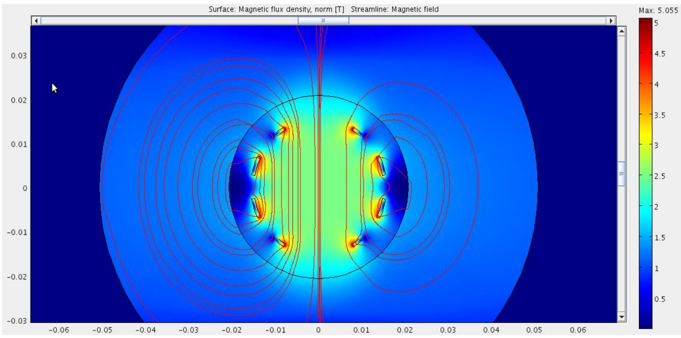

Fig. 3 – Magnetic flux density, surface color map and field lines.

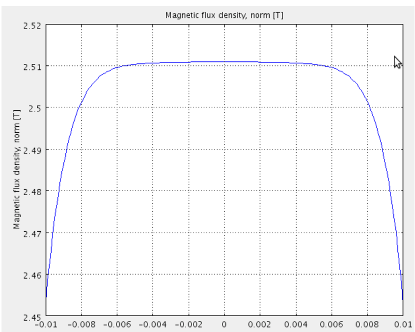

Fig. 4 – Magnetic flux density in the ”good field” region.

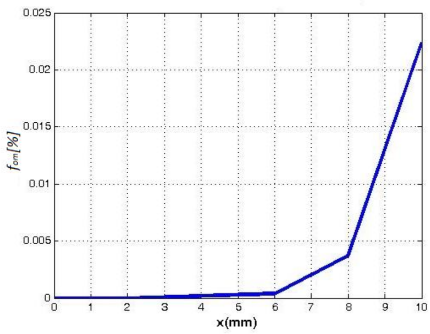

Fig. 5 – The degree of non-uniformity in the “good field” region.

Fig. 4 depicts the magnetic field uniformity in the so-called “good field” (GDF) region only, a cylinder with a value of 2/3 from the aperture (30 mm). The non-uniformity of the magnetic field can be seen in Fig. 5.

3. The Electromagnet with a Parallel Configuration of Racetrack Type Winding

Next, we studied an electromagnet with a parallel configuration of racetrack type winding, in which the physical model is composed of an assembly of two parallel coils with double pancake, with a distance between them of 30 mm. Each coil has an aperture radius of 15 mm. The winding is made of HTS tape, 12 mm wide and 0.22 mm thick with insulation (Fig. 6).

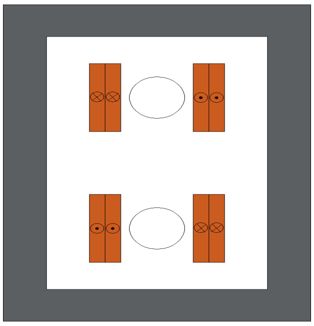

Fig. 6 – The parallel configuration of racetrack type winding.

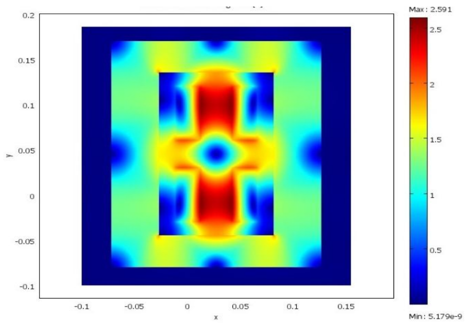

Fig. 7 – Magnetic field (flux density) distribution in the electromagnet.

The magnetic field obtained through numerical simulations is shown in Fig. 7. The maximum magnetic flux density is less than 1.9 T in the yoke, and its maximum value in the “good field” region is 2.59 T.

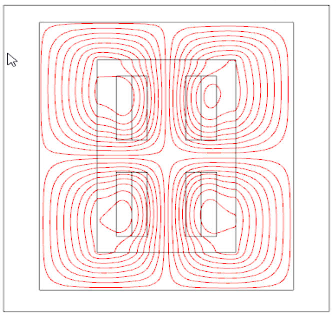

Fig. 8 – Streamline plot for the magnetic field in the electromagnet.

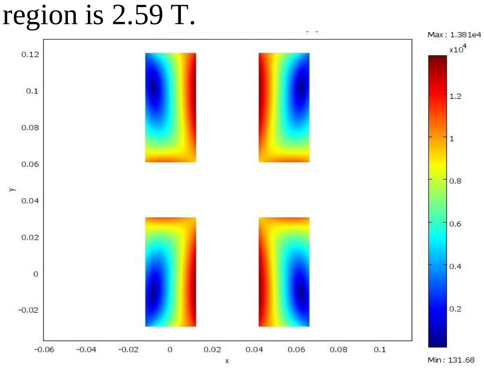

Fig. 9 – Laplace forces distribution in the HTS coils – SI units.

From Fig. 9 we can see that Laplace force is higher in the outer parts of the coils. We may conclude that the coils are subject to rejection forces, which require mechanical compensation means to stabilize the system.

Fig. 10 shows of that f_{om} = 3.3%. The load line of the coil can be seen in

Fig. 11. For a maximum current of 185 A, the magnetic flux density reaches the highest value 2.75 T. The degree of non-uniformity increases with the distances. So, it is advisable to reduce the spacing as much as possible for better uniformity.

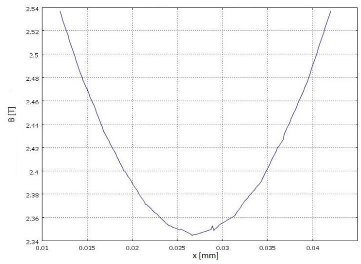

Fig. 10 – Magnetic flux density in the ”good field” region.

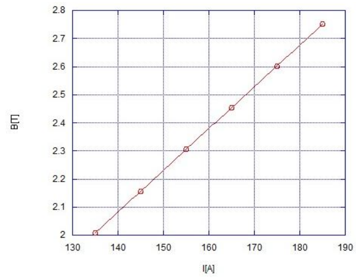

Fig. 11 – Magnetic flux density, maximum value, *vs*. field current.

A parameter relevant for the uniformity of the magnetic flux density is the coil “thickness” of the winding. Apparently, the thicker the winding (more turns) the bigger the uniformity of the produced magnetic field is.

Finally the inner radius of the coil and its influence on the uniformity of the generated field was calculated for a given distance between the coils (30 mm). This study shows the maximum degree of uniformity is obtained for 37 mm. The benchmarking of the magnetic field quality in the two analyzed situations is summarized in Table 2.

TABLE 2
Main Parameters of the Two Constructive Models

Type of electromagnet	B_{max}, [T]	f_{om} %	Number of turns	I, [A]	Aperture radius [mm]
cos θ winding	2.51	0.96	265	290	15
Planar coils winding	2.44	3.30	273	170	15

4. Conclusions

The results obtained for HTS electromagnets with same aperture (30 mm diameter) shows that a cosine winding provides for best field uniformity (0.96%) while requiring lower number of turns (265).

However for cos θ winding there are two main disadvantages: higher current (290 A) is required, and technical difficulties may occur in the process of manufacturing the windings besides the needs for a mechanical system for support due the high Laplace forces. Moreover the parallel coils type winding electromagnet uses more HTS tapes and lower current.

Finally, as the main objective here is a high degree of uniformity of the magnetic flux density, the cosine winding electromagnet is superior.

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ELECTROMAGNEȚI DIPOLARI SUPRACONDUCTORI PENTRU ACCELERATOARE DE PARTICULE
Două modele constructive

(Rezumat)

Sunt prezentate rezultatele analizei numerice 2-D asupra a două configurații diferite de bobinaje supraconductoare HTS proiectate pentru a genera un câmp magnetic intens (~3T) si uniform (~0,1%), precum si evaluări numerice 3-D ale câmpului magnetic generat şi a forțelor mecanice produse in bobinajele supraconductoare.

Simulările numerice au pus în evidență avantajele şi dezavantajele fiecărui tip de bobinaj, ceea ce a permis selectarea configurației care îndeplineşte cel mai bine scopul pentru care au fost proiectate. Geometria acestor electromagneți analizați este cilindrică şi respectiv plană, permițând trecerea particulelor accelerate prin zona de câmp generat, fiind astfel adecvați utilizării într-un accelerator. Bobinajele supraconductoare vor fi realizate din bandă HTS de tip YBCO, de generația a 2-a.