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Design of a Vector Magnet Generating up to 3 T with 3 Axis Orientation

Rafael Linares, Kévin Berger, Melika Hinaje, Bruno Douine and Jean Lévêque

Abstract—The Low Temperature Superconducting (LTS) coils are designed to produce strong magnetic fields at the working temperature of liquid Helium. Some kinds of them have been created to produce strong and homogeneous magnetic fields, as in Magnetic Resonance Imaging (MRI) systems. However, the critical and mechanical parameters of superconducting material limit the performances of the coils. Most of the time, LTS coils are built to produce a homogeneous magnetic flux density in one single direction. Consequently, it is necessary to rotate the subject or the sample, when a study is needed depending on the magnetic field orientation. This is not suitable for special kinds of experiments involving High Temperature Superconducting (HTS) systems or biomedical applications in which the subject must not be rotated. In order to satisfy these requirements, we have designed a new coil setup. The design was made using a 3D electromagnetic software in order to calculate the performances of the coils system, to optimize the magnetic field homogeneity and to find a cost effective solution. The first results reported in this paper concern the design of a magnet of three Helmholtz coils, each of which generates a unidirectional magnetic field (x , y and z). Each Helmholtz coil can generate 1.73 T, so the flux density magnitude in the center of system could reach 3 T. The price of the all system, including the cryostat, is around 45 k€.

Index Terms—Design of LTS coils, Helmholtz coil, superconducting applications, vector magnet.

I. INTRODUCTION

RESEARCH and development in energy management problems is booming. Since superconductivity has the advantage of saving energy with its low electric losses [1], it is desirable to make superconducting applications accessible. Superconductors are mainly used to generate high magnetic fields. Some superconducting magnets are used in material and biomedical research [2]. In these areas, it is sometimes necessary to have a strong magnetic field that can be oriented without the need to modify the sample position.

Thus, a special magnet in which the magnetic flux density can be set with high homogeneity is needed [3]. This magnet is composed by several coils which can individually provide a magnetic flux density in an expected direction. This set of coils can produce two and/or three dimensional magnetic fields and is called a vector magnet.

In previous work [4], the study of various coil geometries was carried out, and the goal was to establish important

relationships to produce homogeneous magnetic fields, e.g. the Merrit coil system which consists of four concentric square coils, that provides a large homogeneous space.

The main objective of our work is to find a geometry being able to combine homogeneity, strong field and low cost. In this article, we propose a design of vector magnet with the capability of producing a strong magnetic field in any direction with high homogeneity. In the designed vector magnet, the strength of the magnetic flux density norm $|\mathbf{B}|$ in the working space will be 3 T. In order to ensure this, the Helmholtz coil must provide the three components (B_x , B_y , B_z) of the magnetic flux density with an individual strength of 1.73 T. Subsequently, we plan to feed the coils of this magnet with fuel cells in order to study the stability of such system [5]. This magnet would probably be the first three axis vector magnet being able to characterize HTS samples with a large working space.

II. MATERIALS AND METHODS

A. Description

We want to characterize High Temperature Superconductor (HTS) samples in a high and directional magnetic field. The desired strength of the magnetic flux density was defined to 3 T, and the working space, where the sample will be placed, is a sphere of 100 mm in diameter. In order to ensure the proper orientation, the magnetic flux density \mathbf{B} must have three components, B_x , B_y and B_z , which can be controlled independently. The access of the sample into the magnet is designed as a tube that passes through the coils and allows two ways to access at the center. Then, various types of coils arrangements were compared for uniformity, cost and ease of construction. Some authors have already reported some interesting results on coils configurations so-called: “Merrit”, “Lee-Whiting” [4], “Helmholtz coil” [6], [7], and “sector coil” [8]. From these studies, we have concluded that the arrangement of coils that best suits to our constraints is the Helmholtz coil. Its construction is less complex and quicker than the others. Moreover, its magnetic field homogeneity and strength are enough for the required tasks.

Helmholtz coil consists of two circular coils of radius R , placed along a common axis, and separated by a distance equal to their radius. It can produce magnetic fields with homogeneity greater than 90 % in the desired working space. This meets the conditions that we have set for the proposed magnet. A Helmholtz coil will be placed along each axis of a Cartesian coordinate system. The whole system will consist of six circular coils, two per axis, shown in Fig. 1.

The value of the radius of each Helmholtz coil is calculated

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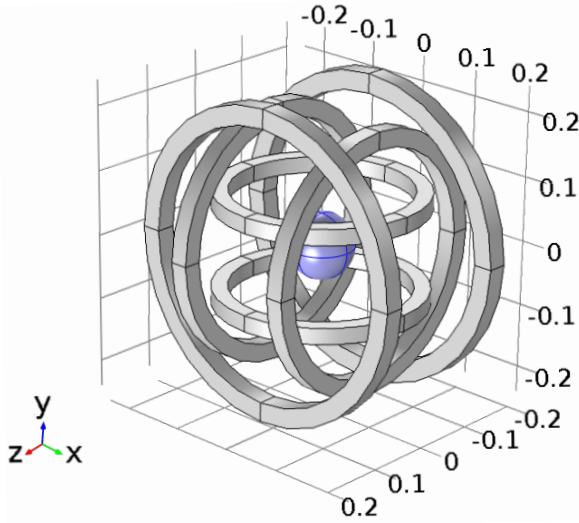


Fig. 1. Proposed vector magnet: system of 3 Helmholtz coils. The sphere located in the center represents the working space.

TABLE I
VECTOR MAGNET PARAMETERS

Name	Description	Units
I_c, B_c	Critical current and magnetic flux density	A, T
I, B	Operating current and magnetic flux density	A, T
$B_{x,y,z}$	Magnetic flux density following each axis of the Helmholtz coil	T
$N_{x,y,z}$	Number of turns of each Helmholtz coil	tr
$R_{x,y,z}$	Helmholtz coil radius for each axis	m
H_0	Homogeneity in the working volume	%
B_{\max}	Maximal magnetic flux density over the coils	T
d_{wire}	Diameter of the superconducting wire	mm
$S_{x,y,z}$	Cross-sectional area of each Helmholtz coil	mm ²
F	Filing factor: ratio of wire volume/cross section	

T = Tesla, A = Ampere, tr = turns, m = meters.

in order to facilitate the assembly of the coils, and also to fulfill the conditions of homogeneity. The radius R_y of the smallest Helmholtz coil, which is placed along the y -axis, is taken as reference. The other radii are then calculated according to R_y , as follow: $R_x = 1.310 R_y$ for the Helmholtz coil following the x -axis and $R_z = 1.644 R_y$ for the z -axis. The Helmholtz coils are serially coupled to each other. The parameters of the vector magnet were shown in Table I.

The cross-section of each coil is square shape. Indeed, this leads to a biggest space of homogeneous magnetic flux density compared to circular shape or rectangular shape. Numerical calculations have shown the influence of the cross section shape of a coil on the homogeneity of \mathbf{B} [8]. Moreover, the cross-sectional area of each coil depends on its number of turns:

$$S_{x,y,z} = N_{x,y,z} (\pi (d_{\text{wire}} / 2))^2 / F, \quad (1)$$

$$\text{with } F = 0.75 \text{ and } N_{x,y,z} = \frac{B_{x,y,z} R_{x,y,z}}{\mu_0 I} \left(\frac{5}{4}\right)^{3/2} \quad (2)$$

The coil system is placed in the air and does not contain iron in its construction. Indeed, the magnetic saturation of the

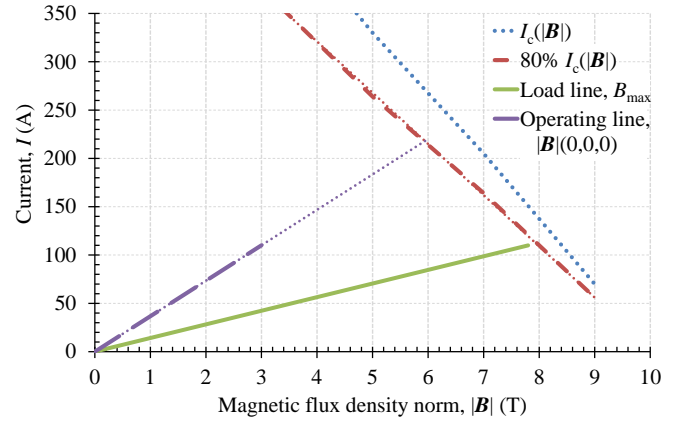


Fig. 2. Characteristic of the NbTi SC56S53 wire of SuperCon Inc. with safety margin of 20 %. Load line, B_{\max} and operating line, $|\mathbf{B}|(0,0,0)$ of the designed magnet for $R = 15$ cm are also shown.

iron can affect the homogeneity of \mathbf{B} in the working space and can produce undesirable induced currents when \mathbf{B} varies. In order to avoid these perturbations, a resistant structure that can hold the vector magnet in an accurate position has to be built: assembly pieces in epoxy resin were chosen. The influence of the thermal contraction of the epoxy resin structure has been neglected at this time. However, it will be evaluated at the final manufacturing stage. Hence it is important to ensure the clamping of the coils as it directly affects the homogeneity. The mechanic constraints are calculated to design the supporting structures.

The formula (3) and (4) represent the homogeneity H_0 calculated with the maximum, minimum and average value of \mathbf{B} inside of the working volume.

$$H_0 = \left(1 - \frac{\max(|\mathbf{B}|) - \min(|\mathbf{B}|)}{\langle |\mathbf{B}| \rangle} \right) \times 100 [\%] \quad (3)$$

The homogeneity can be also calculated for each component in order to assure its quality using

$$H_0^{x,y,z} = \left(1 - \frac{\max(|B_{x,y,z}|) - \min(|B_{x,y,z}|)}{\langle |B_{x,y,z}| \rangle} \right) \times 100 [\%] \quad (4)$$

The superconducting NbTi wire SC56S53 of Supercon Inc. [9] was chosen for its high proportion of superconducting (SC) material (Cu:SC, 0.9:1). The diameter d_{wire} of the wire is 0.54 mm. With 56 NbTi filaments, this wire can carry a high current density. Conversely, its thermal stability is less than that of wire with higher ratios, as the MR16 wire (Cu:SC, 11:1) dedicated for MRI imaging magnets requiring more stability. Moreover, to prevent the superconductors from transiting to the normal state, the magnet must have a load characteristic that does not exceed the characteristic of the wire. In other words, the current that flows in the magnet must never be higher than the critical current I_c of the SC wire. Thus, for a maximal value of the magnetic flux density B_{\max} over the wire, there is a maximal value of current I to be used. In order to avoid an accidental and devastating transition of the magnet, which can be very fast when using LTS wires, a 20 % margin from the $I_c(|\mathbf{B}|)$ curve is proposed as a criterion in Fig. 2.

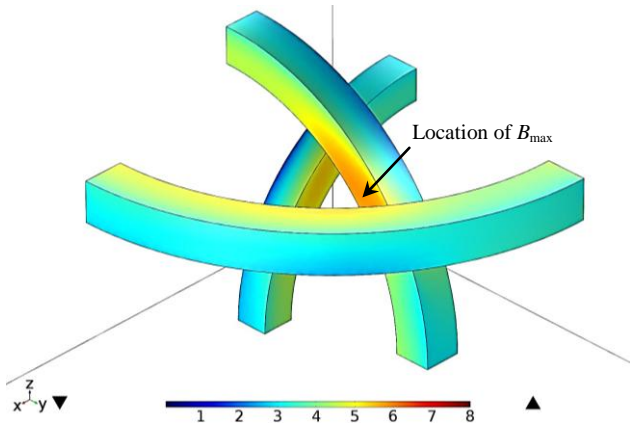


Fig. 3. Picture of the magnetic flux density norm $|\mathbf{B}|$ in a 1/8 model of the magnet and the location of B_{\max} .

It is important to define the load line of the coil system. For this purpose, a parametric study has been conducted for different values of I and R_y .

B. Simulations

To ensure the right configuration of the magnetic calculation made by the electromagnetic calculation software, we have used an analytical calculation to verify the accuracy of the obtained results. This verification process was carried out using analytical equations for a Helmholtz coil. Then we have created a Comsol model for the entire magnet. Comsol is a 3D software for electromagnetic calculations using finite element method. The model was designed with the electromagnetic module and configured with the “multi-turn coil” function. This function allows to manage a large number of turns and ensures uniformity in the spatial distribution of the turns. The coils are placed in the air. A very fine mesh was used throughout the magnet, in order to minimize the potential errors that a bigger mesh would have caused. Unfortunately, this high level of mesh leads to a larger calculation time. Indeed, when the three Helmholtz coils are fed with current, there is no plane of symmetry, and this leads to a completely 3D problem, i.e. the magnetic flux density has three components that vary with the three space coordinates. In order to reduce the computational domain and time, we have considered each Helmholtz coil as an axisymmetric problem with the midplane as symmetry plane, and applying the principle of superposition, only one eighth of the whole geometry has been studied. Fig. 3 shows the magnetic flux density norm $|\mathbf{B}|$ in a 1/8 model of the vector magnet and the location of B_{\max} .

Within the constraints mentioned in Section II.A, we found solutions that meet with the specifications of the vector magnet. Then, the model parameters I and R_y will allow the implementation of the parametric study under the critical values B_c and I_c . The whole geometry of the model coil is built and automatically adjusted according to the value of the reference radius R_y . The method used for building the geometry prevents the coil overlapping each other, and ensures their separation.

The worst operating condition is obtained when the 3 Helmholtz coils are fed with the same current I . Thus, to find

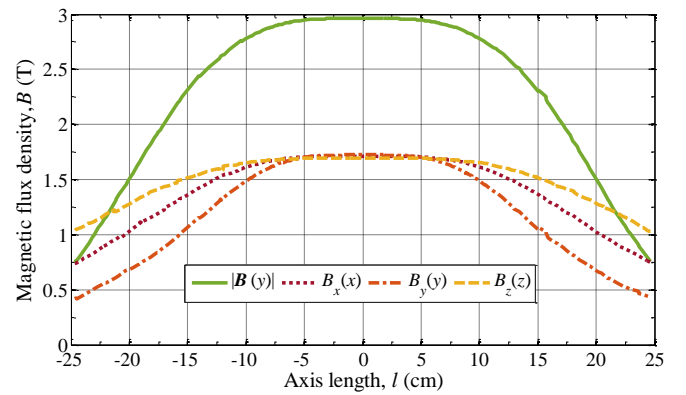


Fig. 4. Values of $B_x(x)$, $B_y(y)$, $B_z(z)$, and $|\mathbf{B}|(y)$ obtained with $R_y = 15$ cm and $I = 110$ A. As an example, the curve labeled $B_x(x)$ is the x -component of the magnetic field produced by the Helmholtz coil following the x -axis.

B_{\max} over the superconducting wire, it is necessary to make this study with all the coils serially connected. This value of B_{\max} is used to estimate the critical current I_c , and defines then the operating current that avoid the normal conducting transition of the magnet. In Fig. 2, with the value of B_{\max} about 8 T obtained during the simulation of the system with $R_y = 15$ cm, the value of the maximal operating current I is 110 A, which is 80 % of the critical current I_c .

In order to analyze the homogeneity of the magnetic flux density, a Comsol post processing calculation of (3) and (4) was performed.

III. RESULTS

Simulations with Comsol Multiphysics helped us for the determination of the critical values for the proper operation of the desired vector magnet. The relevant values to be determined are the maximal magnetic flux density B_{\max} over the superconducting wire, the homogeneity H_0 , B_x , B_y , B_z and $|\mathbf{B}|$ in the working space. In Fig. 4, the curves corresponding to B_x , B_y and B_z at $R_y = 15$ cm and $I = 110$ A are shown. The curve labeled B_x is the x -component of the magnetic flux density produced by the Helmholtz coil following the x -axis. B_y and B_z are labeled in the same way, while $|\mathbf{B}|$ is the magnetic flux density norm, produced by the whole magnet, plotted along the y -axis.

The maximum magnetic flux density B_{\max} over the vector magnet has been calculated using Comsol. The results for B_{\max} from the parametric study are shown in Table II. The values of the magnetic flux density norm $|\mathbf{B}|$ at the center of the vector magnet are presented in Table III. At a given current, e.g. 100 A, $|\mathbf{B}|$ does not change if the radius R_y is modified.

Table IV represents the total length of wire required to construct the vector magnet, its weight and the corresponding cost, assuming 0.6 €/m (June 2015).

The variation of the homogeneity which is computed in the entire working space, denoted as H_0 vs. R_y , is plotted in Fig. 5.

IV. DISCUSSION

The simulation of the vector magnet has been accomplished with some constraints. In order to facilitate the direction control of \mathbf{B} , the model ensures that all the components of \mathbf{B}

TABLE II
 B_{\max} OVER THE VECTOR MAGNET

I (A)	R_y (cm)									
	10	11	12	13	14	15	16	17	18	19
100	6.52	6.65	6.64	6.93	7.03	7.34	7.66	7.66	7.77	7.81
110	7.25	7.31	7.31	7.62	7.73	8.08	8.43	8.43	8.55	8.60
120	7.90	7.98	7.97	8.31	8.43	8.81	9.19	9.20	9.33	9.38

Maximum magnetic flux density B_{\max} over the vector magnet for different values of R_y and I .

TABLE III
 $|\mathbf{B}|$ AT THE CENTER OF THE VECTOR MAGNET

I (A)	R_y (cm)									
	10	11	12	13	14	15	16	17	18	19
100	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72	2.72
110	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
120	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27	3.27

Magnetic flux density norm $|\mathbf{B}|$ at the center of the vector magnet for different values of R_y and I .

TABLE IV
TOTAL LENGTH, WEIGHT AND COST OF WIRE

R_y (cm)	10	11	12	13	14	15	16	17	18	19
L	11.9	14.4	17.1	20.1	23.3	26.8	30.5	34.4	38.6	43.0
m	12.3	14.9	17.7	20.8	24.1	27.7	31.5	35.5	39.8	44.4
Cost	7.1	8.6	10.3	12.1	14.0	16.1	18.3	20.6	23.2	25.8

Total length, weight and cost of the wire SC56S53 required to build the vector magnet for different values of R_y .

The values are presented for cost and size comparison.

Total length $L = \text{km}$, Weight $m = \text{kg}$, Cost = k€.

have the same value in the center of the working space, as shown in Fig. 4. Moreover, the magnetic flux density produced by each Helmholtz coil, fed with the same current, has to be of the same magnitude in the center of the vector magnet.

The sizes of vector magnet that are the most interesting for us correspond to a value of radius R_y set between 12 and 15 cm. For higher values, it would require a greater length of wire which not helps to improve significantly the homogeneity but increases quickly the cost, beyond our budget. Indeed, the only benefit of a bigger coil would be a better homogeneity in a given volume. As regards the cryostat of the vector magnet, a thickness of about 30 mm has been selected for the stainless steel wall of the cryostat and the thermally insulating layers inside. Radius R_y of 15 cm enables us to gain a sphere of 10 cm for a working space and a surplus of 2 cm between the cryostat and wire of the magnet to place the mechanical structure. That is why a radius R_y of 15 cm has been chosen.

The values of B_{\max} shown in Table II must be compared with the 80% $I_c(|\mathbf{B}|)$ line of the wire in Fig. 2. If these values of B_{\max} exceed the 80% $I_c(|\mathbf{B}|)$ line, the stability of the vector magnet is not guaranteed, and the values of B_{\max} and $|\mathbf{B}|$ are reported in a cell with a white background in Table II and Table III, respectively. As an example, at a current of 100 A, B_{\max} must not exceed 8.17 T in order to prevent the superconducting wire from transiting to the normal state. Since B_{\max} is always lower than 8.17 T at 100 A, all the values reported on the corresponding line of Table II have a gray background. Therefore, the parameters with a gray

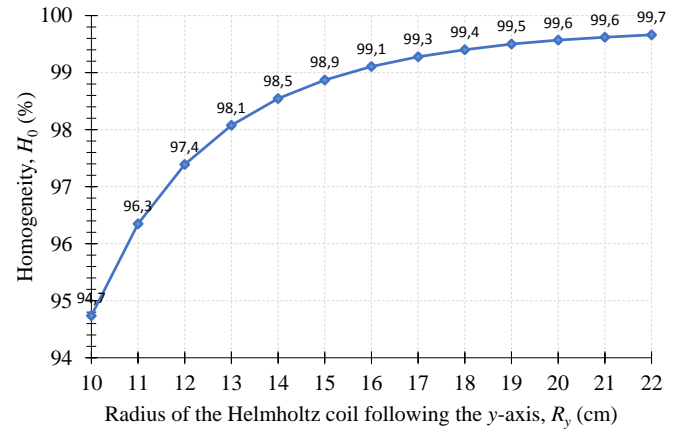


Fig. 5. Variation of the homogeneity H_0 vs. R_y .

background in Table II and Table III are the only values that will ensure the proper operation of the vector magnet in the superconducting state.

As shown in Table III, a bigger R_y does not increase $|\mathbf{B}|$ at the center; however the B_{\max} value is increasing with increasing R_y . A way to change this tendency would consist of increasing the cross section of the coils, i.e. the number of turns. Indeed, B_{\max} decreases if the cross section of the coils increases. It was unnecessary to increase the cross section of the coils in our case since a design of vector magnet that satisfies all our requirements has been found. The range of values from 100 A to 120 A for I , and from 10 cm to 19 cm for R_y are shown because the vector magnet can produce a magnetic field norm around the desired one of 3 T in this range.

Fig. 5 shows the variation of the homogeneity H_0 vs. R_y . One can obtain a homogeneity of 98.87% for $R_y = 15$ cm. The curve shows the behavior of H_0 as a function of the magnet size. If a larger homogeneity is required, the size of the magnet must be increased, leading irrevocably to an increase of its cost. The price of the cryostat for such a system is around 20 k€. By adding 16.1 k€ for the NbTi wire and approximately 9 k€ for the raw material (epoxy resin...) and the machining, the total cost of the designed vector magnet grows up to 45 k€. The values of weight represented in Table IV are useful to design the thermal performances of the cryostat.

V. CONCLUSION

The objective of this work was to study and to design a superconducting vector magnet which is able to produce a high, directional and uniform magnetic flux density to perform the characterization of HTS samples. The results demonstrated that a coil system consisting of Helmholtz coils can be adapted to these requirements with a total cost of around 45 k€. Due to the lack of iron in the structure, the behavior of the vector magnet is completely linear. The effects of an external magnetic screen in order to reduce the magnetic pollution around the magnetic system, i.e. the 5 gauss curve, remain to be examined. The presence of the three Helmholtz coils significantly reduces the performance of the wire unlike a single magnet. Since the design of the vector magnet is mostly

influenced by B_{\max} , we can say that the B_{\max} value is the key variable in this design. The mechanical problems have not been addressed in the present article because work is ongoing.

The uniformity of the magnetic flux density has a nonlinear behavior in the defined working zone. The configuration composed of three Helmholtz coils has a very good homogeneity. It fits well to the applications in electrical engineering for which 95 % of homogeneity is sufficient. Thus, we have designed an important device that will be very useful for the research in the superconducting field. This system is currently under construction and will be tested in the first semester of 2016.

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