Design & Development of Helmholtz Coil for Hyperpolarized MRI

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Abstract: The Helmholtz coil generates a uniform magnetic field. The coil serves as a component in the system for Hyperpolarization of Xenon. HPMRI enhances the quality of images in the low proton density organs such as lungs by 10000 times. The requirement was of customized coil with all non magnetic parts. Comsol Multiphysics AC DC Module Version 3.5a simulated results and actual results were compared.

Keywords: Helmholtz coil, uniform magnetic field, hyperpolarization

1.Introduction

Helmholtz coil is an arrangement to obtain uniform magnetic field. Magnetic field of known strength and uniformity is useful for various applications. It is useful as a magnetic field standard for calibration of magnetic field meters[1], for various extremely low frequency in vivo bio electromagnetic studies[2], to generate homogeneous magnetic flux density in the cross section of flow pipe of electromagnetic flow meter for obtaining accurate flow rate[3], to study toxicological or neurochemical alterations influenced by a magnetic field on chick embryo[4]etc. It consists of two similar circular coils with a distance between them equal to their radius and equal number of wire winding on each loop (Fig.-1). The magnetic field intensity is directly proportional to current and the number of turns in the coil and it is inversely proportional to the distance between the coils.

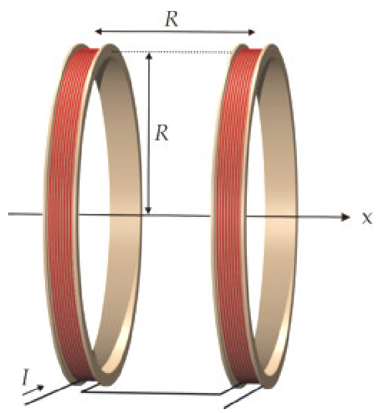

Figure 1. Helmholtz coil schematic drawing

2.Governing Equations

On-axis field due to a single wire loop from Biot Savart Law:

Where:

$B=\mu_0 IR^2/\{2(R^2+a^2)^{3/2}\}$ (1)

μ_0= the permeability constant = $4\Pi\times10^{-7}$ Tm/A

I = coil current, in amperes

R = coil radius in meters

a = coil distance, on axis, to point, in meters

Since the coil consists of number of wire loops, the total current in the coil is given by

NI = total current (2)

In a Helmholtz Coil, a point halfway between the two loops has an

a=R/2 (3)

Substituting equations (2) and (3) in equation (1)

$B = \mu_0 NIR^2/2\{R^2+(R/2)^2\}^{3/2}$ (4)

Since there are two coils instead of one, so multiplying the formula by 2 and simplifying:-

$B = (4/5)^{3/2}\mu_0 NI/R$ (Tesla) (5)

Or

B = 0.899 NI/R (Gauss) (6)

3. Theory

Design Considerations:

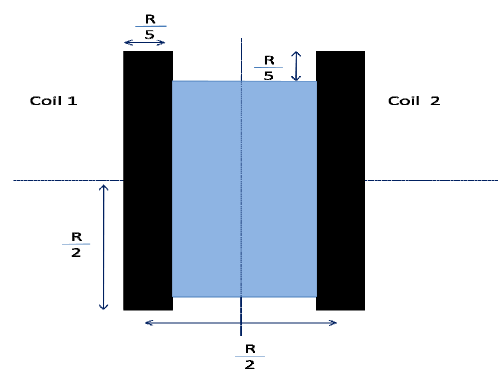

Figure 2. Structure of the coil

1. The mean radius of the coil bundles should be equal to the mean coil spacing.
2. For best performance, width and the depth of the wound coil cross section should not exceed D/10 of the coil diameter.
3. Coil diameter should be at least three times the length of the test specimen or four times its diameter or both.
4. As stability of magnetic field is extremely important in HPMRI so constant current source is required for the coil.

5. Frame and fittings should be made by non-magnetic materials.
6. A free wheel diode should be used to release the magnetic field energy for switching.
7. For winding annealed high conductivity copper wire should be used.
8. Odd No. of winding layers should be used so that leads exit on opposite edge of the coil.

4. Method

The coil was designed for 30 Gauss magnetic field. We fixed the radius at 30 centimeter based on the cell size of our hyperpolarized MRI system. The width of the coil form was set to less than one tenth of diameter as per geometric rule and hence it was freezed to 4 cm. First the structure was constructed using the plywood with thickness 1.4 cm. 3 rings of this plywood were pasted. Two such rings were made. Then these two rings were joined at a distance equal to the radius of the coil with the help of wood patches, bars and non magnetic brass screws.

The 20 SWG enameled copper wire was taken having current capacity upto 14 ampere and diameter of 0.92 mm. 5 layers of copper wire were wound on each side and 200 turns of wire was wounded. Since magnetic field B, number of turns of copper wire and radius were fixed current required to generate 30 Gauss magnetic field was calculated to be 5 ampere.

5.Numerical Model:

Comsol Multiphysics AC DC Module Version 3.5a was used for simulating the magnetic field generated by the coil. The model is built using the 3D magnetostatic application mode.

5.1 Domain Equations:

Assuming static currents and fields, the magnetic vector potential **A** must satisfy the following equation:

$$\nabla\times(\mu^{-1}\nabla\times\mathbf{A}) = \mathbf{J}^e \qquad (7)$$

Where

μ - is the permeability

$\mathbf{J}^e$ - denotes the externally applied current density

The relation between field & potential is given by:-

$$\mathbf{B} = \nabla\times\mathbf{A} \qquad (8)$$

Where B = Magnetic Flux Density in Tesla

This model uses the permeability of vacuum, i.e $\mu = 4\pi.10^{-7}$ H/m.

Current density in the coil $J=N.I/A$ (9)

Where N= number of turns in the coil

I = current in the coil

A = cross section area of the coil winding

$J = 5\times10^6$ A/m^2

5.2 Boundary Conditions:

The only boundary condition that we need to specify is for the exterior boundary i.e the spherical surface, where we apply the condition corresponding to zero magnetic flux.

5.3 Modelling:

In AC/DC module 3D from space dimension list was selected. Current density was fed as a constant parameter. Axes & grid settings were done and rectangles were drawn as per the coil winding cross section area, maintaining the basic Helmholtz Principle i.e radius = distance between the coils. The rectangles were revolved to draw the coils. After sub domain settings and mesh generation solution was obtained for the magnetic field plot. Finally magnetic flux density was plotted to check uniformity of the field.

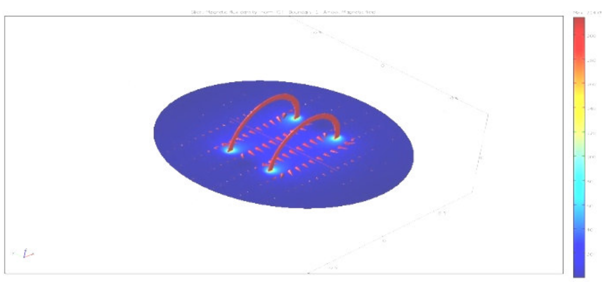

Figure 3. Slice plot of magnetic flux density

6.Experimental Results:

Figure 4. Arrangement of Helmholtz Coil

The coil was placed vertically with its axis parallel to earth. The reading of Gauss meter was adjusted to zero. Magnetic field at various points was measured. The results were compared from simulation & practical coil. The uniformity of the field is visible in both the cases.

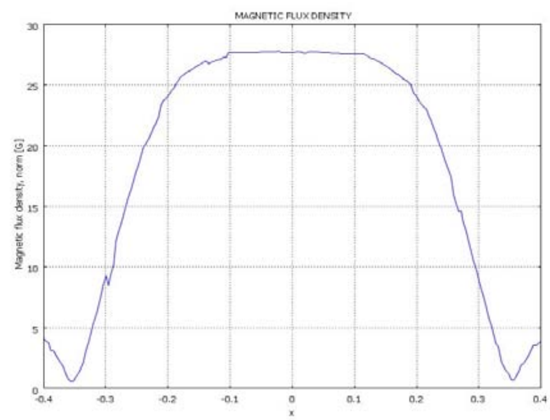

Figure 5. Cross section plot along X axis form Comsol

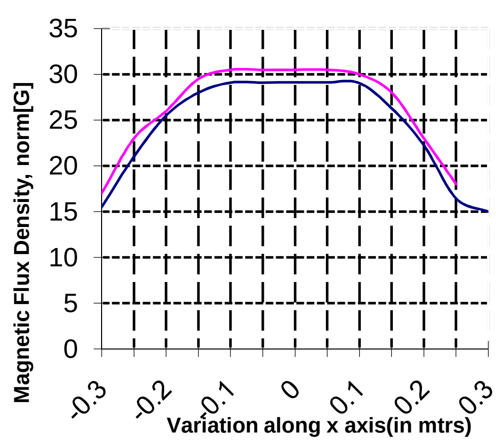

Figure 6. Graphical Representation of Uniform Magnetic field along the x- axis using COMSOL Multiphysics and Experimenal analysis. Pink line shows experimental plot whereas Blue line shows simulated result.

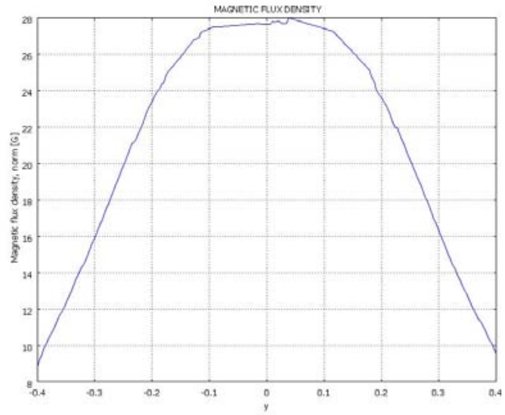

Figure 7. Cross section plot along Y axis from Comsol

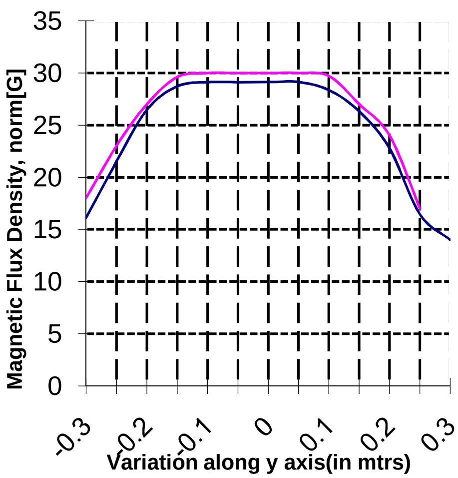

Figure8. Graphical Representation of Uniform Magnetic field along the y- axis using COMSOL Multiphysics and Experimental analysis. Pink line shows experimental plot whereas Blue line shows simulated

7. Discussion:

The field was uniform. The magnetic field takes some time to stabilize. On continuous supply the coil winding gets heated, resulting in increase in resistance, reduction in current and hence decrease in magnetic field value. The coil structure must have arrangement for cross ventilation through holes. While constructing the structure this was taken care of.

8. Conclusions:

Comparative study of simulation and practical results were done to check the magnetic field uniformity of Helmholtz coil. The magnetic field value was attained successfully for which the coil was designed. Helmholtz coil is excellent source of uniform magnetic field. The coil was built within a very economic budget.

9. References:

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