

# SIMULATION, DESIGN AND IMPLEMENTATION OF MAGNETIC FIELD GRADIENT COILS FOR EARTH'S FIELD MRI

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**Abstract** - Earth's field Magnetic Resonance Imaging requires gradient coils to have high strength for better resolution. The current work aims at designing gradient coils for Earth's field MRI with increased field. MATLAB simulation and the hardware for gradient coils is simulated and built. Gradients along z direction are obtained using Maxwell's coil and transverse gradients using Golay coil. The primary function of gradients, therefore, is to allow spatial encoding of the MR signal. The work also aims at integrating the gradient coil with the EFNMR system and produce linearly varying magnetic field along the direction perpendicular to the Earth's field.

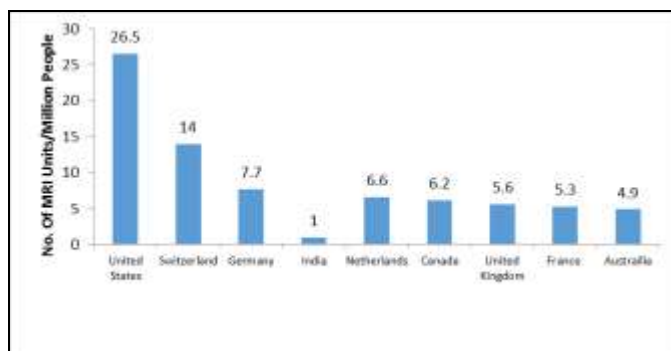
**Key Words:** Magnetic Field, Gradient Coils, Spatial Encoding, Resolution, Magnetic Resonance Imaging, Earth's Field

## 1. INTRODUCTION

### 1.1 Background

Global MRI market is currently valued in the region of US \$ 7.5 billion. Magnetic Resonance Imaging has become a well-established standard in particular anatomies/pathologies (among others) related to brain, heart and cancer imaging however, MRI is a costly and slow throughput imaging modality and it is highly relevant to a populous country like India.

Scanner time is proportional to cost incurred overall by the patient (includes technician time, clogging of resources).



**Chart -1:** MRI No. of Units per million persons around the world v/s India

Therefore, portable low field MRI for brain, spine and extremities would address these challenges, for building up of a low-field MRI and the low-field NMR would be the base and addition of gradient coils to the NMR equipment would result to low-field MRI.

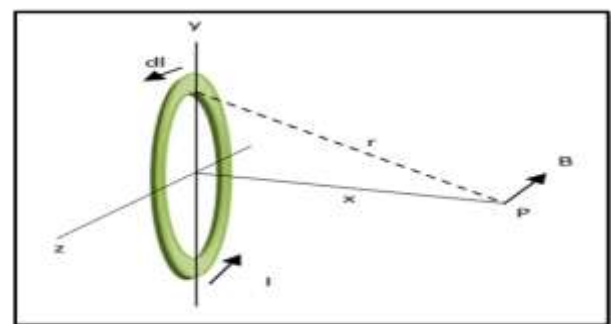
### 1.2 Principle of MRI – Biot-Savart's Law

The Biot–Savart's law is an equation describing the magnetic field generated by an electric current. It relates the magnetic field to the magnitude, direction, length, and electric current. Biot-Savart's law is stated for a small current element ( $I \cdot dl$ ) of wire carrying current. Magnetic field due to extended wire carrying current can be found by using a vector sum of the fields created by each section of the wire individually. The point in space at which the magnetic field is to be computed will be chosen, and integration is carried out over the path of the current ( $I$ ) by applying the equation of Biot-Savart's Law.

For loop carrying current:

$$B = \frac{\mu_0 I dl \sin\theta}{4\pi r^2}$$

$B$  is magnetic field in mT,  
 $\mu_0 = 4\pi \times 10^{-7}$  in NA-2 (permeability in free space),  
 $I$  is current in Amperes,  
 $dl$  is differential length in cm,  
 $r$  is radius of the loop in cm and,  
 $\theta$  is angle between the center and the point in space



**Figure -1:** Biot-Savart's Law for current carrying loop

## 2. GRADIENT SYSTEM

Gradients are loops of wire or thin conductive sheets on a cylindrical shell lying inside the bore of an MR scanner. When current is passed through these coils a linearly varying magnetic field is created. This gradient slightly distorts the main magnetic field in a predictable pattern, causing the resonance frequency of protons to vary in as a function of position. The primary function of gradients, therefore, is to allow spatial encoding of the MR signal. Gradients also are critical for a wide range of "physiologic" techniques, such as MR angiography, diffusion, and perfusion imaging.

Three sets of gradient coils are used in nearly all MR systems: the x-, y- and z- gradients. Each coil set is driven by an independent power amplifier and creates a gradient field whose z-component varies linearly along the x-, y-, and z-directions, respectively. The design of the z-gradients is usually based on circular (Maxwell) coils, while the transverse (x- and y) gradients typically have a saddle (Golay) coil configuration.

## 2.1 Software

MATLAB (matrix laboratory) is a multi-paradigm numerical computing environment and fourth-generation programming language. A proprietary programming language developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, Java, Fortran and Python. The MATLAB version that we have used is R2015a.

### 2.1.1 Simulations

The function used for the simulation is quiver command in MATLAB. Quiver3 is a 3-D quiver plot. Quiver3 ( $x,y,z,u,v,w$ ) plots velocity vectors as arrows with components ( $u,v,w$ ) at the points ( $x,y,z$ ). The matrices  $x,y,z,u,v,w$  must all be the same size and contain the corresponding position and velocity components. Quiver3 automatically scales the arrows to fit. Quiver3 ( $z, u, v, w$ ) plots velocity vectors at the equally spaced surface points specified by the matrix  $Z$ .

This function is used to show the magnetic field distribution of the coils by giving current as the input in the MATLAB code.

## 2.2 Hardware Implementation

### 2.2.1 Maxwell's Coil

A coil of 25 turns was hand wound using copper wire on a PVC pipe of diameter 7.5cm. The gauge of the copper wire used was 22 AWG and the width of the coil was 3cm. The L, C, R values of the coil was 124.5 $\mu$ H, 203  $\mu$ F and 0.788 $\Omega$  which were calculated using LCR meter (Model MS5308).

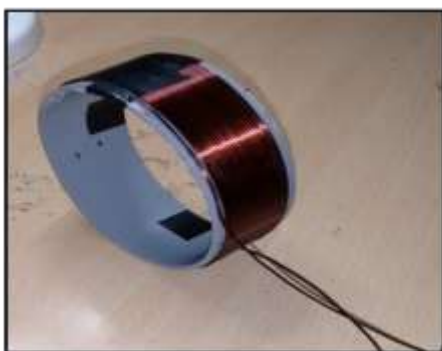


Figure - 2: Maxwell Coil Winding

### 2.2.2 Golay Coil

A Golay coil was built using copper wire of 22 AWG on a PVC pipe of length 35 cm and radius 6.5 cm. The coil was hand wound and length of each coil was 14.11cm ( $2.17*r$ ). The distance between 2 coils was 5.07cm ( $0.78*r$ ). Each coil consisted of 62 turns and the angle of the arc of each coil was 1200. An insulating varnish was applied on the coil.



## 3. MATERIALS AND METHODS

### 3.1 Simulation of Gradient Coils

A Maxwell's coil pair each of 25 turns and two Golay coil pairs each of 62 turns separated by a distance of 10cm and 13.56cm ( $2.17*radius$ ) respectively were simulated using Biot- Savart law. The simulations were carried out over an isotropic volume of  $8 \times 10 \times 10 \text{ cm}^3$  for Maxwell's coil and  $10 \times 10 \times 10 \text{ cm}^3$  for Golay coil. The length of a coil in a Golay pair was 4.88cm ( $0.78*radius$ ). The maximum gradient amplitude ( $G_{max}$ ) and efficiency of these coils were calculated and determined. All simulations were performed using MATLAB, The MathWorks, Natick, MA, USA.

### 3.2 Experimental Setup

Gradients along z direction are obtained using Maxwell's coil and x and y gradients using Golay coil. The Maxwell coil and Golay coil each of radius 3.75cm and 6.25cm respectively were built using AWG 22 copper wire. The magnetic field for Maxwell's coil was measured using a Gauss meter (Vasals Engineering Industries, Model VM2000D) for a current of 12A. The obtained values were in steps of 1cm between the centers of both the coils. The magnetic field values for Golay coil were measured in the same manner for varying current in steps of 0.5cm. The currents in Maxwell's coil were in opposite direction. One Golay pair (above) had current in the same direction whereas current in the other Golay pair (below) was given in the opposite direction.

## 4 RESULTS AND DISCUSSION

### 4.1 Results

Figures 4 and 5 shows the simulation, implementation and characterization of Maxwell's coil and Golay coil. The

simulations of these coils are shown in figure (4a and 5a) respectively which shows varying magnetic field using quiver plots. Figure (4b and 5b) shows a 1D plot of magnetic field distribution, figure(4c and 5c) shows the hardware setup for Maxwell's and Goley coil. The graph for obtained values is shown in figure(4d and 5d).

lowest magnetic and red region shows the highest magnetic field. This shows the linearly varying magnetic field from -0.2mT to 0.3mT in the 6cm field of view (FOV) center plane.

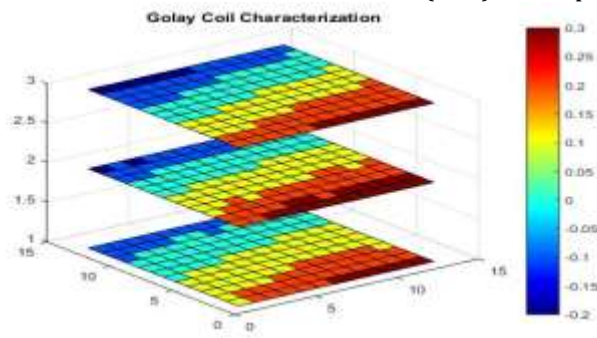


Figure - 6: Slice -wise distribution of magnetic field for Goley coil

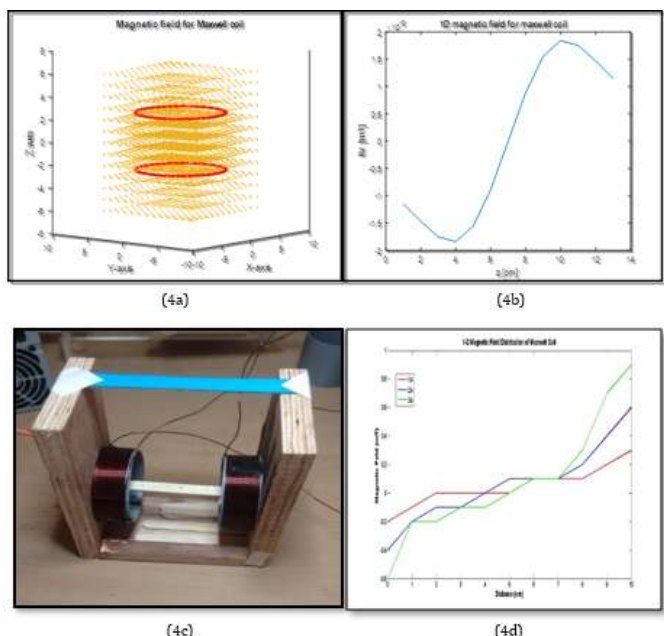


Figure - 4: (a) Simulation of Maxwell's Coil in MATLAB. (b) 1D magnetic field for Maxwell's coil. (c) Hardware of Maxwell's Coil. (d) Magnetic field values of Maxwell's coil plotted in MATLAB.

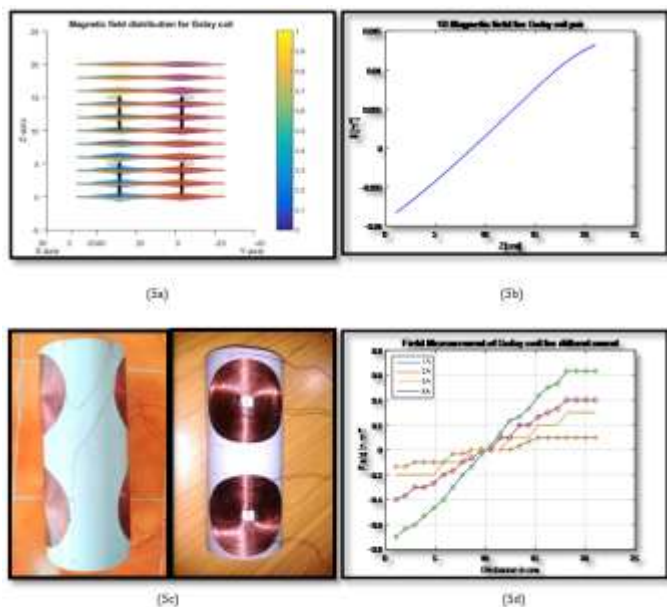


Figure - 5: (a) Simulation of Goley coil in MATLAB. (b) 1D magnetic field for Goley coil. (c) Hardware of Goley coil. (d) Magnetic field values of Goley coil plotted in MATLAB.

Figure 6 shows the magnetic field distribution of Goley coil for 3A. Using gaussmeter, we measured magnetic field for three different slices with 1cm distance in Z-direction and 5mm distance in the X and Y direction. Blue region shows the

## 4.2 Discussion

### 4.2.1 System Integration

The gradient coil built was integrated with the EFNMR system. This coil was placed inside the polarization coil and shielded AF coil within the gradient coil. The sample in turn was placed inside the AF coil.

The system was placed in such a way that the direction of the magnetic field produced was perpendicular to the direction of the Earth's field. The direction of the Earth's field is as shown in figure 5.1.

The internal circuitry of the system involves polarization circuit, transmit-receive circuit and microcontroller. The T/R switch was programmed to switch between ON and OFF of the polarization coil. Two power supplies were used to run the system, one for polarization coil and the other for gradient coil.

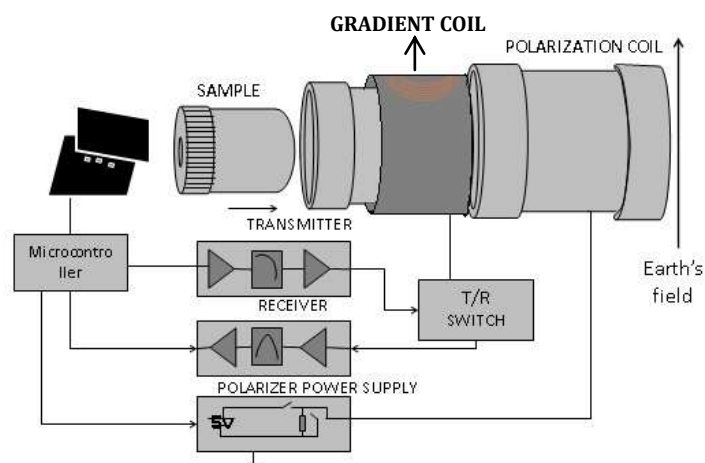


Figure - 7: Block diagram of EFNMR system with gradient coil integration

The integration of gradient coil with the EFNMR system was implemented. The polarization coil consisted of 310 turns and AF coil consisted of 10 layers with 280 turns in each layer. Aluminum foil was used for the purpose of AF

shielding. The gradient coil consisted of 62 turns each, as mentioned in previous sections. The sample used was a 3-D magnetic compass and the precession of the magnet was observed when the current was supplied.

## 5. CONCLUSION AND FUTURE WORK

### 5.1 Conclusions

The gradient coils built for EFMRI were simulated, designed and implemented. Linear magnetic field was obtained when plotted in MATLAB. The gradient strength of the Maxwell's coil and Golay coil was 11.67mT/m and 5mT/m and gradient efficiency of these coils being 5.835mT/m/A and 1.67mT/m/A.

Simulated output and the hardware output were compared and are found to be in agreement. Hence linear magnetic field gradients were obtained along x and/or y direction using Golay coil. The gradient coil was integrated with the EFMRI system for a smaller field of view(FOV). The magnetic field produced by the gradient was observed and tested by the precession of 3-D magnetic compass.

### 5.2 Future Work

The future work aims at 3-D projection imaging. In this, the gradient coil is rotated by an angle of 3600 in steps of 10. Purpose of this imaging is to have a better spatial resolution and spatial encoding as the information is extracted for every 10 of rotation of gradient coil.

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