# Shielding the Earth Magnetic Field using Spherical Coils

# Teerapat Payupol, Narumon Suwonjandee and Burin Asavapibhop

Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok 10330, Thailand

E-mail: teerapatfb@gmail.com, snarumon@gmail.com and burin.a@chula.ac.th

**Abstract.** The Jiangmen Underground Neutrino Observatory (JUNO) is a neutrino experiment consisting of 2 systems; central detector (CD) and veto systems. The CD is composed of thousands of photomultiplier tubes (PMTs) used to detect light signals from neutrino induced interactions with liquid scintillator inside the CD. Another set of PMTs is used as water Cherenkov detector, together with muon top tracker forming the veto system for background rejection [1]. However, the PMTs' efficiency decreases when they are used in magnetic field. At JUNO's construction site, the Earth Magnetic Field (EMF) is approximately 0.45 G [2]. Therefore, the PMTs of JUNO detector are necessary to be shielded from the EMF.

This work aims to design current-carrying coils that generate magnetic field in the opposite direction to the EMF, thus, the two fields tend to cancel each other. We found that the magnetic field generated by the 32 circular coils forming a sphere of diameter 43.5 m can reduce the residual magnetic field to be lower than 10% of the EMF at the CD region and less than 20% at the veto region. Moreover, considering the secular change of the EMF's inclination angle of approximately  $2.87^{\circ}$  over the 20 years of its operation, the coils can maintain the residual magnetic field both in the CD and the veto regions to be less than 10% and 20%, respectively.

## 1. Introduction

The Jiangmen Underground Neutrino Observatory's (JUNO) detector is a liquid scintillator neutrino detector under construction at Jiangmen in China. Its primary goals are to determine the neutrino mass hierarchy and neutrino oscillation's parameters. The detector is composed of photomultiplier tubes (PMTs) detecting the light signal from neutrino induced interactions. The PMTs are mounted on a spherical surface of 39.5 m in diameter for the coverage of 75% of the surface area of the sphere as shown in Figure 1 [1].

These PMTs are significantly sensitive to magnetic field, i.e. the magnetic field can reduce the PMT's efficiency. Since the Earth Magnetic Field (EMF) at Jiangmen is 0.44839 Gauss [2], a compensation coils system is necessary for reducing this effect. The coils will be installed inside the water tank of JUNO's detector and surround the Central Detector (CD).

### 2. Research Procedure and Optimization of the Residual Magnetic Field

The compensation coils are designed to be a set of circular coils forming a sphere of diameter 43.5 m. This diameter is the same as the diameter of the water tank. The coils are designed to have the same spacing along their axis of symmetry. The single spherical coils have an axis of symmetry lying opposite to the Earth Magnetic Field's direction as shown in Figure 2. Thus, the



Figure 1: Scheme of JUNO's detector

Figure 2: Single spherical coils are composed of 32 circular coils.

generated magnetic field from the coils is opposite to the EMF and consequently compensates with the EMF. The resultant magnetic field is called residual magnetic field or residue.

Seven models of the compensation coils are designed by varying the number of circular coils from 20-32 coils. Then, the currents of circular coils are obtained from the optimization of residual magnetic field regarded as matrix-based optimization as follows;

$$\mathbf{Bx} = \mathbf{EMF} \tag{1}$$

$$\begin{bmatrix} B_{x1}^{c1} & B_{x2}^{c1} & B_{x1}^{c3} & \dots & B_{x1}^{cm} \\ B_{y1}^{c1} & B_{y1}^{c2} & B_{y1}^{c3} & \dots & B_{y1}^{cm} \\ B_{z1}^{c1} & B_{z1}^{c2} & B_{z1}^{c3} & \dots & B_{z1}^{cm} \\ B_{x2}^{c1} & B_{z2}^{c2} & B_{x2}^{c3} & \dots & B_{x2}^{cm} \\ B_{y2}^{c1} & B_{y2}^{c2} & B_{y2}^{c3} & \dots & B_{y2}^{cm} \\ B_{z2}^{c1} & B_{z2}^{c2} & B_{z2}^{c3} & \dots & B_{z2}^{cm} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ B_{xn}^{c1} & B_{xn}^{c2} & B_{xn}^{c3} & \dots & B_{xn}^{cm} \\ B_{yn}^{c1} & B_{yn}^{c2} & B_{xn}^{c3} & \dots & B_{yn}^{cm} \\ B_{zn}^{c1} & B_{zn}^{c2} & B_{zn}^{c3} & \dots & B_{zn}^{cm} \\ \end{bmatrix}_{3n \times m}^{a \times m}$$

where **B** is the matrix of magnetic fields, generated by all coils at any positions of interest with the initial electric current of 1 A. Note that  $B_{xn}^{cm}$  represents the x-component of magnetic field at the  $n^{th}$  position generated by the m<sup>th</sup> coil.

 $\mathbf{x}$  is a column matrix of scaling factors of the currents.

**EMF** is a column matrix containing the x, y and z components of EMF, which are 0.37988, 0.01505, 0.23772 G, respectively [2].

In order to optimize the residual magnetic field for the currents, the "LeastSquares" command in Mathematica is applied to find the column matrix  $\mathbf{x}$  that can minimize the norm of matrix **Bx-EMF**. This gives the electric currents of each coil (scaling factors) that minimize the norm of residual magnetic field at any location of interest. In this research, the residual magnetic field is optimized using approximately 17000 points on a spherical surface of diameter 39.5 m, which is the region of central detector PMTs.

#### 3. Results

The results are considered as the percentage of residue-to-EMF ratio (R) defined in Equation 3 at 2 regions;

- On the spherical surface of diameter 39.5 m, which is a region corresponding to CD PMTs' region, this ratio is expected to be less than 10%.
- On the spherical surface of diameter 41.5 m, which is veto PMTs' region, this ratio is expected to be less than 20%.

$$R = \frac{\sqrt{(B_x + EMF_x)^2 + (B_y + EMF_y)^2 + (B_z + EMF_z)^2}}{EMF} \times 100\%$$
(3)

where  $B_x$ ,  $B_y$  and  $B_z$  are the x, y and z components of generated magnetic field from coils, respectively.  $EMF_x$ ,  $EMF_y$  and  $EMF_z$  are the x, y and z components of the Earth Magnetic Field, respectively, and EMF is the norm of the Earth Magnetic Field.

#### 3.1. The Magnetic Field from Coils

The design of SS1 to SS7 are summarized in Table 1 (SS refers to single sphere). According to the results, the more the number of circular coils the less the current in each coil, since when the number of coils increases, there are more coils to share the currents. The R calculated by Radia [3] is presented in Table 2. It shows that models SS3 to SS7 meet the requirements and model SS7 can provide the lowest of the maximum of R on the CD PMTs' and veto PMTs' regions. Moreover, the model SS7 also requires the lowest of the maximum of electric currents as compared to the other models. Thus, model SS7 is selected to be an acceptable model among other models.

The distributions of R from model SS1 to SS7 are presented in Figure 3. The histograms show that as the number of circular coils increases, the peak of the histograms are located closer to zero, i.e. the generated magnetic field is close to the EMF, which is taken to be constant throughout the detector. The more circular coils or less spacing between coils, the more likely constant magnetic field inside the coils, since narrower spacing provides smoother magnetic field similar to an ideal solenoid case.

| Model | Number   | Spacing | Current (A) |         |  |  |
|-------|----------|---------|-------------|---------|--|--|
|       | of Coils | (m)     | Maximum     | Minimum |  |  |
| SS1   | 20       | 2.17    | 120.32      | 91.12   |  |  |
| SS2   | 22       | 1.98    | 109.89      | 83.37   |  |  |
| SS3   | 24       | 1.81    | 101.13      | 76.81   |  |  |
| SS4   | 26       | 1.67    | 93.67       | 71.21   |  |  |
| SS5   | 28       | 1.55    | 87.24       | 66.35   |  |  |
| SS6   | 30       | 1.45    | 81.64       | 62.10   |  |  |
| SS7   | 32       | 1.36    | 76.67       | 58.40   |  |  |

Table 1: The parameters of the single spherical coils model SS1 to SS7

Table 2: The percentage of residue-to-EMF ratio of single spherical coils model SS1 to SS7

| Diameter (m) | Maximum of percentage of residue-to-EMF ratio (%) |       |       |       |       |       |       |
|--------------|---|-------|-------|-------|-------|-------|-------|
|              | SS1   | SS2   | SS3   | SS4   | SS5   | SS6   | SS7   |
| 39.5         | 7.00  | 5.95  | 5.10  | 4.40  | 3.83  | 3.35  | 2.95  |
| 41.5         | 24.71   | 21.68 | 19.19 | 17.12 | 15.39 | 13.91 | 12.65 |

## 3.2. The Effect of EMF Secular Variation

The Earth Magnetic Field slightly changes its magnitude and direction every year. This phenomenon is known as EMF secular variation. The changes of the EMF at JUNO's site are  $0.0607^{\circ}$  per year and  $0.1437^{\circ}$  per year for declination and inclination, respectively. The



Figure 3: The distribution of percentage of residue-to-EMF ratio

dominant change is the inclination, which is approximately  $2.87^{\circ}$  within 20 years [2]. This section demonstrates the effect of EMF's inclination changes for  $\pm 1^{\circ}$ ,  $\pm 2^{\circ}$ ,  $\pm 3^{\circ}$ , and  $\pm 5^{\circ}$  on the percentage of residue-to-EMF ratio of model SS7. The results are shown in Table 3.

| Diameter (m) | Maximum of percentage of residue-to-EMF ratio $(\%)$ |       |              |       |       |       |             |             |             |
|--------------|--|-------|--------------|-------|-------|-------|-------------|-------------|-------------|
|              | $-5^{\circ}$   | -3°   | $-2^{\circ}$ | -1°   | 0°    | 1°    | $2^{\circ}$ | $3^{\circ}$ | $5^{\circ}$ |
| 39.5         | 11.41  | 7.92  | 6.18         | 4.44  | 2.95  | 4.44  | 6.13        | 7.87        | 11.36       |
| 41.5         | 20.55  | 17.18 | 15.52        | 13.97 | 12.65 | 13.97 | 15.62       | 17.30       | 20.68       |

Table 3: The R of model SS7 when the EMF changes its inclination

When we consider the secular change of the EMF's inclination angle of approximately  $2.87^{\circ}$  over 20 years of coils operation, the percentage residue-to-EMF ratio is below 10% and 20% for CD PMTs' and veto PMTs' regions, respectively. The generated magnetic field can reduce the residual magnetic field below the requirements during this inclination change.

# 4. Conclusion

The 32 circular coils forming a sphere of diameter 43.5 m in model SS7 can reduce the residual magnetic field to lower than 10% of the EMF at CD PMTs' region and lower than 20% at veto PMTs' region. In addition, considering the secular change of the EMF's inclination angle of approximately 2.87° over 20 years of the coils operation, it can maintain the percentage of residue-to-EMF ratio in the CD and the veto regions to be less than 10% and 20%, respectively.

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