EMF Shielding of One Set of Circular Coils with Slight Distortion

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Abstract. Jiangmen Undergroud Neutrino Observatory (JUNO) is a reactor antineutrino experiment with the main purpose for determining the neutrino mass hierarchy by precisely measuring the energy spectrum of nuclear reactor electron antineutrinos. The JUNO central detector consists of 20 kilotons an organic liquid scintillator filling the spherical CD or acrylic sphere whose diameter is 35.4 meters, surrounded by a water pool, approximately $18,000$ $20''$ and $25,000$ $3''$ photomultiplier tubes (PMTs) on the inner CD truss and $2,400$ $20''$ Veto-PMT on the outer CD truss. The PMTs are very sensitive to external magnetic fields, the earth magnetic field (EMF) passing through the PMTs without any shielding would largely reduce the efficiency of the PMTs. In order to minimize the effect of EMF inside the detector, JUNO has been planing to use the DC coils to shield EMF, aiming at the residual EMF to less than 10 % on PMT areas.

1. Introduction

After the discovery of the neutrino mixing or neutrino oscillation phenomena, so far this phenomena has stimulated physicists to study oscillating properties. Neutrino mixing parameters are couplings in Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS) [1]. The matrix is composed of the three mixing angles (θ_{23}, θ_{12}, and θ_{13}), the Dirac CP violation phase $\delta = [0, 2\pi]$. These parameters may be determined via the transition probability between the neutrino flavor states. For example, the transition probability that an electron antineutrino from a source will be found elsewhere as an electron antineutrino, can be written as

$$\begin{aligned} P(\bar{\nu_e} \to \bar{\nu_e}) = 1 - \sin^2(2\theta_{13}) &\left[\cos^2(\theta_{12})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + \sin^2(\theta_{12})\sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)\right] \\ &- \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) \end{aligned} . \tag{1}$$

where L is the traveled distance of the neutrino and Δm_{31}, Δm_{32}, and Δm_{21} are the difference of squared neutrino masses [2]. In present, The latest parameter of the measured neutrino mixing parameters is the mixing angle θ_{13}, which was determined by the reactor neutrino experiments at Daya Bay [3]. The next generation neutrino experiments are going to determine the sign of

Δm^2_{32} (mass hierarchy), by precisely measuring all oscillation parameters and searching for CP violation in the neutrino oscillation. Eq. 1 is very important for one of the next generation reactor neutrino experiments, the Jiangmen Underground Neutrino Observatory (JUNO) since JUNO will precisely measure the energy spectrum of nuclear reactor electron antineutrinos at a distance of 53 kilometers from the reactors (Yangjiang and Taishan nuclear power plants). JUNO will measure antineutrino from the reactors via the inverse beta decay (IBD) reaction $\bar{\nu}_e + p \longrightarrow n + e^+$ [4]. The PMT is very sensitive to external magnetic fields, the earth magnetic field (EMF) passing through the PMTs without any shielding would largely reduce the efficiency of the PMTs. So, JUNO has been planing to use the DC coils to shield EMF in the PMTs. The efficiency of the PMTs is above 90% when the external magnetic field is lower than $10\mu T$ as shown in figure 1. Thus, the residual intensity is expected to be less than 10% on CD-PMT (diameter 39.5 m.) and 15% on Veto-PMT (diameter 41.5 m.) after coil shielding [5].

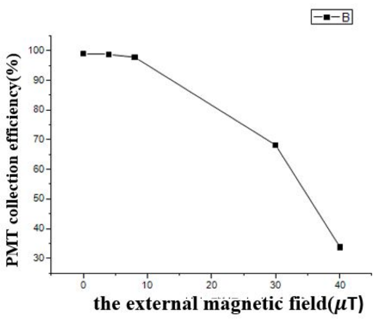

Figure 1. PMTs correction efficiency vs the external magnetic field.

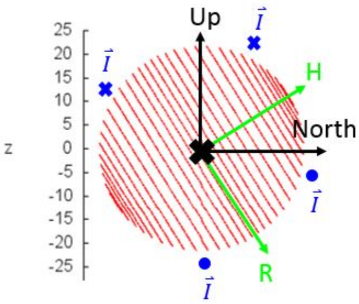

Figure 2. The 15 pairs of circular coils model with the EMF direction and it parameters.

2. Coils Design with Slightly Distorted Coils

At JUNO site, the horizontal component of the geomagnetic field is about 40 μT or 0.4 Gauss and vertical component is about 24 μT or 0.24 Gauss. The inclination and declination angles of the EMF in Jiangmen are approximately 32° and -2.3°, respectively [6]. The JUNO Collaboration basically agree to install one set of circular coils according to JUNO conceptual design report [6]. The report shows that the model of 15 pairs of circular coils with the parameters in table 1 can generate quite uniform magnetic field inside the coils. Thus the shielding coils in this study are 15 pairs of circular coils aligned about 2° to the EMF as shown in figure 2, where the diameter of the biggest coils is 43.3 meters. In the work we further optimize the currents of the coils to get the minimum remanent magnetic field in PMTs region, and also consider the effect of possible distortion to the perfect coils. The magnetic induction created by a coil is evaluated by applying Gauss-Legendre formula [7] to the Biot-Savart law,

$$\begin{aligned}\vec{B} = \frac{\mu_0 I}{4\pi}\ [\ &\left(\int \frac{(z_p - z_q)dy_q - (y_p - y_q)dz_q}{|\vec{r}|^3}\right)\hat{i} + \left(\int \frac{(x_p - x_q)dz_q - (z_p - z_q)dx_q}{|\vec{r}|^3}\right)\hat{j} \\ &+ \left(\int \frac{(y_p - y_q)dx_q - (x_p - x_q)dy_q}{|\vec{r}|^3}\right)\hat{k}\ ]\end{aligned}, \quad (2)$$

with

$$\vec{r} = (x_p - x_q)\hat{i} + (y_p - y_q)\hat{j} + (z_p - z_q)\hat{k}. \tag{3}$$

where (x_q, y_q, z_q) are the coordinates of the coils and (x_p, y_p, z_p) the coordinates of the generated magnetic field, and I are the currents of the coils. The magnetic field residual intensity is defined as

$$RI = \frac{\sqrt{(B_x - EMF_x)^2 + (B_y - EMF_y)^2 + (B_z - EMF_z)^2}}{EMF}, \tag{4}$$

where EMF, EMF_x, EMF_y, and EMF_z are the resultant of EMF, 0.37988, -0.01505, and 0.23772 Gauss, respectively. The size parameters of the 15 pairs of circular coils and the interval between two neighbor coils (the relative distance from the origin to a center of each coil) are predetermined, as shown in table 1. The current of each coil is determined by minimizing the magnetic field residual intensity in Eq.(4), where about 16,000 points are chosen in the CD-PMT and Veto-PMT regions. The optimized currents are listed in the fourth column of table 1. The magnetic field residual intensity in case (b) on the CD-PMT region (the worst results on the CD-PMT region) is shown in figure 4, as spherical surface plots (top and side views). It is found from a figure 4 that the maximum residual intensity is in the regions near high current coils. In practice, small bumps on the circular coils are unavoidable. For instance, coils may have to be installed detoring supporting trusses. This paper compare the results of slightly distorted coils with the results of perfect coils. The possible small bump is separated into three cases as shown in figure 3. These small bumps are on the coils numbered as 5, 6, 7, and 8. We consider here four cases, that is, (1) outer half circle with radius 10 cm, (2) inner half circle with radius 20 cm, (3) perpendicular half circle with radius 30 cm, and (4) no distortion to coils. The residual intensities of CD-PMT and Veto-PMT of four cases are shown in the histogram plots of figure 5 and figure 6. These events in histogram plots are collected from the sampling points on the spherical surface of CD-PMT and Veto-PMT regions. The maximum residual intensity of the four cases on the CD-PMT region is about 5.26 % which is less than 10 % while The maximum residual intensity of the four cases on the Veto-PMT region is above 15 %. Because, The maximum residual intensity of the four cases on the Veto-PMT region is 21.74 %. Finally, the histogram plots reveals that the effect of possible distortions to the four coils is negligible.

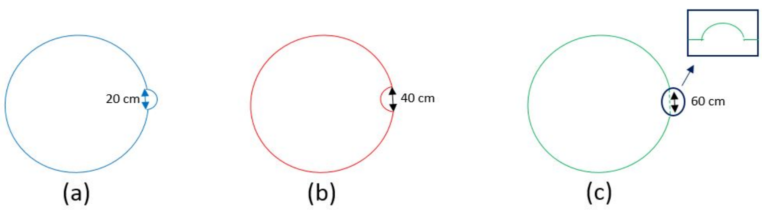

Figure 3. (a) Outer half circle with radius 10 cm. (OH10) (b) Inner half circle with radius 20 cm. (IH20) (c) Perpendicular half circle with radius 30 cm. (PH30)

3. Conclusion

In this work we study the shielding effect of models of 15 pair circular coils. It is found that a model of 15 circular coils has the achievement that the maximum residual intensity of the four cases is 5.26 % in the CD-PMT region and 21.74 % in the Veto-PMT region. The work also reveals that the effect of possible distortions to the coils and installation errors is negligible.

Acknowledgments

This work was supported by Suranaree University of Technology (SUT) and by SUT-OROG scholarship (contract no. 64/2559). The computing resource has been provided by the Center for Computer Services at SUT. The authors would like to acknowledge Thai-JUNO Consortium and IHEP EMF Shielding Group for instruction and comments.

Table 1. The parameters of circular coils.

Coil	R(m)	H(m)	I(A)	Coil	R(m)	H(m)	I(A)
1,30	2.59	±21.50	12.22	9,22	17.69	±12.49	122.20
2,29	4.62	±21.26	24.44	10,21	19.10	±10.20	122.20
3,28	6.74	±20.56	36.66	11,20	20.10	±8.05	109.98
4,27	8.53	±19.90	36.66	12,19	20.80	±6.01	109.98
5,26	10.39	±19.00	61.10	13,18	21.26	±4.06	97.76
6,25	12.40	±17.75	73.32	14,17	21.52	±2.38	85.54
7,24	14.30	±16.26	85.54	15,16	21.64	±0.79	85.54
8,23	16.02	±14.56	97.76	-	-	-	-

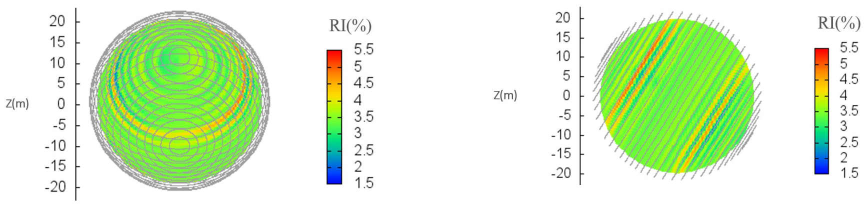

Figure 4. The left side and right side figures are front and side views of the spherical surface plot of RI in case (b) on the veto-PMT region, respectively.

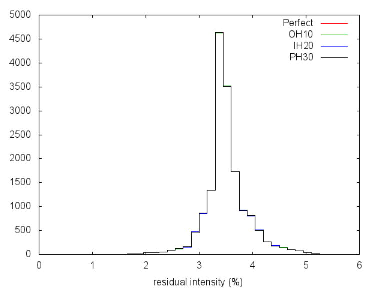

Figure 5. The RI histogram of four cases in CD-PMT region with 16111 events.

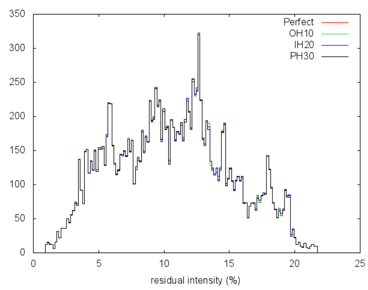

Figure 6. The RI histogram of four cases in Veto-PMT region with 16111 events.

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