PRAMANA — journal of physics

© Indian Academy of Sciences

Vol. 86, No. 2
February 2016
pp. 465–469

Muon response in ICAL detector at India-based neutrino observatory

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DOI: 10.1007/s12043-015-1165-7; ***e*Publication:** 13 January 2016

Abstract. The magnetized iron calorimeter (ICAL) detector, proposed to be built in the India-based neutrino observatory (INO) laboratory, aims to study atmospheric neutrino oscillations. A simulations study of response of muons to the ICAL detector is presented in the form of momentum reconstruction, angle resolution and reconstruction, and charge identification efficiency (CID).

Keywords. Iron calorimeter; reconstruction; resolution; charge identification efficiency.

PACS Nos 14.60.Ef; 14.60.Lm; 14.60.St

1. Introduction

India-based neutrino observatory (INO) [1] is the proposed underground facility, primarily designed to determine neutrino oscillation parameters precisely with atmospheric muon neutrinos, and the sign of Δm^2_{32} with matter effects, using a magnetized iron calorimeter (ICAL) detector. Oscillation sensitivity for neutrinos and antineutrinos is different in the presence of matter effects. Oscillation signatures and mass hierarchy are sensitive to the momentum P and zenith angle $\cos\theta$ of neutrinos. But, reconstruction of momentum and $\cos\theta$ further depends on the energy and direction of muons and hadrons [2] together produced in charge–current (CC) interactions of the neutrinos in the detector, and hence, the resolution and efficiency studies are crucial. Neutrinos further interact in ICAL to give μ^- and antineutrinos give μ^+. Hence, to identify them, charge identification (CID) is also important, and ICAL has good CID. The paper is organized as follows: In §2 we briefly discuss some relevant details of the detector. We discuss the results for the muon momentum resolution, angular resolution and efficiencies in different regions of ICAL in §3 and conclude in §4.

2. ICAL detector

Iron calorimeter (ICAL) has three identical modules of dimension 16 m × 16 m × 14.45 m, with 151 layers of 5.6 cm thick magnetized iron plates interleaved by resistive plate chambers (RPCs) [3], which are the active detector elements. In the detector, coil slots and support structures are the dead spaces that affect the muon reconstruction (discussed in the next subsection). Also, the magnetic field is non-uniform everywhere, and so the quality of reconstruction depends on the region where the event is located. The magnetic field lines in a single iron plate in the central module are shown in figure 1. In the figure, the thin white vertical lines represent the coil slots through which copper coils pass and have the field that is generated by passing a current through them. The length and direction of arrows denote the magnitude and direction of the magnetic field. The 'central region' [5] within the coil slots has the uniform (B_y) and highest magnetic field, while in the 'side region' (outside the coil slots in the x-direction) it is about 15% smaller and in the opposite direction. The region labelled with 'peripheral region' (outside the central region in the y-direction) has changing magnetic field in both direction and magnitude. Therefore, the peripheral and side regions will be affected by edge effects.

2.1 *Track reconstruction*

Charged particles traversing a single RPC leave hits in that layer. The coordinates of hits are then determined from the strip information for both x and y and the layer number information for the z-direction. Clusters of these hits in different layers form tracks. Muons are reconstructed with GEANT4-based INO–ICAL code [5] using a Kalman filter algorithm, that returns both the magnitude and direction of the muon momentum by fitting these tracks, whereas direction of the curvature gives the charge of the muon.

3. Muon reconstruction

In each region of ICAL, 10,000 events are generated with the muon vertex in the central region, in the peripheral region (with small and large (both x and y components non-zero) magnetic fields respectively) and in the side region, as highlighted in figure 1.

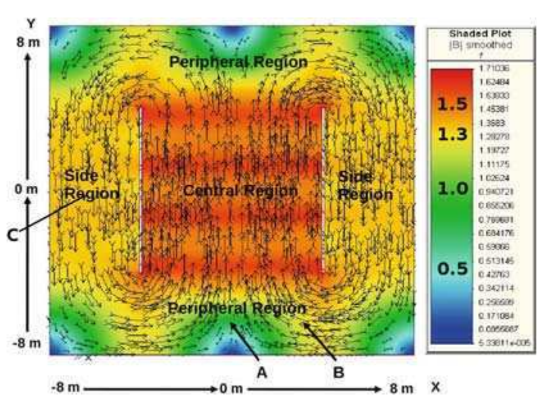

Figure 1. Magnetic field map as generated by the MAGNET6 [4] software. Here, A ($x = 0$, $y = -650$, $z = 0$) cm, B ($x = 300$, $y = -650$, $z = 0$) cm, C ($x = -2270$, $y = 0$, $z = 0$) cm are actually located in the left-most module.

3.1 *Central, side and peripheral regions*

Muons are generated in the peripheral region of the vertex $(x, y, z) = (0, -600, 0)$ cm with a small smearing $\pm(2420, 200, 720)$ cm, with fixed input momenta $P_{\rm in}$ (1–15 GeV/c) and $\cos\theta$ (0.35−0.85), as mentioned in figure 2. Muons with different ϕ (azimuthal angle) ($\phi = 0$ corresponds to the x-direction) have different detector responses due to the presence of the magnetic field besides support structures, etc. The muon sample is divided into four sets: Set I: $\phi < \pi/4$, Set II: $\pi/4 \leq \phi < 3\pi/4$, Set III: $-3\pi/4 \leq \phi - \pi/4$ and Set IV: $\phi \geq 3\pi/4$. Tracks fitted with $\chi^2/\text{dof} < 10$ are chosen for the analysis. Similar studies were done in central [5] and side regions with the vertex information taken according to the regions described in figure 1.

The reconstructed momentum distribution is fitted separately in these regions with Landau convoluted Gauss functions for $E < 2$ GeV and Gauss function for $E > 2$ GeV, and then its mean and σ are determined. The momentum resolution (R) is: $R = (\sigma)/P_{\rm in}$, and its error is: $(\delta R/R)^2 = (\delta\sigma/\sigma)^2$. Figure 2 shows momentum and $\cos\theta$ resolution in the peripheral region as a function of input momentum $P_{\rm in}$ for different values of $\cos\theta$, and in the ϕ averaged bin. Among all, the central region resolutions [5] are better because of the higher magnetic field. Also, the momentum resolution improves with the increase of energy as the number of hits increases, but worsens at higher energy because particles leave the detector at higher energy (partially contained events). The angular resolution of muons is good, and better than a degree for $P_{\rm in} > 4$ GeV in all the regions.

Efficiency studies have also been performed. The reconstruction efficiency is defined as the ratio of the number of reconstructed events $n_{\rm rec}$ (irrespective of charge) to the total number of events, $N_{\rm total}$. We have

$$\epsilon_{\rm rec} = \frac{n_{\rm rec}}{N_{\rm total}}, \tag{1}$$

$$\delta\epsilon_{\rm rec} = \sqrt{r(1-r)/N_{\rm total}}, \tag{2}$$

where

$$r = \frac{n_{\rm rec}}{N_{\rm total}}.$$

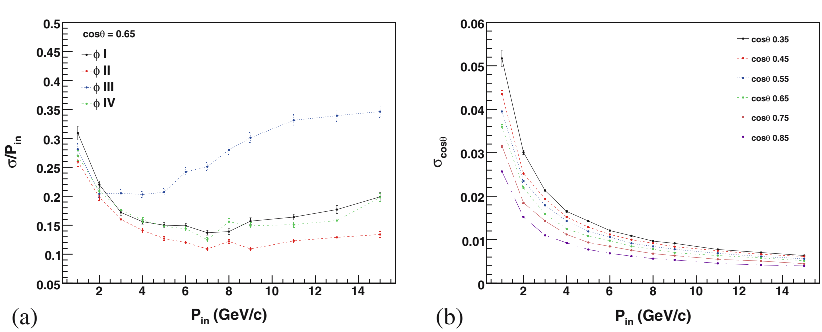

Figure 2. (**a**) Momentum resolution and (**b**) $\cos\theta$ resolution in the peripheral region as a function of input momentum $P_{\rm in}$ for different values of $\cos\theta$, in the ϕ averaged bin. Note that y-axes are different for the two plots.

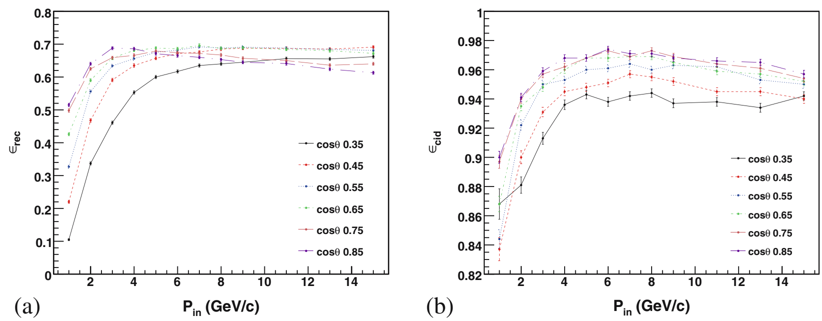

Figure 3. (**a**) Reconstruction and (**b**) CID efficiency of peripheral region as a function of input momentum P_{in} for different values of $\cos\theta$, in the averaged ϕ bin. Note that y-axes are different for the two plots.

Relative charge identification efficiency (CID) is defined as the ratio of the number of events with correct charge identification, n_{CID}, to the total number of reconstructed events n_{rec}, i.e.,

$$\epsilon_{\text{CID}} = \frac{n_{\text{CID}}}{n_{\text{rec}}}, \tag{3}$$

where δn_{CID} and δn_{rec} are interdependent so that the error in the ratio given by eq. (3) is calculated as $\sqrt{r(1-r)/n_{\text{rec}}}$, where $r = n_{\text{CID}}/n_{\text{rec}}$. Figure 3 shows reconstruction and CID efficiency in the peripheral region in the averaged ϕ bin. The reconstruction efficiency increases for all angles and energies, because the number of hits increases as the particle crosses more number of layers. But CID efficiency is relatively poor at lower energies, and as the energy increases CID efficiency also improves. Similar results were obtained for side region also, and it has slightly better reconstruction efficiency than peripheral region, whereas central region [5] gives the best efficiency. The CID efficiency is good and similar in all the regions.

4. Conclusions

The ICAL simulations indicate that the detector has a good response to muons. Also, it determines whether the particle is upward-going or downward-coming. The momentum resolution is about 15–24% in the peripheral and side regions, whereas central region [5] has the best resolution of about 9–14%. The angular resolution is better than a degree for energies greater than 4 GeV, for all the regions. The ICAL has good charge identification (CID) of about 97% in all the regions and reconstruction efficiency is about 60–70% in the peripheral region, whereas central region has 80% efficiency.

Acknowledgements

Work on central region is done in collaboration with A Chatterjee, T Thakore, K K Meghna, R Gandhi, N K Mondal and N Sinha. Work on the side and peripheral regions is done in collaboration with K K Meghna and N Sinha. The authors thank G Majumder, A Redij and all the simulation coordinators for their comments and suggestions. The authors also thank INO Collaboration for the help and support. R Kanishka acknowledges UGC/DAE/DST (Govt. of India) for financial support.

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