# Improvements on the Iron Calorimeter Magnet design for INO

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## Introduction

The design of the ICAL magnet is similar to that in the MONOLITH proposal [1]. Initial studies have been carried out to find the slot configuration which gives more piecewise uniformity of magnetic induction (|B|) in iron and the effect of tiling with different gaps between successive tiles of the ICAL magnet on its strength [2]. This contribution presents some investigations, using finite element simulations of the ICAL magnet, aimed at finding the optimal slot length and its positions (through which pass the copper coils energizing ICAL) in order to optimize the area of the magnet for which $|B| \geq 1$Tesla (T) and reduce its variation in iron.

## ICAL Magnet Geometry

The 50 k-ton iron calorimetric (ICAL) magnet consists of three modules each weighing ~17 k-ton and having about 150 layers of low carbon steel. The details of ICAL magnet are given in INO Report [3] and Ref. [2].

## Simulation results

The simulation has been carried out using the finite element method based commercial software Magnet 6.26 from Infolytica, Canada. A single iron plate with continuous slots (giving more piecewise uniformity in |B|, [2]) has been used to study magnetic induction variation and increase the area of the ICAL magnet for which $|B| \geq 1$T.

The studies have been carried out by increasing number of coils and varying the length ($L_S$) of the slots in the ICAL magnet. The width of the side section ($W_S$) as shown in Fig.1 has been reduced to minimize |B| variation in iron. To simulate the ICAL magnet, coils of length 8m and height 0.456m have been used. Four coils carrying total current of 60 kA-turn have been used to magnetize the low carbon steel. Continuous slots ($L_S$ = 8m) are placed ~ 4m away from each side of the layer (standard configuration) so that magnetic flux is distributed uniformly in iron. Figure 2 shows the magnetic induction

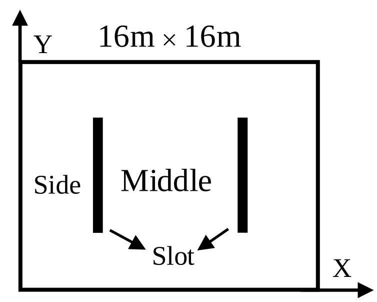


**Fig. 1** Schematic of ICAL magnet

($B_x$, $B_y$, $B_z$) variation with X in iron (XY plane) at (a) Y = 3m, (b) Y = 8m. At Y = 3m, $B_x$ has varying field behavior while $B_y$ is constant over specific region but at Y = 8m $B_x$ is almost zero and $B_y$ is constant. The $B_z$ component is almost zero at both places.

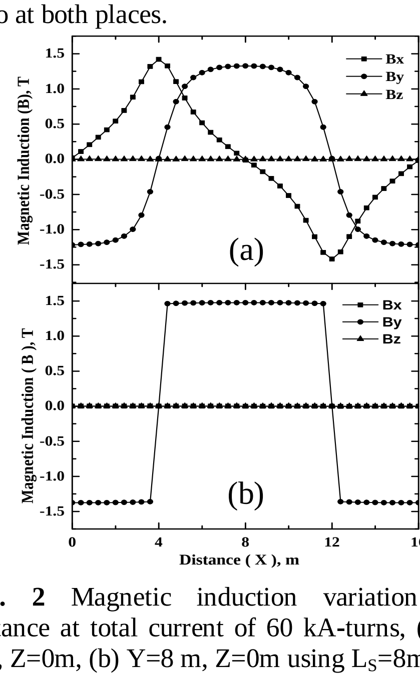


**Fig. 2** Magnetic induction variation with distance at total current of 60 kA-turns, (a) Y= 3m, Z=0m, (b) Y=8 m, Z=0m using $L_S$=8m.

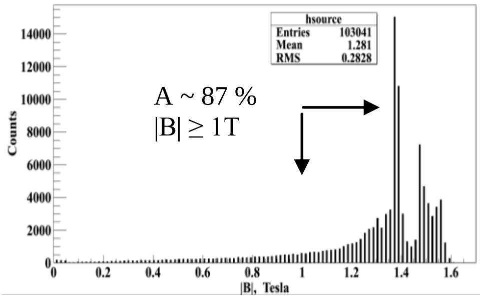


**Fig. 3** Distribution of |B| in area of 16 m × 16 m for standard configuration.

The limitation in above mentioned configuration is that only 86.9% of its full area |B| ≥ 1T as shown in Fig.3. At the same time, Δ|B|/|B| i.e. the difference in |B| between either sides of a slot is about 8.2%. To increase the area of the magnet (with |B| ≥ 1T) and reduce the variation in |B|, standard configuration having 10 coils as shown in Fig.4 has been used for simulation. At constant current (60kA-turns), it has been found that with increase in current in side coils and

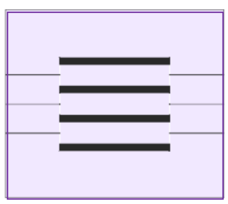

**Fig. 4** ICAL magnet with 10 coils (black color)

corresponding decrease in middle coils, |B| variation in iron at either side of the slot decreases. The minimum variation (~3%) is achieved for the case where each side and middle coils carry current of 3.5 and 9.75 kA respectively but the area over which |B|≥1T, decreased to ~84% from 87%.

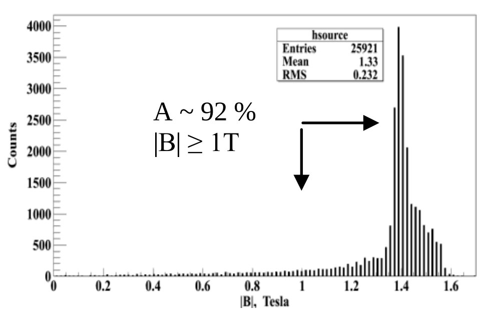


**Fig. 5** Distribution of |B| in area of 16 m × 16 m for nonstandard configuration.

**Table -1**

| Configurations | Area(%), for \|B\|≥1T | <\|B\|> T | Δ\|B\|/\|B\| % |
|---|---|---|---|
| $L_S$=8m, $W_S$=3.95m | 86.9 | 1.28 | 8.2 |
| $L_S$=8m, $W_S$=3.5m | 86.8 | 1.29 | 0.62 |
| $L_S$=7m,$W_S$=4.5m | 64.0 | 1.07 | 25.9 |
| $L_S$=9m, $W_S$=3.95m | 88.3 | 1.28 | 7.4 |
| $L_S$=10m,$W_S$=3.95m | 89.6 | 1.28 | 7.4 |
| $L_S$=10m,$W_S$=3.5m | 91.6 | 1.33 | -1.0 |

In addition, studies have been carried out to improve the area magnet for which |B|≥1T and minimize the variation in |B|, using various non-standard configurations. From the Table-1 the best configuration emerges for $L_S$ = 10m, $W_S$ = 3.5m. However, |B| in middle section reduces as compared to standard configuration. The statistical distribution of |B| for this case is shown in Fig.5.

Similar studies have also been carried out by putting 32 tiles each one having a size of 4m × 2m of nominal thickness 56 mm with gap of 2mm between successive tiles to construct the full ICAL magnet that suits practical construction of the same [2]. The iron layer consists of slots with, Ls=8m and 11.2m containing 4 and 6 groups of coils respectively. At total current of 80kA-turns, the iron layer having slots of $L_S$ = 11.2m gives the area for |B| ≥ 1T as ~88 % with Δ|B|/|B| as ~ 4%.

## Summary

For the smallest variation in |B| and largest fractional area where |B|≥1T, the non-standard configuration having $L_S$=10m and $W_S$=3.5m appears to be optimal. The ICAL magnet having tiling configuration with $L_S$=11.2m has |B| ≥ 1T over ~88% of the area with Δ|B|/|B| as small as ~ 4%.

## References

[1] N. Y. Agafonova et al., MONOLITH: A massive magnetized iron detector for neutrino oscillation studies, LNGS-P26-2000

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[3] INO Project Report, INO/2006/01, June 2006. (http://www.imsc.res.in/ino).