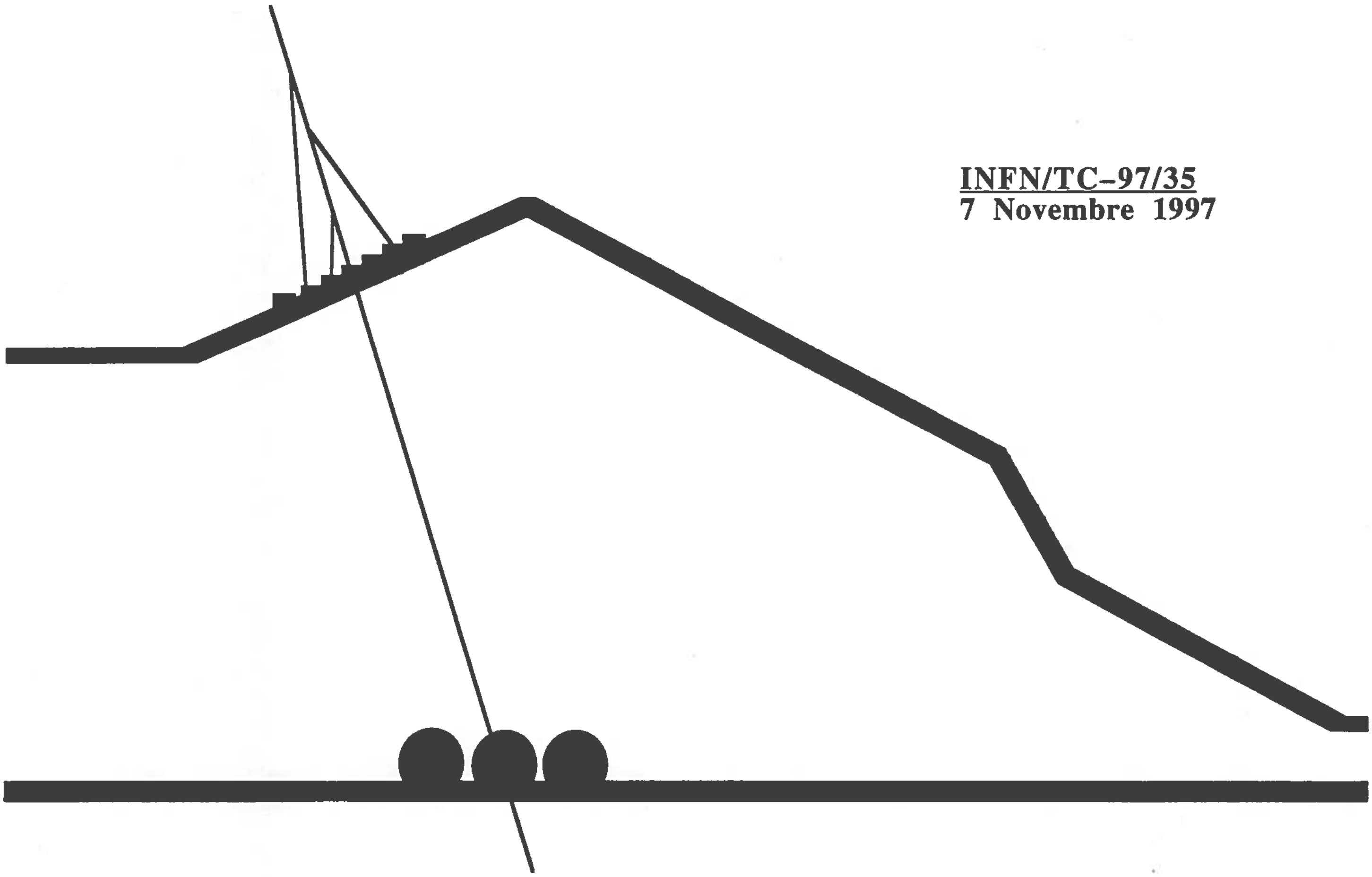
INFN/TC-97/35
7 Novembre 1997



The Earth's Magnetic Field Compensation in the Borexino Phototubes Facility

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INFN – Laboratori Nazionali del Gran Sasso

Published by ***SIS–Pubblicazioni***
dei Laboratori Nazionali di Frascati

INFN – Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

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Abstract

In this paper a multi-coils system to compensate the Earth's magnetic field in a volume of 2mx2mx0.6m is presented. This system will be used in the phototubes test facility of the Borexino solar neutrinos experiment. The residual magnetic field after the compensation is measured to be at a level of 1.5μT for the north-south component of the Earth's magnetic field, 5μT for the vertical one and 8.5μT for the east-west one (not compensated).

1 Introduction

In the present paper a system of square coils to compensate the Earth's magnetic field (EMF) within the dark room of the Borexino [1] phototubes test facility is presented. Many square coil systems have been studied in the literature for the production of homogeneus magnetic field [2, 3, 4].
Magnetic fields even as weak as the EMF affect photomultiplier (PMT) performances and it turns out that tubes with linear focusing dynodes (as the Borexino 8" Thorn EMI 9351) are most sensitive to magnetic influence when the field is parallel to dynodes [5, 7]; moreover a 5% degradation of the PMT parameters (*transit time spread, peak-to-valley ratio, single photoelectron response*) is observed when the magnetic field along one reference axis is 10μT[1] [5, 7]. In the location of the Laboratori Nazionali del Gran Sasso (LNGS) the static EMF is about 35μT in the vertical direction, 25μT along the north-south direction and 8μT along the east-west direction. A daily change around 0.05μT is observed. Therefore a compensation of the static EMF north-south and vertical components is needed, while it is worthless to take into account the time changing component of the field. Since Borexino will run with 2200 PMTs a large compensated volume is useful in order to test in the same time as many PMTs as possible. Our choise was to design a system of square coils, easy to realize and characterized by a good access and an excellent ratio of uniform field to coils volume [3]. It is the pourpose of this paper to describe the measurements carried out in the dark room and the coil system designed.

[1] 1μT=10mGauss

2 The coil system

A coil system was studied to compensate the EMF. The system has to be placed in the dark room and it has to provide a compensation at a level of about 5 μT for the vertical and the north-south components of EMF [5, 7] in a volume big enough to locate about 60 PMTs (2mx2mx0.3m). The east-west component is much less important than the other two [5, 7]. Since the dark room is in iron-reinforced concrete building (5mx5mx3m) with two sandwich-walls, we expect spatial variations of the EMF over the useful volume. Therefore the EMF was mapped inside the dark room as described below.

In order to avoid any interference with the compensation system, the support structure for the phototubes has been manufactured with wood.

The compensation has been accomplished independently on the three components of the EMF. A multiple system of rectangular and square coils was studied. A four square coils system (FCMS) as designed by R. Merritt and coworkers was taken into account [3] to compensate the crucial north-south component. To analyze the magnetic field due to the FCMS a master formula for a general rectangular coil was written as described in appendix. To study the field uniformity(U) inside the coils system the field deviations with respect to the field at the center were studied by the formula:

$$U = \frac{|\vec{H}(x,y,z) - \vec{H}(0,0,0)|}{|\vec{H}(0,0,0)|} \quad (1).$$

A FORTRAN program was written to implement the calculations. The field at the center, $\vec{H}(0,0,0)$, was chosen to be equal to the measured field at the dark room center. The coils currents were calculated on the base of the $\vec{H}(0,0,0)$ value.

A FCMS with 2.84m side lenght was chosen. A system consisting of two square coils was studied to compensate the vertical component of the EMF. We studied a system of 2.98m coils side length with spacing equal to 1.4m as the Helmholtz separation, which is 1.62m [8], is not the best solution to achieve the maximum uniformity over a large volume with two square coils [9].

The finite cross section of the coils for a 1mm copper wire with 0.1mm bonding layer (ρ=0.02176 Ω/m) was taken into account as described in [9]. Nevertheless corrections are found to be negligible because of the huge coils size.

To identify the useful volume we studied the 10% variation of the magnetic field around a plane through the center of the coils system. All field components were considered. Concerning the FCMS our calculations show that the magnetic field around the central plane is mainly due to the component along the coils simmetry axis. Therefore a huge coils system can generate a magnetic field uniform over a large surface. In fig. 1 we show the whole coils system with the reference frame, in fig. 2 we show the 10% variations in the plane xz, while in fig. 3 we show the same variations in a plane 0.3m over the xz one. It turns out that for a good uniformity of the EMF a useful volume of 2mx2mx0.6m around the xz plane could be identified. In table 1 all the parameters for the coils system are reported.

3 The EMF measurements

In order to check and evaluate the best way to compensate the EMF in the *photomultiplier test dark room* we proceeded systematically to measure the field *in loco*. After having established a conventional System of Reference as shown in figure 4 we defined a reasonably large rectangular area inside to be tested.

To performe the measurements we used the analog Magnetoscop 1.068 (by Foerster) which is an intensity and gradient magnetic field misurator operating with Foerster probe. It has two scales (30 and 50 divisions) allowing a sensibility from 100 μT to 0.03 μT while the intrinsic precision is ±2.5%

of maximum scale value in all ranges. Summing quadratically the read error and the scale error the global uncertainty is less than 3% (table 2).

The measurements were performed on a grided wood table at 146cm height (about half room height) for each of the previously defined axis (a grid with 20cm wide steps was painted on the table). All data are plotted in figure 5

After having analized the data looking at the EMF disuniformity we decided to place the actual PMTs support table in a suitable area (far away from the entrance door and the cables patch-panel) at a distance of 180cm from y-axis and 120cm from x-axis(figure 4). The EMF *excursion* measured for each component is shown in figure 6: on the base of these data a nonuniformity with respect to the field at the center less than 1.7μT for the north-south component and less than 5μT for the vertical one is expected.

To account for the PMTs dimensions we performed a second set of measurements at 128.5cm height. The EMF variations on this second plane were verified to be smaller with respect to the central plane: the east-west and north-south components were found to be ~1μT smaller, instead the vertical component was found to be ~0.5μT smaller (see *figure 7*).

Since a big bridge-crane is located close to the dark room, we performed further measurements to take into account the effect of its movements. Moving the bridge-crane the EMF was measured very carefully in three positions on the table zone: changes smaller than 22% for B_x, 8% for B_z and 10% for B_y have been found (table 3).

Four coils system

	inner coils	outer coils
side lenght	2.84m	2.84m
spacing to the center	0.363m	1.434m
current	0.34 A/turn	0.80 A/turn
number of turns	47	47

Two coils system

side lenght	2.98m
spacing	1.4m
current	1.11A/turn
number of turns	50

Table 1: *coils parameters*

Error at different scales				
scale	scale error	read error	total	% error
100μT	2.5μT	1μT	2.7μT	2.7%
30μT	0.75μT	0.5μT	0.90μT	3.0%
10μT	0.25μT	0.1μT	0.27μT	2.7%
3μT	0.075μT	0.05μT	0.09μT	3.0%
1μT	0.025μT	0.01μT	0.027μT	2.7%
0.3μT	0.0075μT	0.005μT	0.009μT	3.0%
0.1μT	0.0025μT	0.001μT	0.0027μT	2.7%
0.03μT	0.00075μT	0.0005μT	0.0009μT	3.0%

Table 2: *Errors of the magnetoscop at the available scales*

Effect of the crane moving		
left position		
BX (during meas.)	BX min	BX max
$7\mu T$	$5.5\mu T$	$7\mu T$
BY (during meas.)	BYmin	BYmax
$-23\mu T$	$-25\mu T$	$-23\mu T$
BZ (during meas.)	BZmin	BZmax
$-36\mu T$	$-38\mu T$	$-36\mu T$
Effect of the crane moving		
left position		
BX (during meas.)	BX min	BX max
$7\mu T$	$5.5\mu T$	$7\mu T$
BY (during meas.)	BYmin	BYmax
$-23\mu T$	$-25\mu T$	$-23\mu T$
BZ (during meas.)	BZmin	BZmax
$-36\mu T$	$-38\mu T$	$-36\mu T$
center position		
BX (during meas.)	BX min	BX max
$7.6\mu T$	$6.0\mu T$	$7.6\mu T$
BY (during meas.)	BY min	BY max
$-24\mu T$	$-25.5\mu T$	$-23\mu T$
BZ (during meas.)	BZ min	BZ max
$-34\mu T$	$-37\mu T$	$-34\mu T$
right position		
BX (during meas.)	BX min	BX max
$6.65\mu T$	$5.2\mu T$	$6.65\mu T$
BY (during meas.)	BY min	BY max
$-22.9\mu T$	$-24.5\mu T$	$-21.9\mu T$
BZ (during meas.)	BZ min	BZ max
$-30\mu T$	$-33\mu T$	$-30\mu T$

Table 3: ***Results of the measurement on crane effect***

4 The EMF after the compensation

A 6 coils system as described in the previous sections has been built in the dark room; the power supply is garanteed by one single and by one double Elind generators which are able to give a stabilized current up to 10^{-2} A. Each coil consists of a wood structure with three layers of copper-wire turns. A set of measurements was performed to check if the coils system works properly. These measurements were carried out through the following steps:

- Merrit system outer coils measurement(figure 8);
- Merrit system inner coils measurement(figure 9) ;
- whole Merrit coils system measurement(figure 10);
- horizontal coils system measurement(figure 11);
- 6 coils system measurement (see conclusion);

All the data are *well inside* the experimental errors.

5 Conclusion

In order to know the residual magnetic field felt by the phototubes under test with all coils working, we mapped the magnetic field components on the table hole by hole. These measurements are only *indicative* because in such a weak field the changes in the field strenght over the photocathode area (8" diameter) are large.

On the table (actually, for stability reason, they are four joint tables) there are 64 holes through which the photomultiplier are inserted and fixed; they have been numerated starting from the one in front of the entrance door but on the opposite side and then proceeding towards the door itself (8 columns X 8 raws). The measurements taken at the center of each hole are shown in figure 12: a gap is visible every 8 phototubes corresponding to the table edges. Consequently we can point out that the coils system developed compensates the EMF at the level of 1.5 μT for the north-south component (FCSM), 5 μT for the vertical component (non standard Helmholtz system for square coils) and 8.5 μT for the east-west component (not compensated). On the basis of these results we can conclude our PMTs parameters will have a degradation less than 5% working in the residual EMF [5, 7].

Furthermore changing properly the coils currents we can use our system to investigate the effect of the magnetic field on our PMTs permormaces and the shielding of the μ-metals foreseen for the Borexino detector. To fullfil this goal we suppose to upgrade the 6 coil system setting up other 2 rectangular coils in order to compensate the east-west EMF component.

Acknowledgment

We would like to thank Prof. U. Villante and Dr. M. De Lauretis from the University of L'Aquila, Dr. M. Laubenstein from the I.N.F.N. Laboratori Nazionali del G. Sasso for helpful discussions.

A Appendix: Rectangular coils equations

To figure out the magnetic field due to a rectangular thin-wire-coil, as shown in figure 13, in the absence of ferromagnetic materials we used the Biot-Savart law. First we calculated the field due to a finite lenght wire(segments 1,2,3,4 in figure 13); later we evaluated the field in a generic point (x,y,z) summing up all the contributions coming from each segment of the coil. The magnetic field components in ampere/m are:

$$H_{1x}(x,y,z) = \frac{i}{4\pi}\frac{z}{(d_1-x)^2+z^2}\left(\frac{d_2-y}{\sqrt{(d_1-x)^2+(d_2-y)^2+z^2}}+\frac{d_2+y}{\sqrt{(d_1-x)^2+(d_2+y)^2+z^2}}\right)$$

$$H_{2x}(x,y,z) = 0$$

$$H_{3x}(x,y,z) = -\frac{i}{4\pi}\frac{z}{(d_1+x)^2+z^2}\left(\frac{d_2-y}{\sqrt{(d_1+x)^2+(d_2-y)^2+z^2}}+\frac{d_2+y}{\sqrt{(d_1+x)^2+(d_2+y)^2+z^2}}\right)$$

$$H_{4x}(x,y,z) = 0$$

$$H_{1y}(x,y,z) = 0$$

$$H_{2y}(x,y,z) = \frac{i}{4\pi}\frac{z}{(d_2-y)^2+z^2}\left(\frac{d_1-x}{\sqrt{(d_1-x)^2+(d_2-y)^2+z^2}}+\frac{d_1+x}{\sqrt{(d_1+x)^2+(d_2-y)^2+z^2}}\right)$$

$$H_{3y}(x,y,z) = 0$$

$$H_{4y}(x,y,z) = -\frac{i}{4\pi}\frac{z}{(d_2+y)^2+z^2}\left(\frac{d_1-x}{\sqrt{(d_1-x)^2+(d_2+y)^2+z^2}}+\frac{d_1+x}{\sqrt{(d_1+x)^2+(d_2+y)^2+z^2}}\right)$$

$$H_{1z}(x,y,z) = \frac{i}{4\pi}\frac{d_1 - x}{(d_1 - x)^2 + z^2}\Big(\frac{d_2 - y}{\sqrt{(d_1 - x)^2 + (d_2 - y)^2 + z^2}} + \frac{d_2 + y}{\sqrt{(d_1 - x)^2 + (d_2 + y)^2 + z^2}}\Big)$$

$$H_{2z}(x,y,z) = \frac{i}{4\pi}\frac{d_2 - y}{(d_2 - y)^2 + z^2}\Big(\frac{d_1 - x}{\sqrt{(d_1 - x)^2 + (d_2 - y)^2 + z^2}} + \frac{d_1 + x}{\sqrt{(d_1 + x)^2 + (d_2 - y)^2 + z^2}}\Big)$$

$$H_{3z}(x,y,z) = \frac{i}{4\pi}\frac{d_1 + x}{(d_1 + x)^2 + z^2}\Big(\frac{d_2 - y}{\sqrt{(d_2 + x)^2 + (d_2 - y)^2 + z^2}} + \frac{d_2 + y}{\sqrt{(d_1 + x)^2 + (d_2 + y)^2 + z^2}}\Big)$$

$$H_{4z}(x,y,z) = \frac{i}{4\pi}\frac{d_2 + y}{(d_2 + y)^2 + z^2}\Big(\frac{d_1 - x}{\sqrt{(d_1 - x)^2 + (d_2 + y)^2 + z^2}} + \frac{d_1 + x}{\sqrt{(d_1 + x)^2 + (d_2 + y)^2 + z^2}}\Big)$$

where d_1 and d_2 are the half sides length of the rectangular coil in meter, while i is the coil current in unit of ampere.

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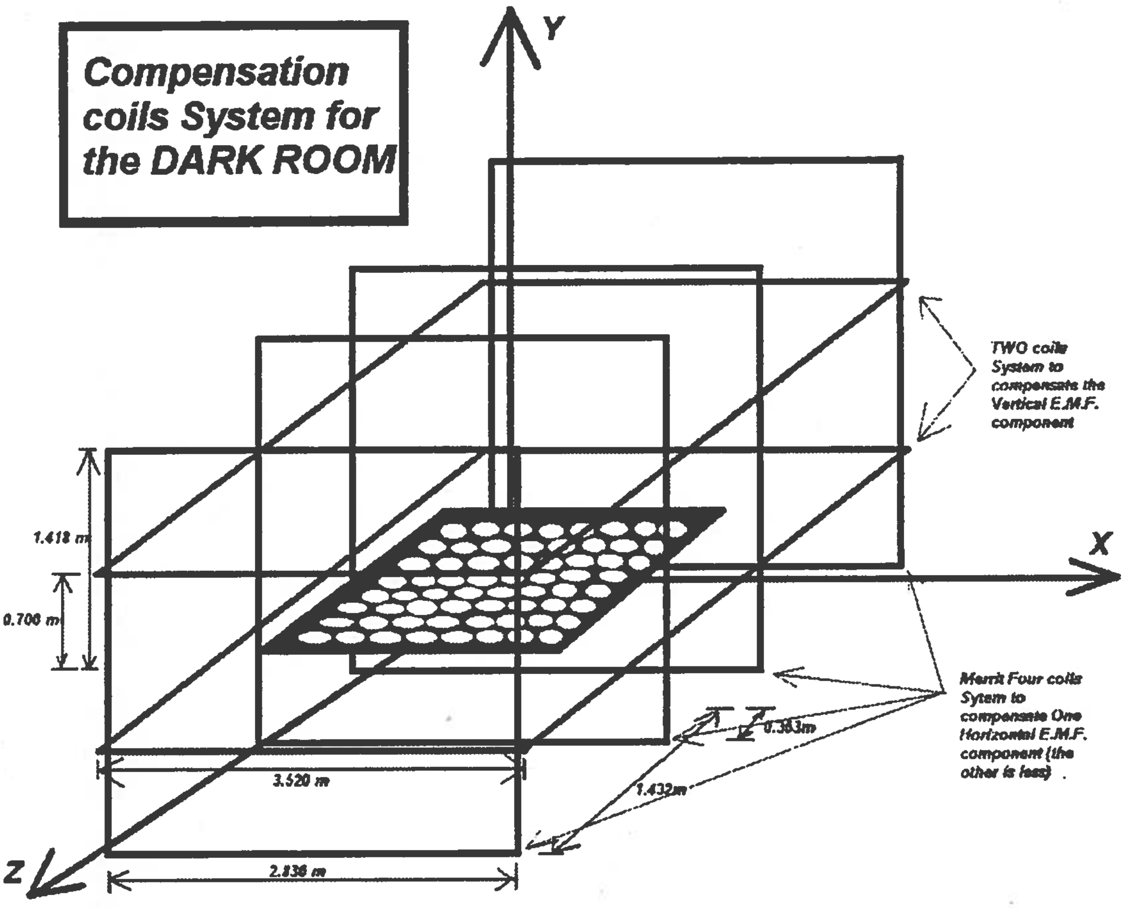

Figure 1: *Whole 6 coils system in the coils system reference frame*

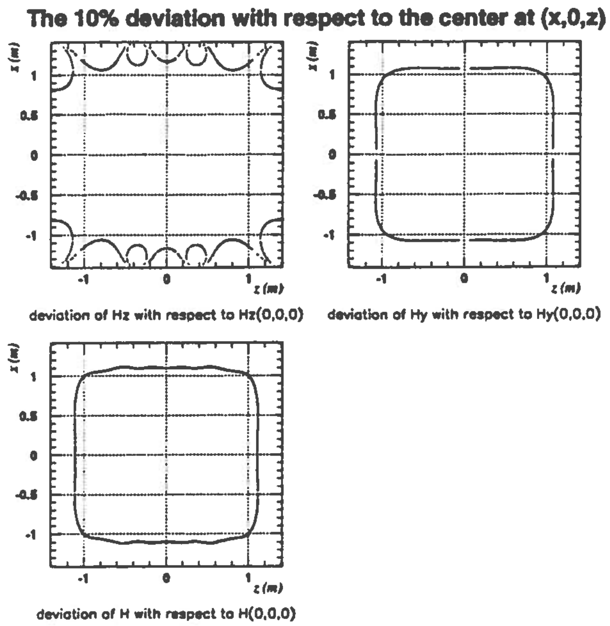

Figure 2: *The 10% deviation with respect to the center at the horizontal plane (x,0,z)*

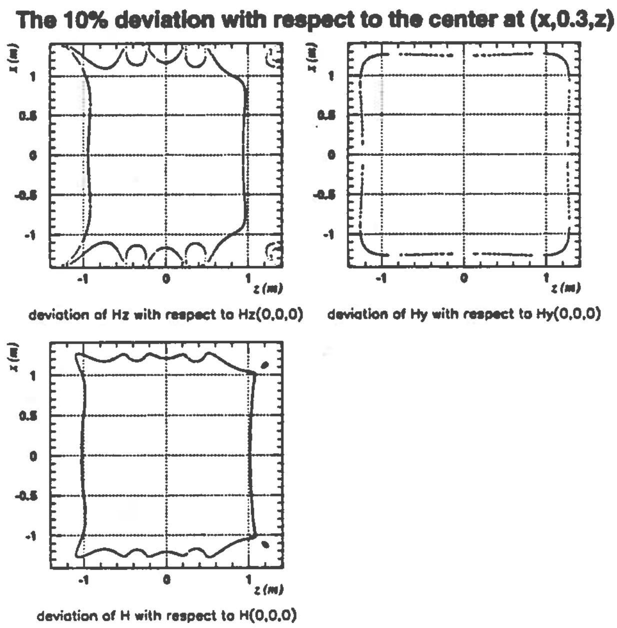

Figure 3: *The 10% deviation with respect to the center at the horizontal plane (x,0.3,z)*

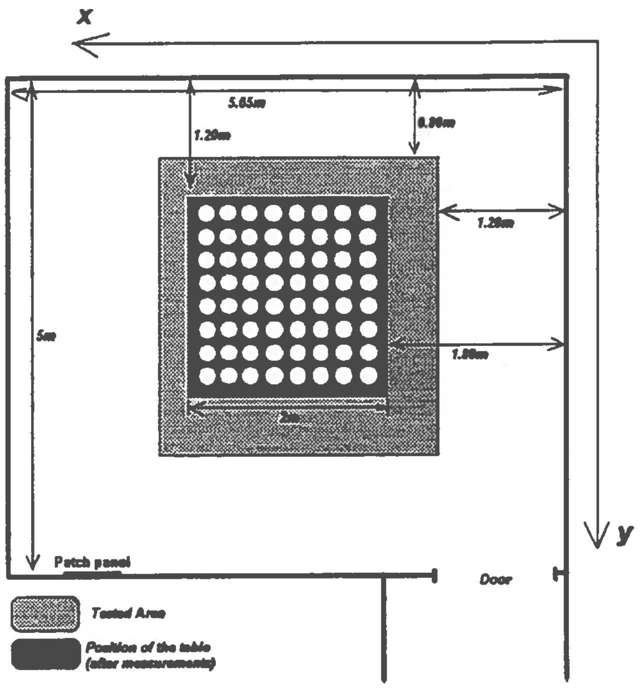

Figure 4: *Coordinate Map of the room with the room-reference-frame*

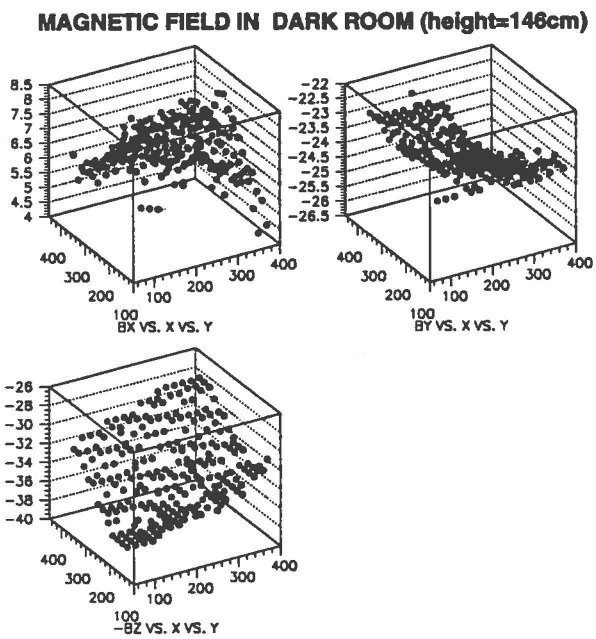

Figure 5: *Magnetic Field Components at height of 128.5cm projected on y axis (table region: 120cm≤y≤320cm) in the room reference frame*

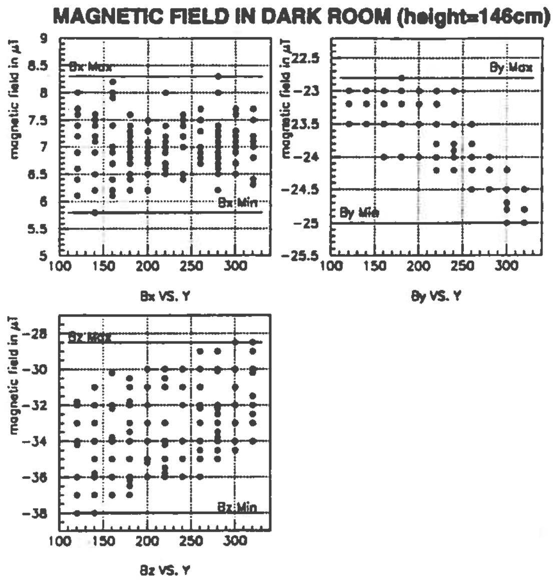

Figure 6: *Magnetic Field Components at height of 146cm projected on y axis (table region: 120cm≤y≤320cm) in the room reference frame*

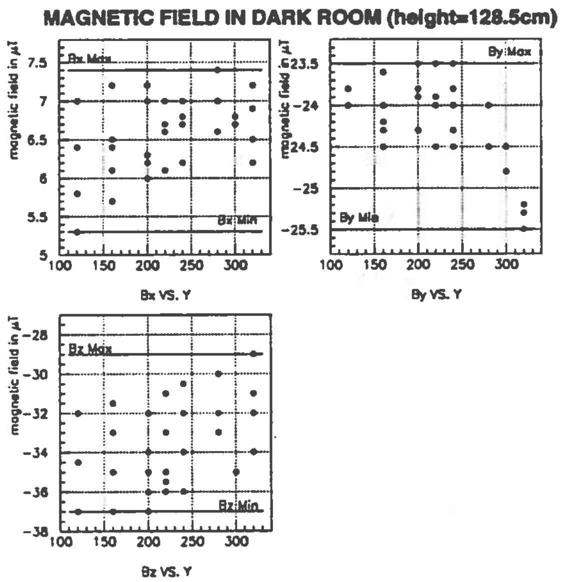

Figure 7: *Magnetic Field Components at height of 128.5cm projected on y axis (table region: 120cm≤y≤320cm)*

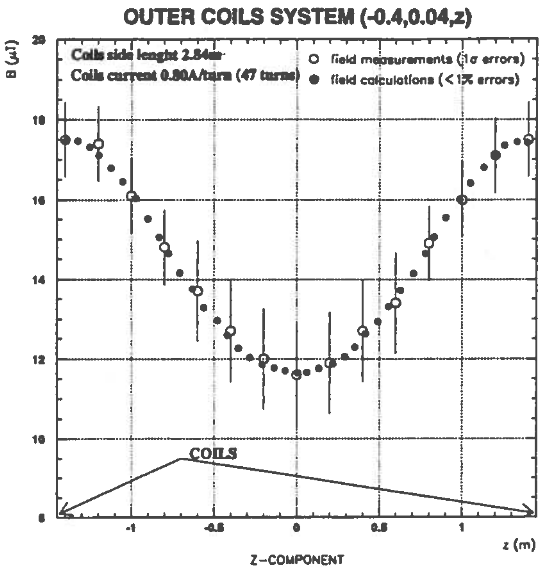

Figure 8: *The outer coils field measurements*

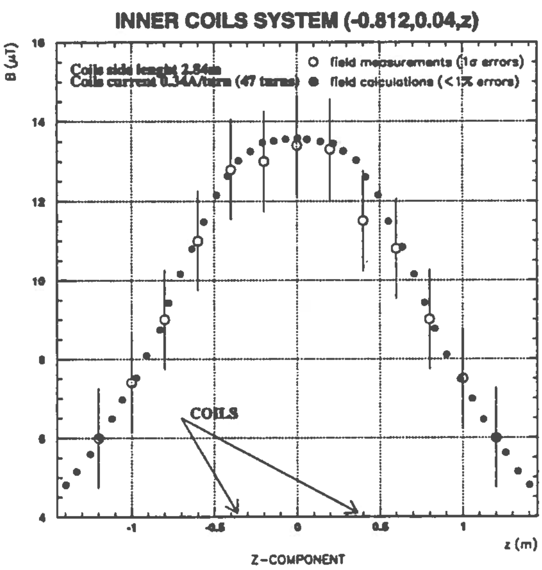

Figure 9: *The inner coils field measurements*

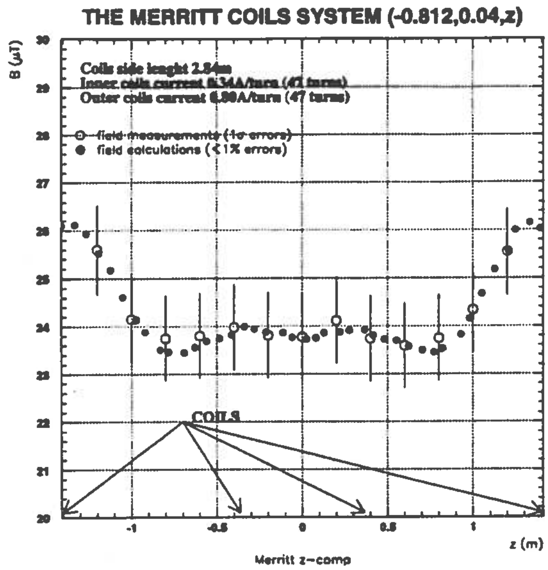

Figure 10: *The Merritt coils system field measurements*

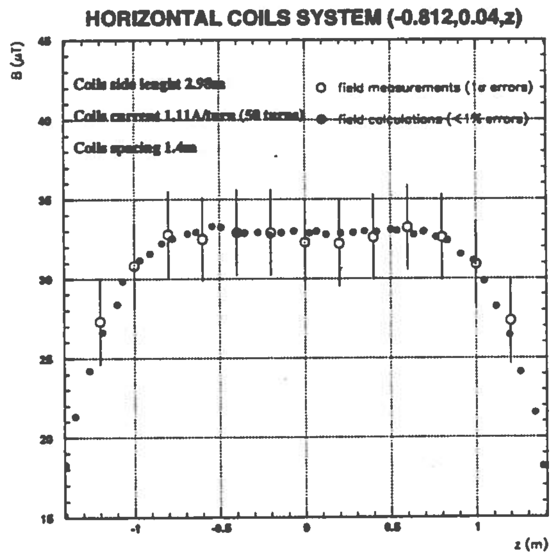

Figure 11: *The horizontal coils system field measurements*

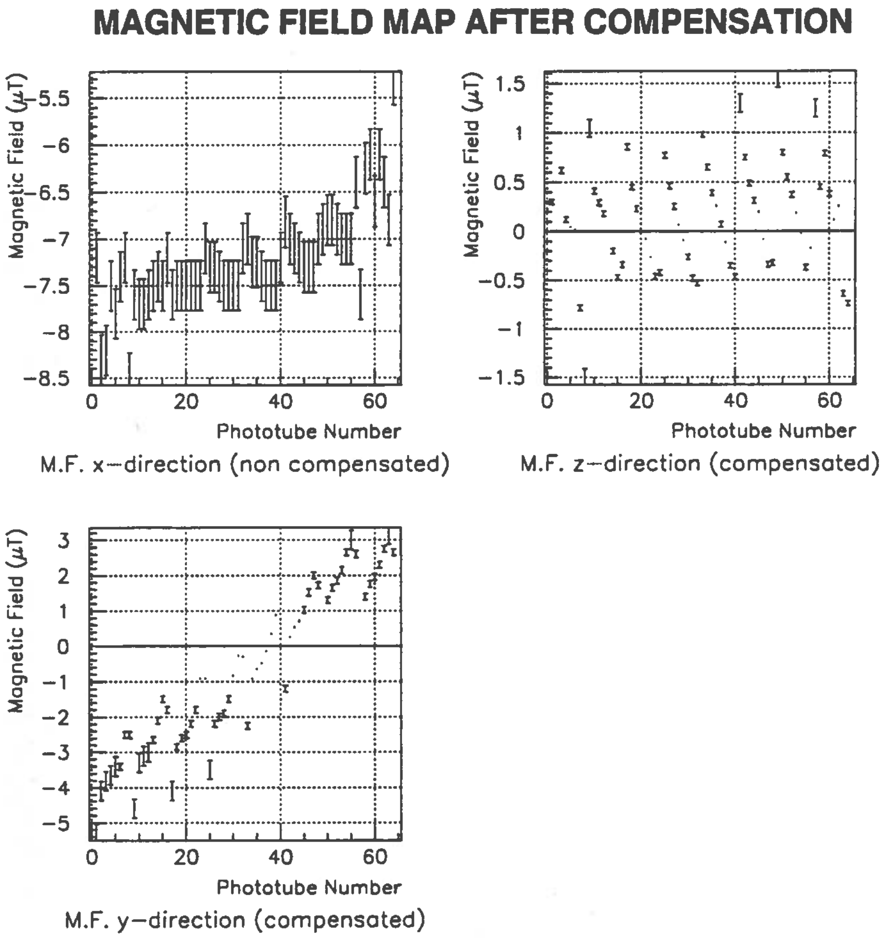

Figure 12: *The residual magnetic field felt in the center by each PMT (abscissa: number of phototube)*

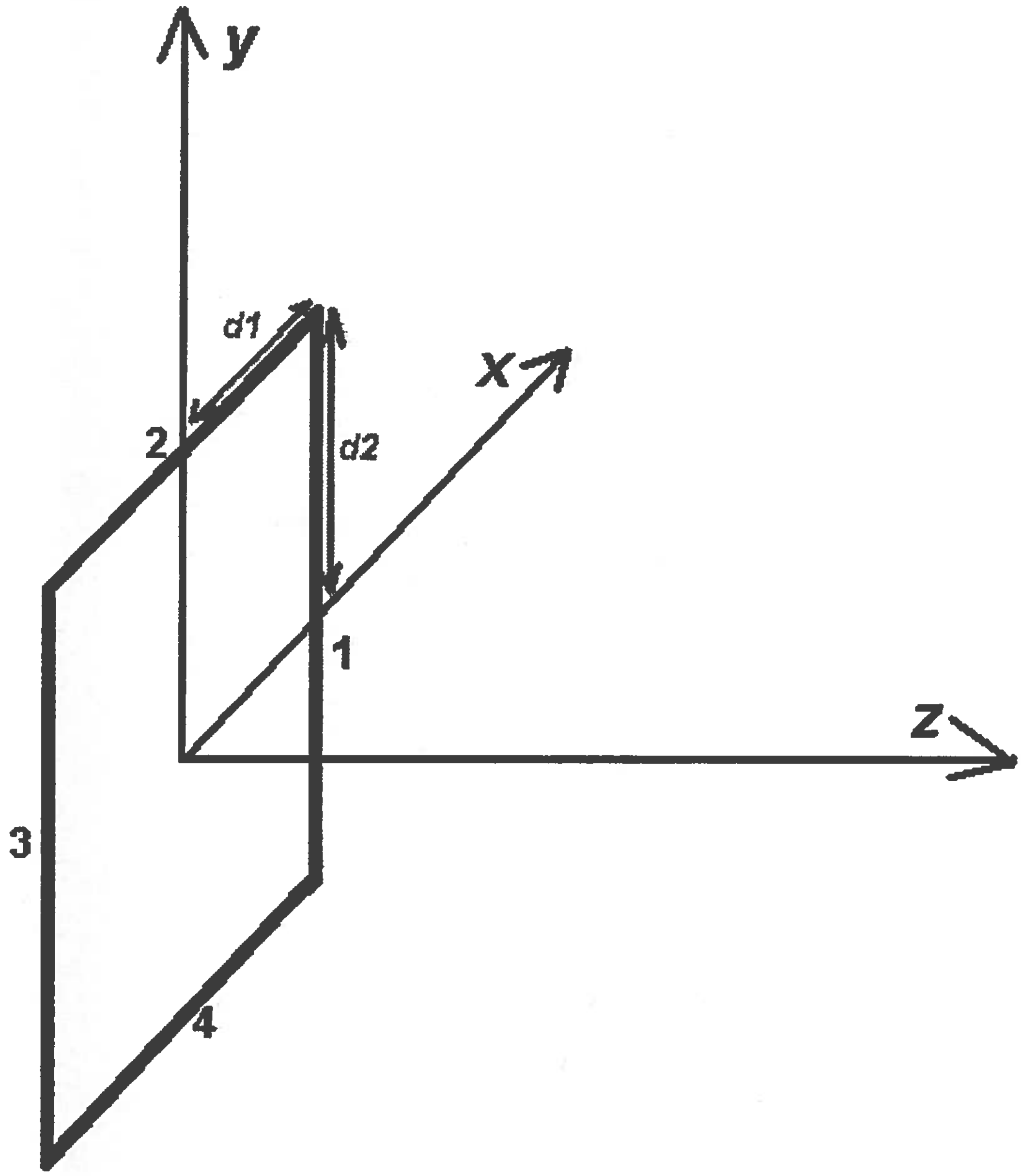

Figure 13: *The reference rectangular coil for magnetic field calculations*