Calibration of 3D magnetic sensors

Preliminary results

F.Bergsma CERN 1/10/2001

- Demand from experiments for device which measures B_x, B_y, B_z with ~ 10^{-4} precision @ 0.5-2.5 T

Difficult to construct conventional calibration device:

two axes with high precision encoders > $2 \pi 10^4$ points/rev

play < 10^{-4} rad

Cheap alternative:

- use 3 small orthogonal coils

rotate in constant homogeneous field

main problems:

integrator drift

smooth movement, no vibration

3D magnetic sensor

Prototype designed and build by NIKHEF Amsterdam for ATLAS detector at CERN-LHC p-p collider.
J.T. van Es (design), J. Kuijt et al.

Features:

Small card containing all analog electronics => electronics in same field as hall probes

Hall sensor 3 x KSY44 Siemens
100 mV @ 2.5 T

Hall current 230 μ A => no heat

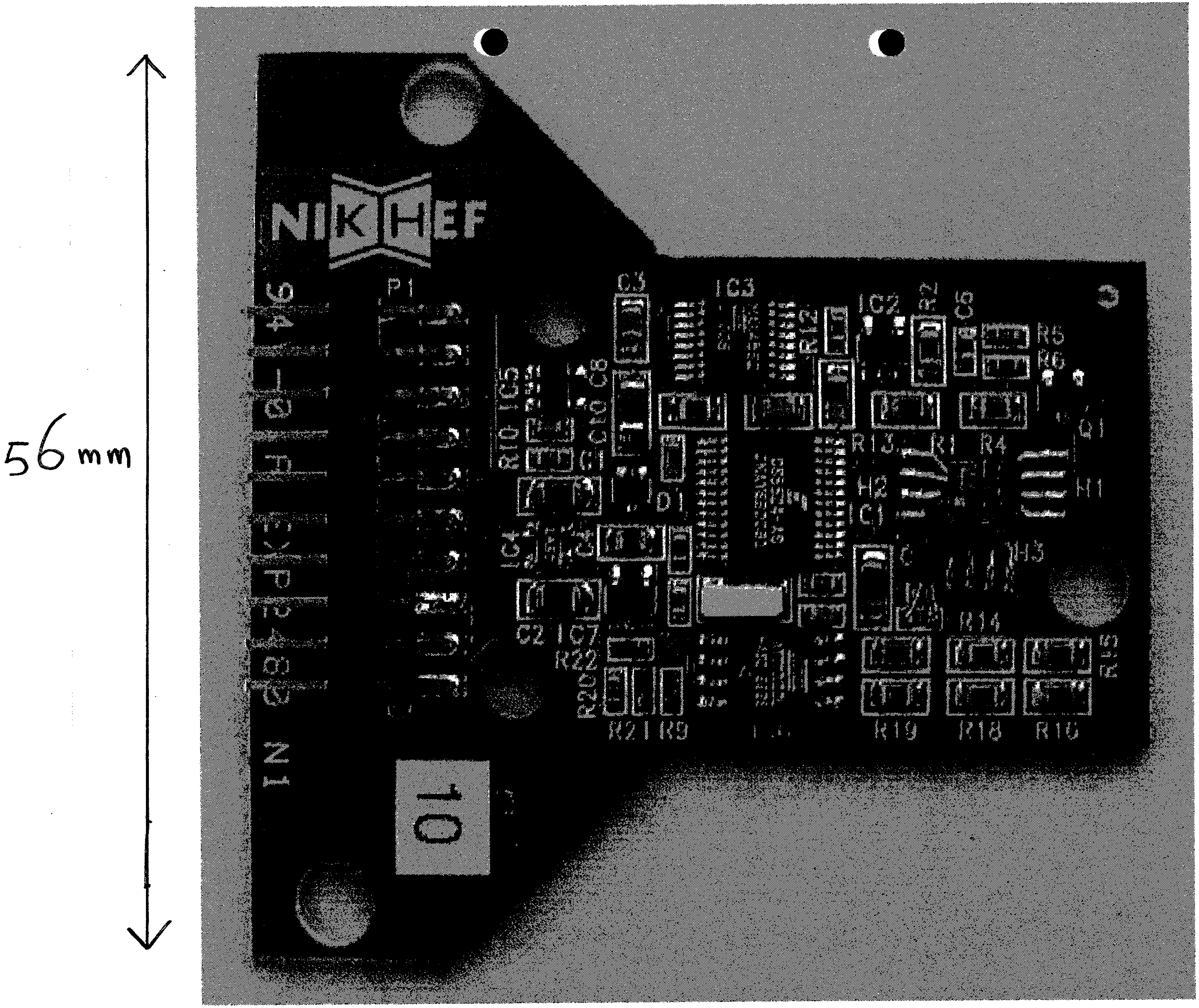
ADC: 24-bits 4th order Δ-Σ modulator with chopper stabilized instrumentation amplifier

Calibration circuit for sensitivity

Thermistor + ref. on card, no thermostat

Addressable: ~~255~~ 127 cards on one serial bus

Precision holes to fit on calibrator's and experiment's dowel pins


56 mm
NIKHEF
P1
IC3
IC2
C3
C5
C8
C10
IC5
R10
R12
R2
R5
R6
R13
R1
R4
Q1
H2
H1
H3
IC1
D1
IC4
C2
IC7
R22
R20
R21
R9
R14
R15
R19
R18
R16
N1
10

Calibrator

3 orthogonal coils, each with own ADC

ADC: 20 bit 4th order Δ-Σ modulator, same type as on sensor-card

Continuous rotation on 2 axes , 1 rev/min on main axes, no stop at conversion, 15 conversions/sec

Temperature stability ± 0.02 deg. C . Peltier element + controller

Corrections made for coil surface, non-orthogonality, offset, time constant, start position

Coils: χ^2 on $\sqrt{(B_x^2+B_y^2+B_z^2)}$ ~ 10^{-5} , |B| normalized to one

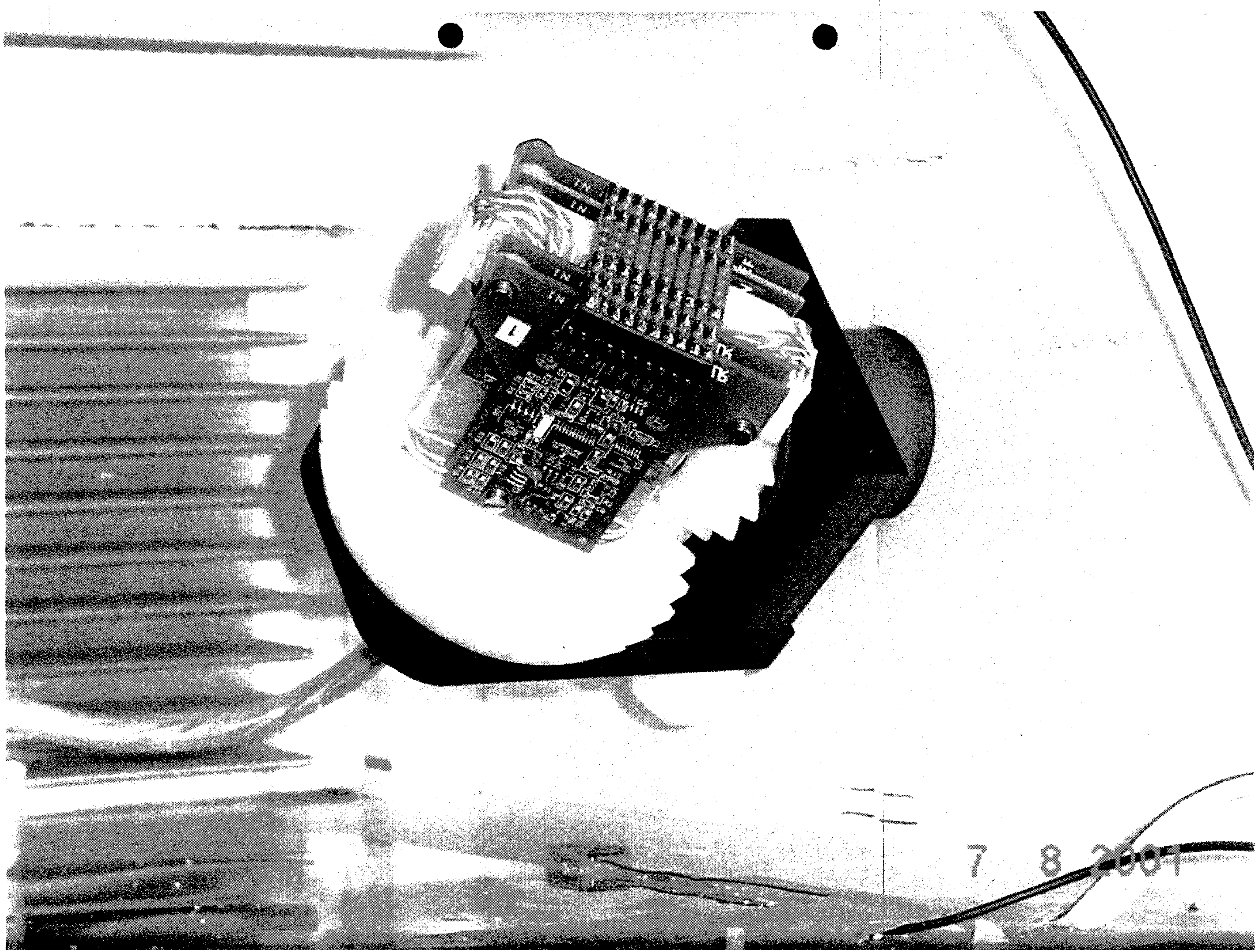
Hall voltage decomposed in spherical harmonics

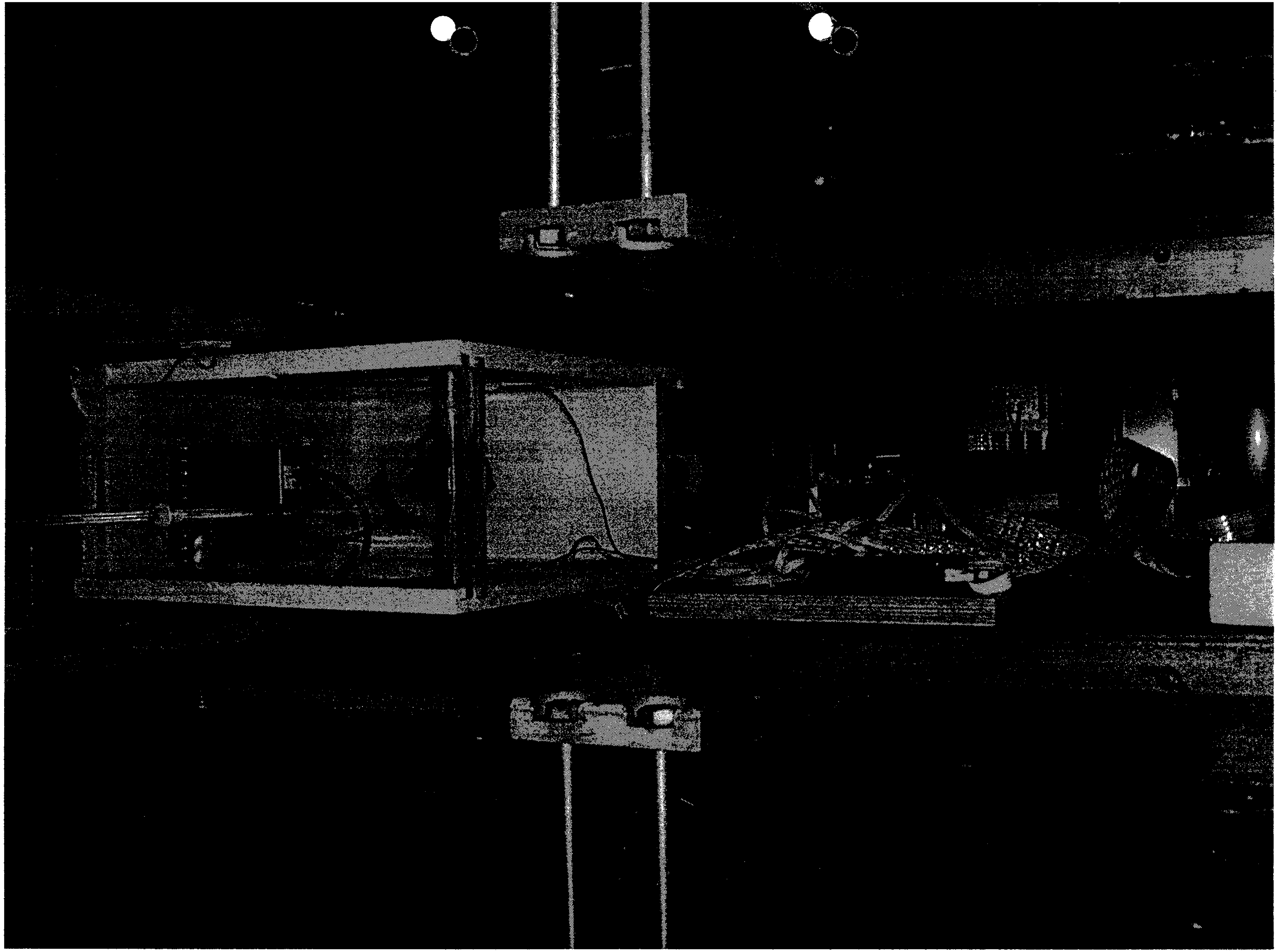
χ^2 on residu ~ $2.10^{-5} * |B|$ @ 5th order Y_{lm}, 4 turns

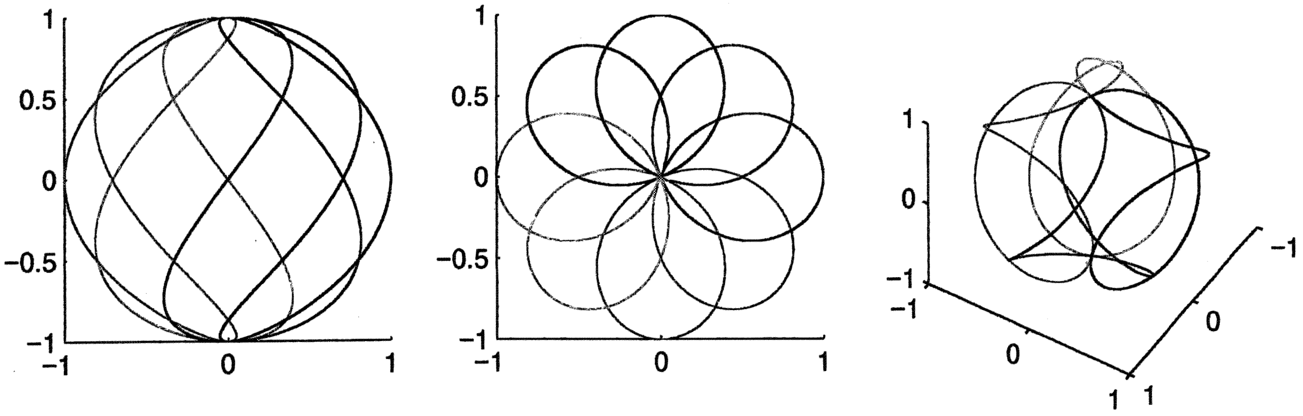
Place for 4 sensor cards, fixed with dowel pins

Support plate with coils and sensor cards easily removable from rest of device

Cable winds by main axis, but unwinds by secondary axis: at end of calibration cable has made only one turn

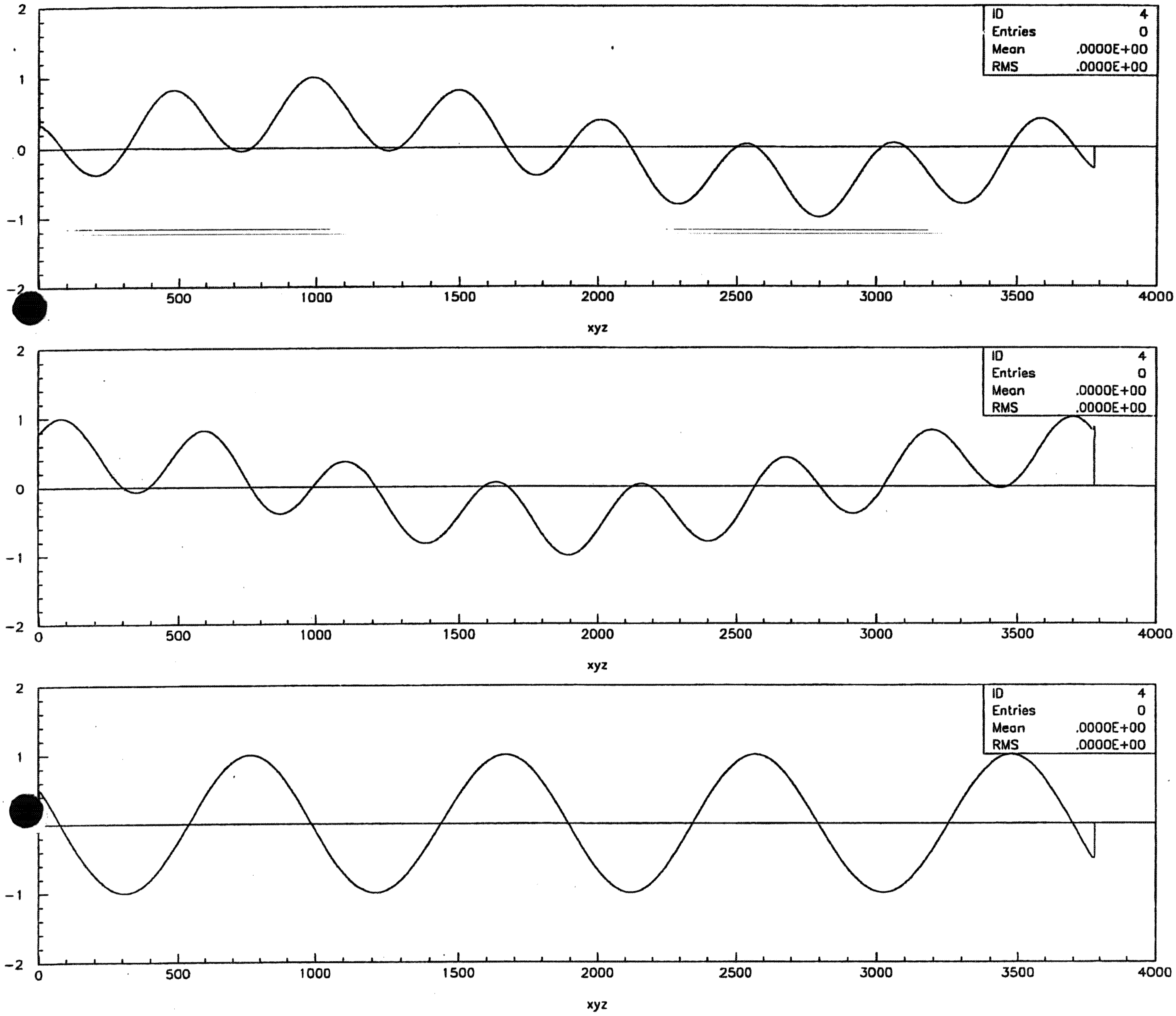

1
7 8 2001





Coverage off unit sphere

B from coils

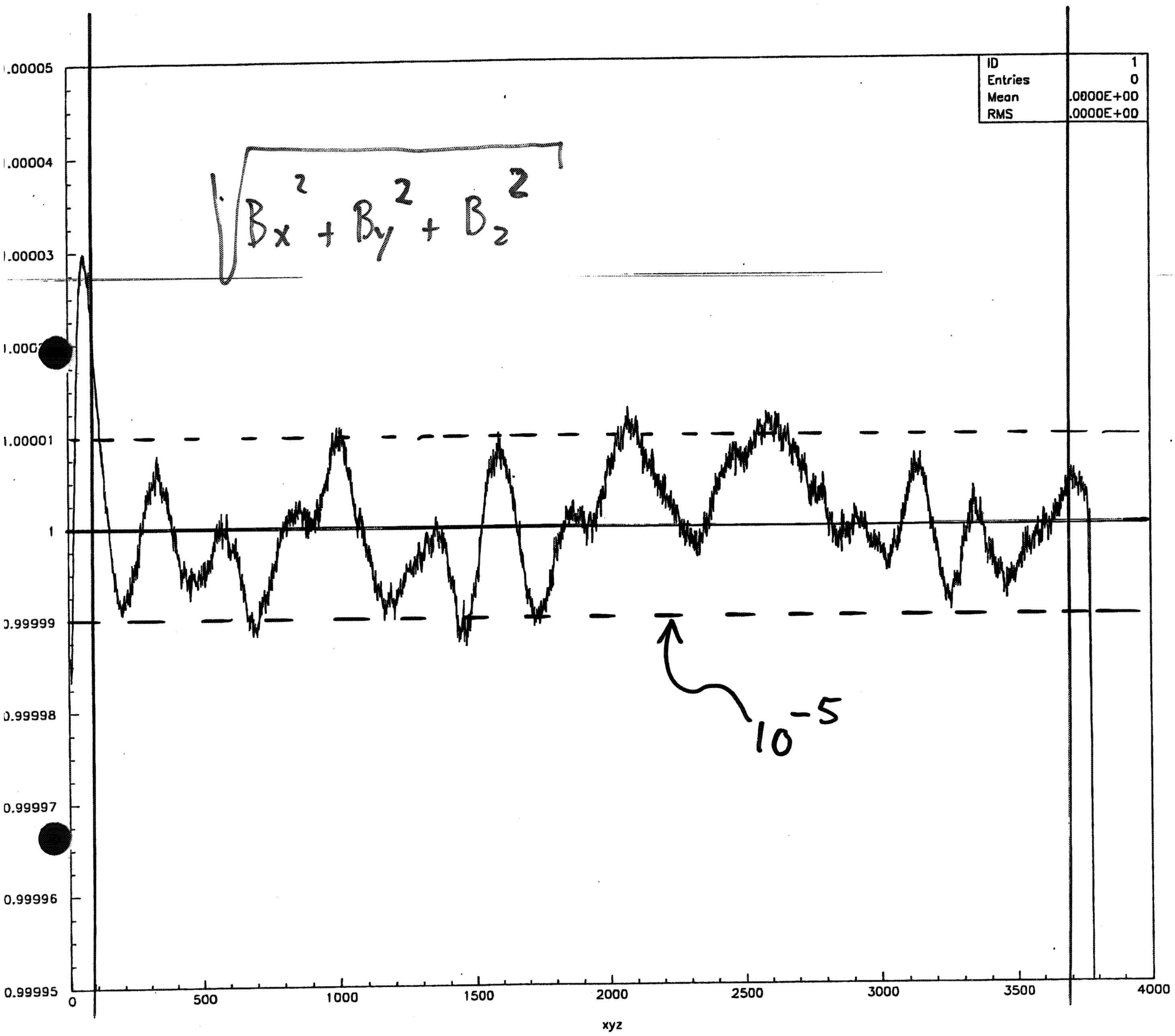


→

time

1.5T 22°C

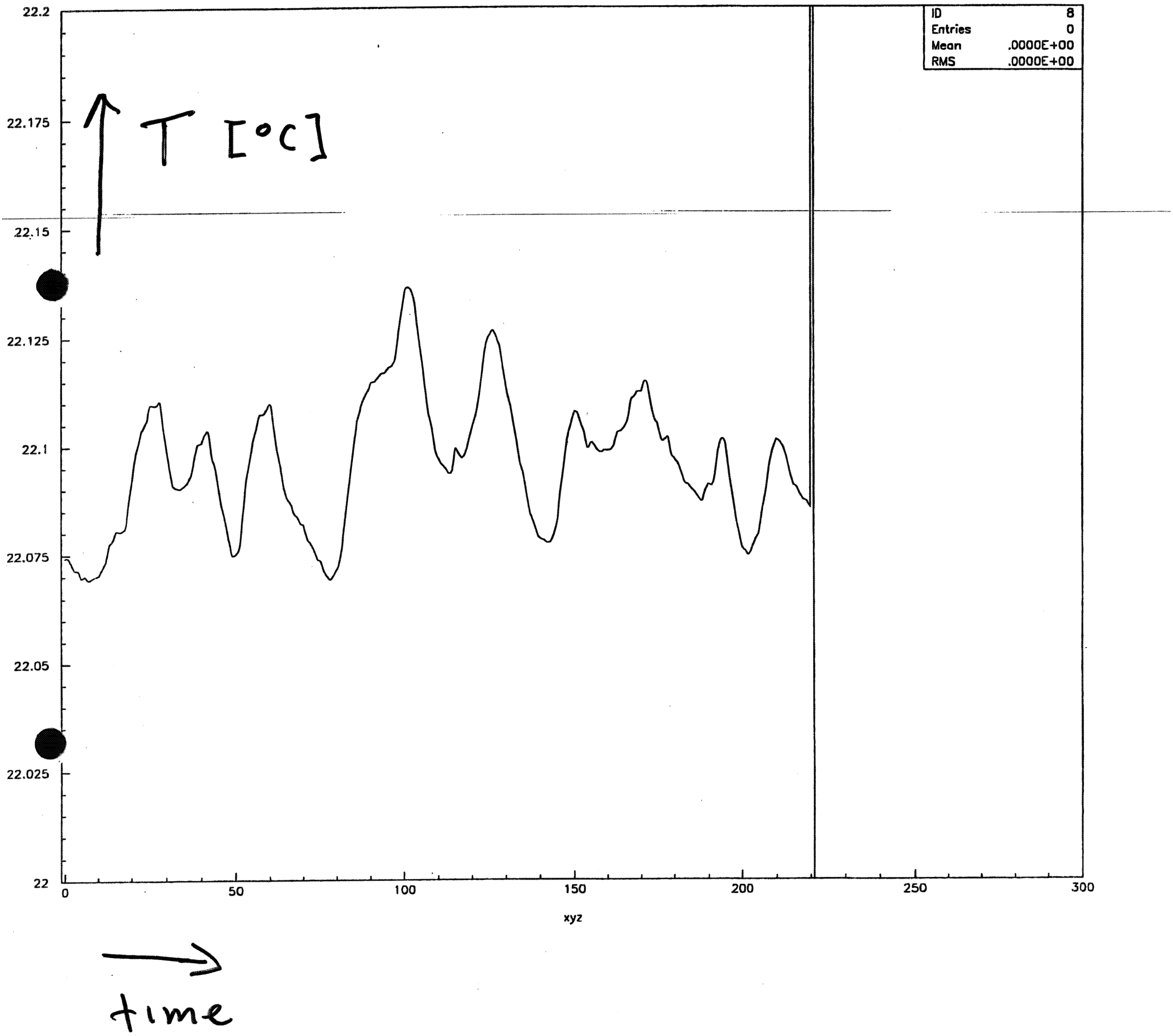
Coil fit



$\longrightarrow$

time

Residue


ID 8
Entries 0
Mean .0000E+00
RMS .0000E+00
22.2
22.175
22.15
22.125
22.1
22.075
22.05
22.025
22
0
50
100
150
200
250
300
xyz
T [°C]
time

2

Spherical harmonics $\mathbf{Y}_{\mathbf{lm}}(\theta,\phi)$

$$Y_{lm}(\theta,\phi) = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}}P_l^m(\cos\theta)e^{im\phi}$$

$$\int_0^{2\pi} d\phi \int_0^{\pi} \sin\theta\, d\theta\, Y_{l'm'}^*(\theta,\phi)Y_{lm}(\theta,\phi) = \delta_{l'l}\delta_{m'm}$$

$$P_l^m(x) = (-1)^m(1-x^2)^{m/2}\frac{d^m}{dx^m}P_l(x) \qquad P_l(x) = \frac{1}{2^l l!}\frac{d^l}{dx^l}(x^2-1)^l$$

$l = 0$ $\quad Y_{00} = \frac{1}{\sqrt{4\pi}}$ ← offset

$l = 1$

$$\begin{cases} Y_{11} = -\sqrt{\frac{3}{8\pi}}\sin\theta e^{i\phi} \\ Y_{10} = \sqrt{\frac{3}{4\pi}}\cos\theta \end{cases}$$

← main term (at Y_{10})

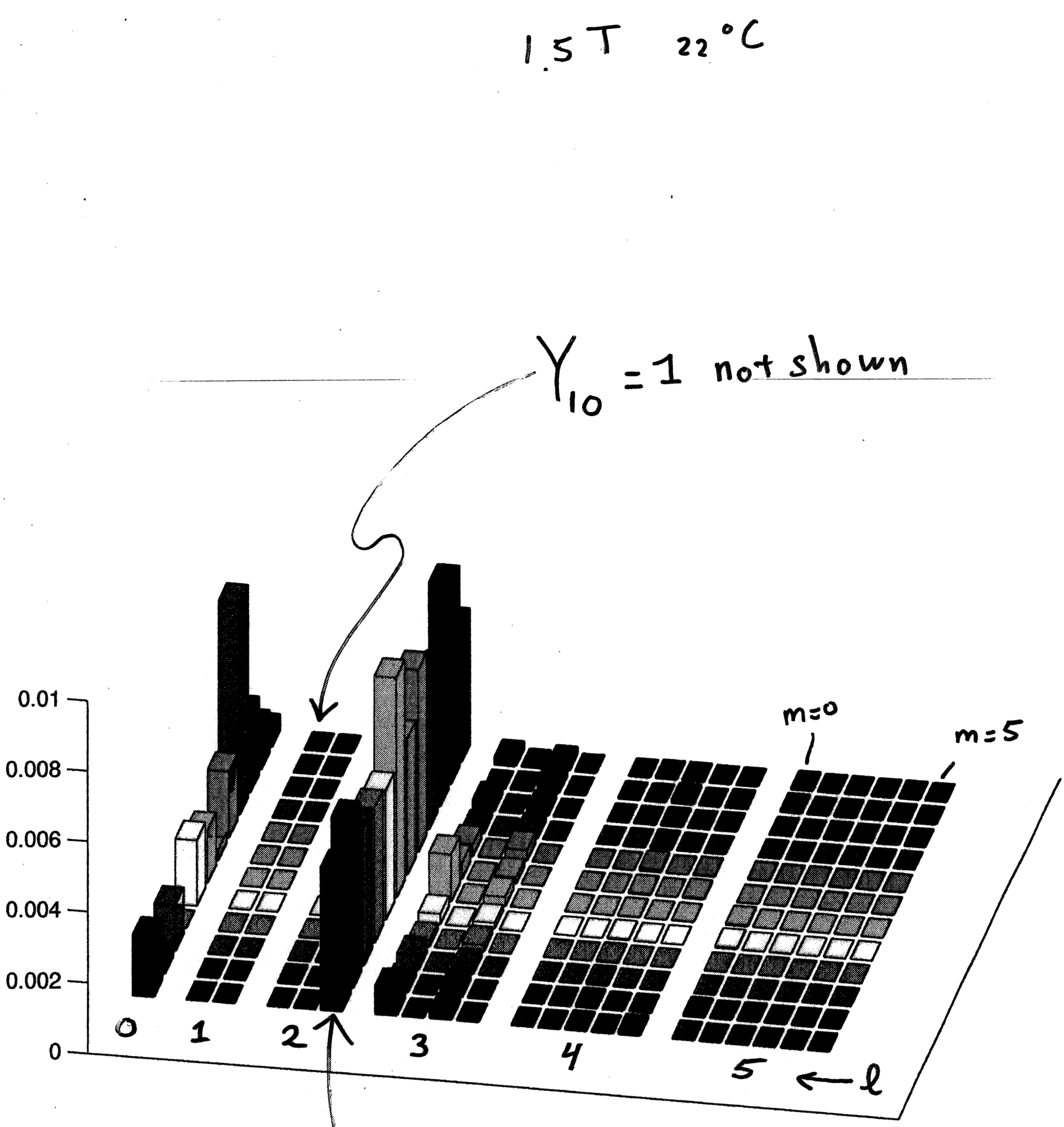
$l = 2$

$$\begin{cases} Y_{22} = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta e^{2i\phi} \\ Y_{21} = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta e^{i\phi} \\ Y_{20} = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) \end{cases}$$

← "planar" Hall effect (at Y_{22})

1.5 T 22 °C

$Y_{10} = 1$ not shown

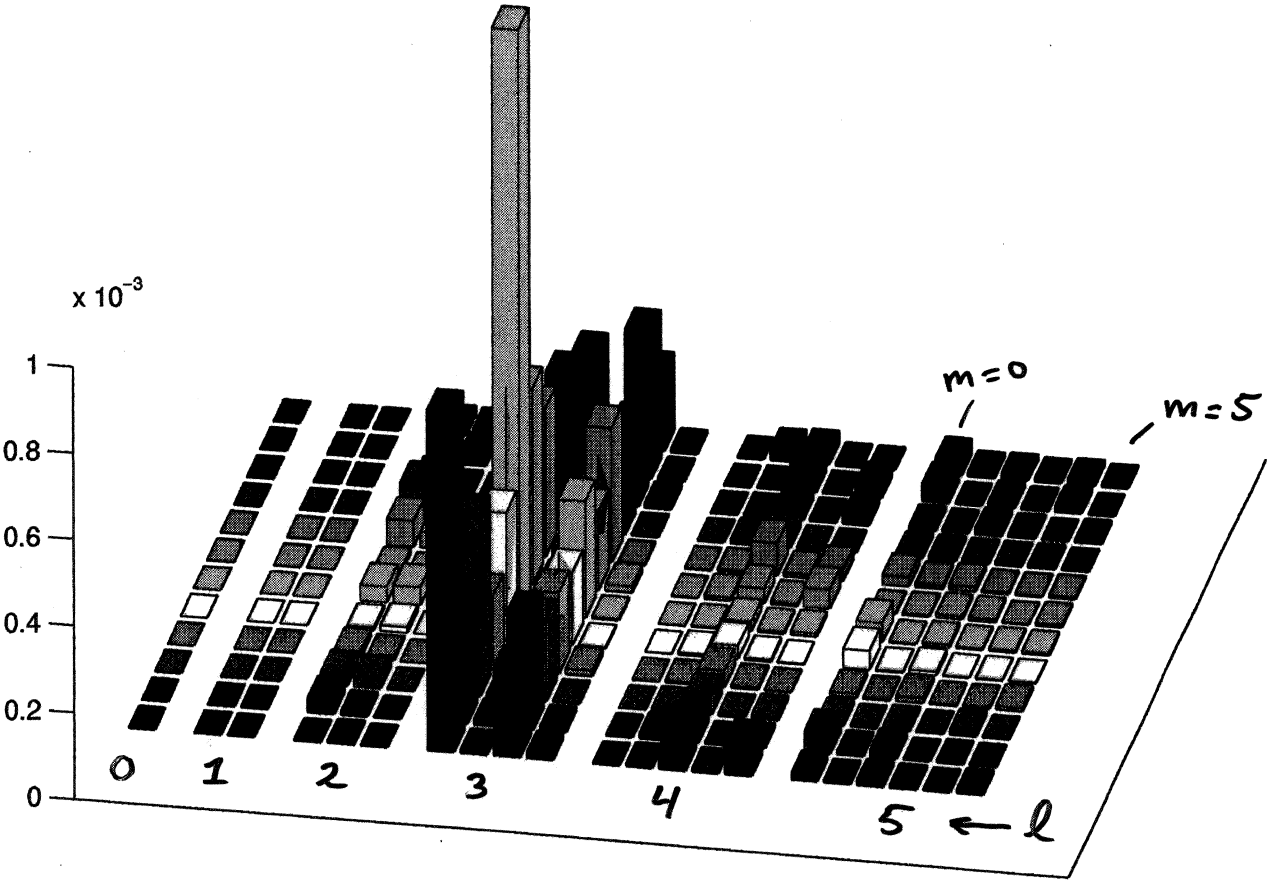


Y_{lm} distribution

Y_{22} = "planar" Hall effect

1.5T 22°C

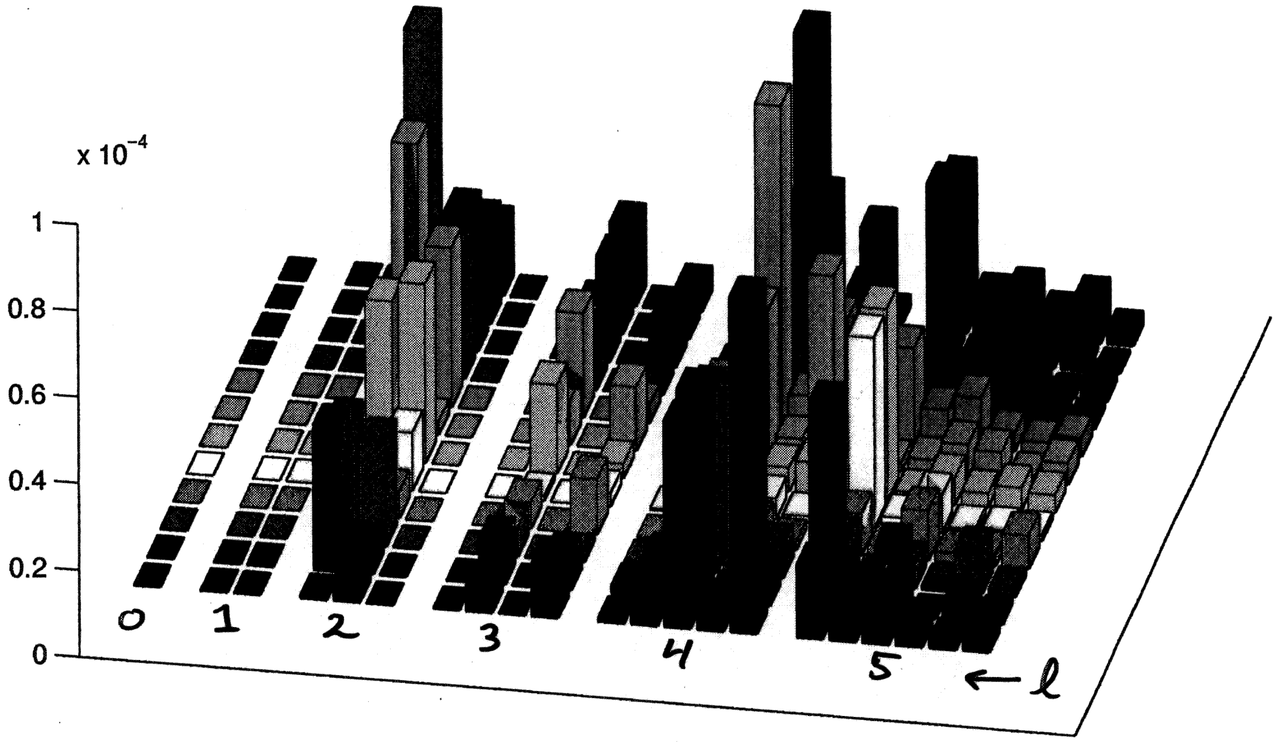
Y (0,0) (1,0) (2,2) not shown



Y_{lm} distribution

1.5T 22°C

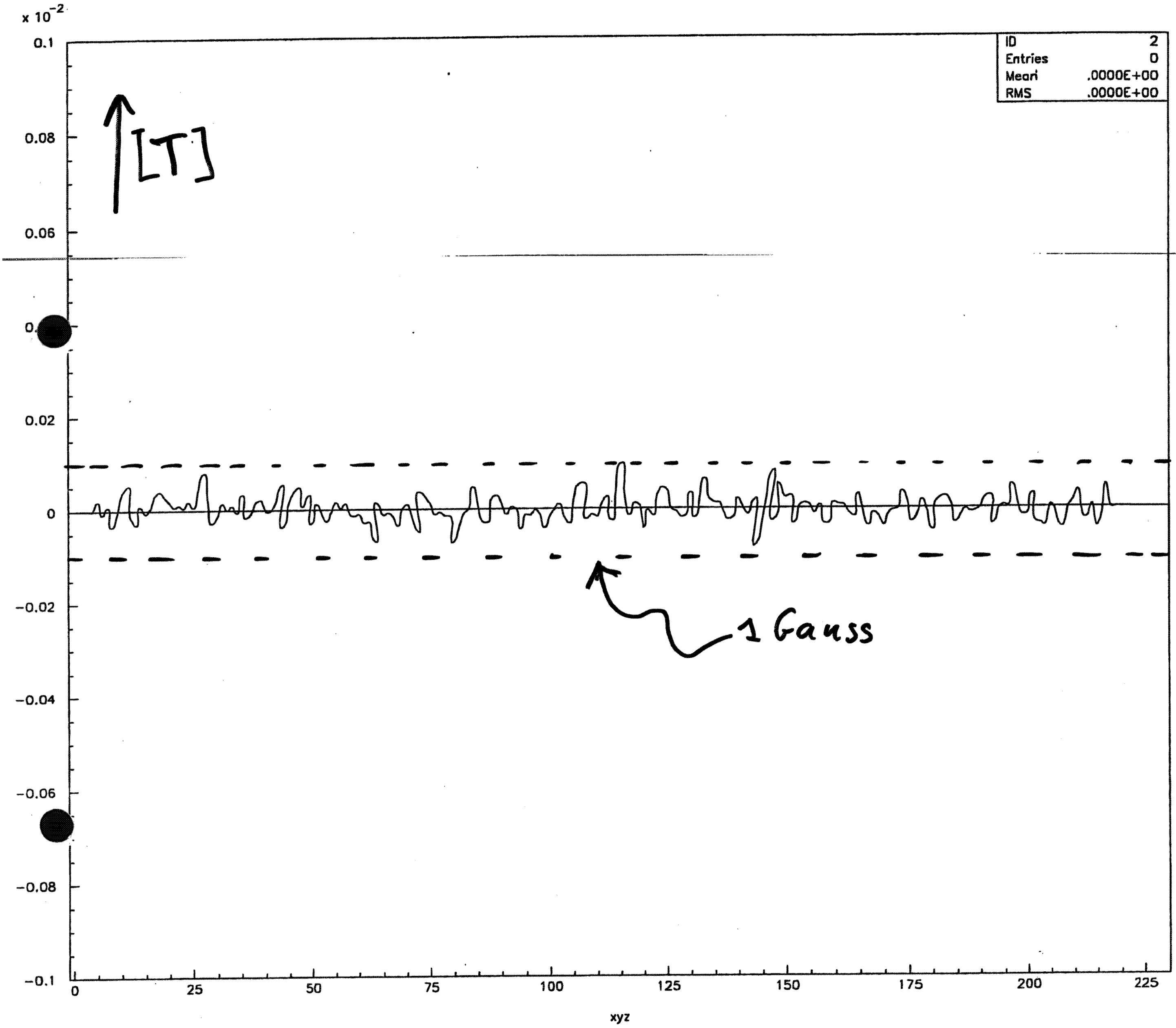
Y (0,0) (1,0) (2,2) (3,0) (3,2) not shown



Y_{lm} distribution

1.5 T 22°C

Hall fit, B from coils

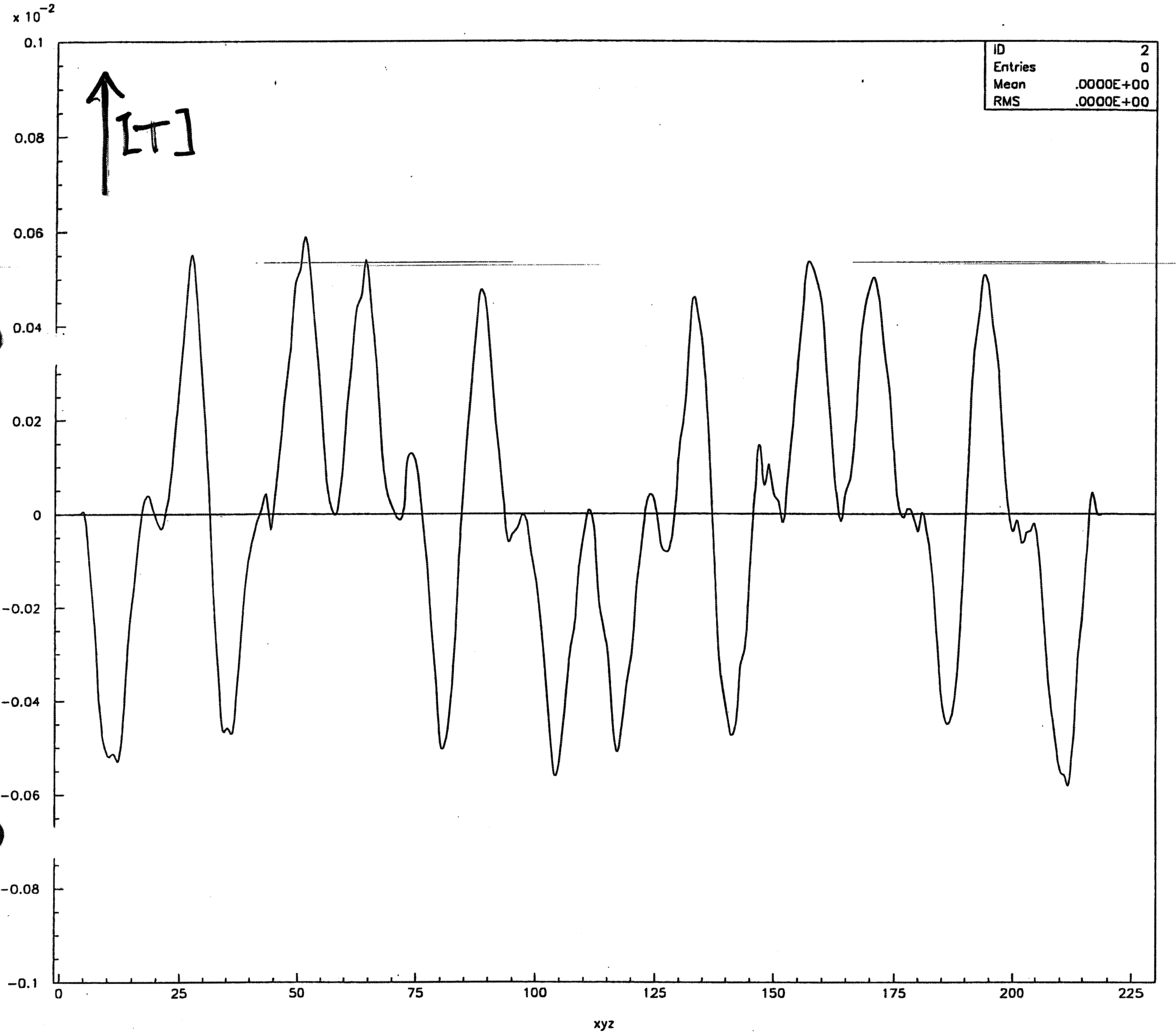


Residue

time →

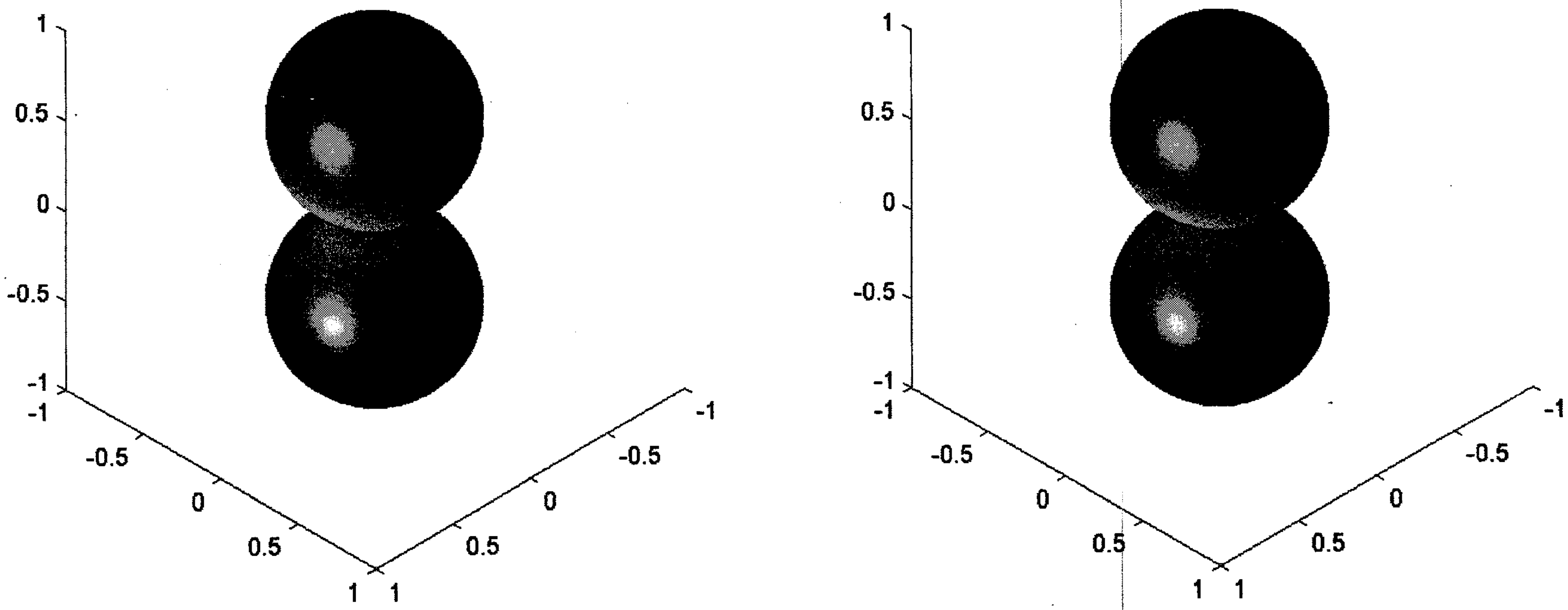
1.5 T 22 °C

no Y32 Hall fit

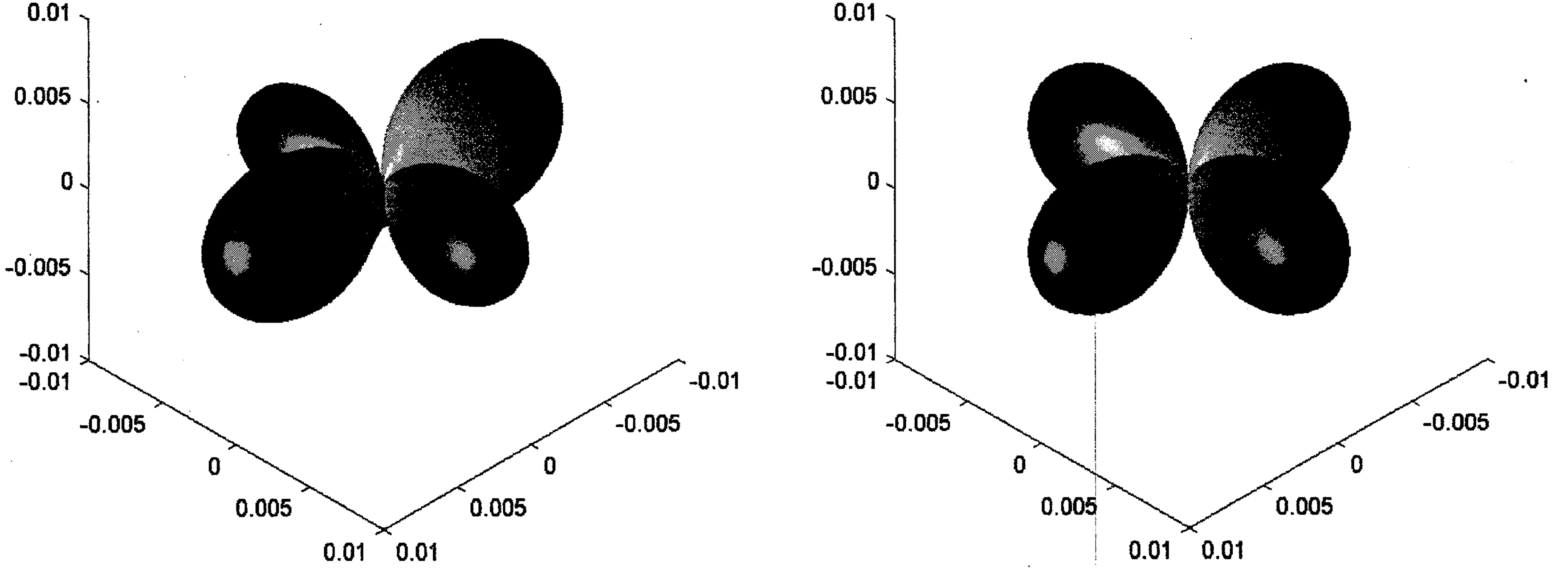


→ time

Residue

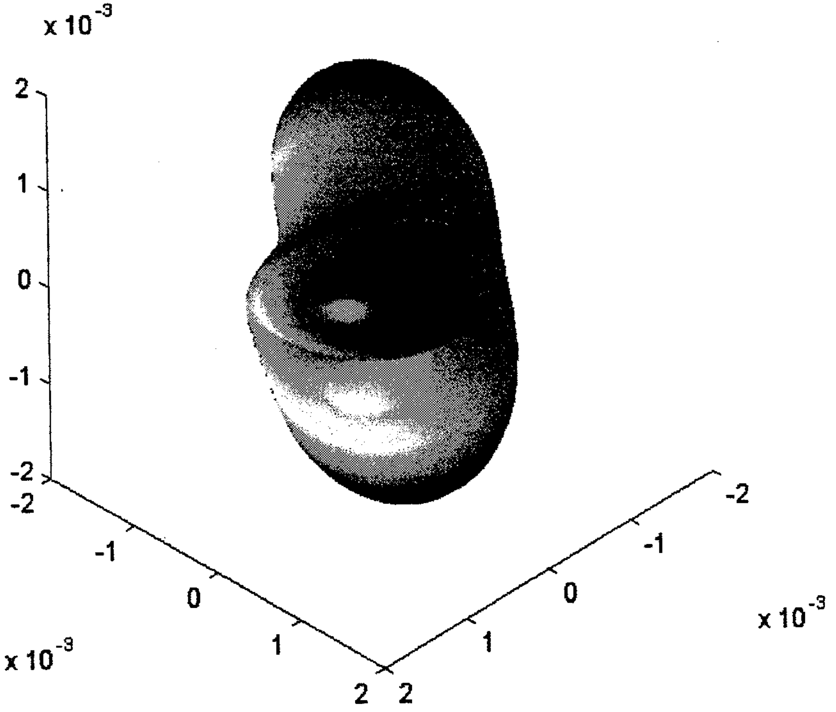


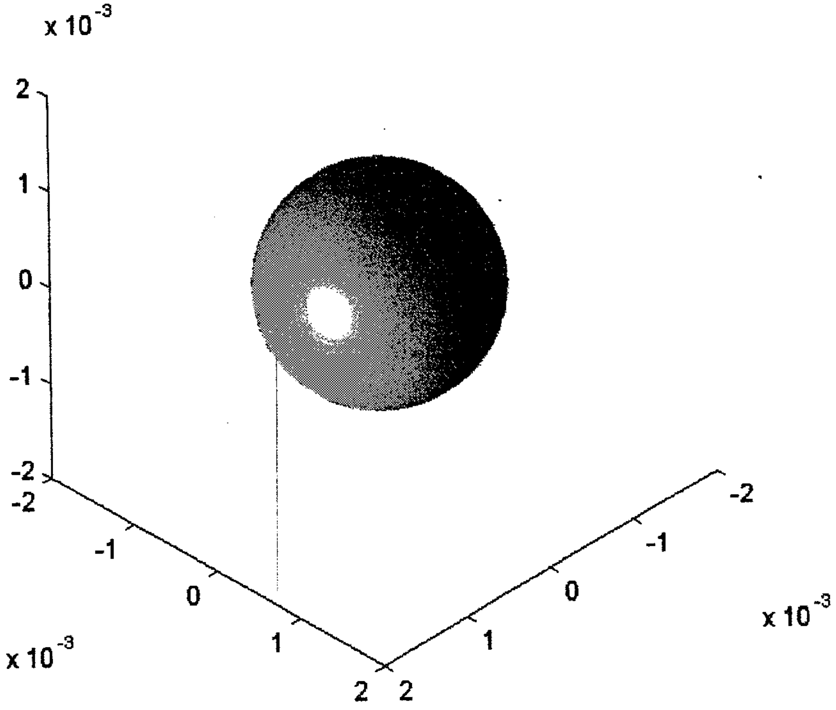
Y_{10}



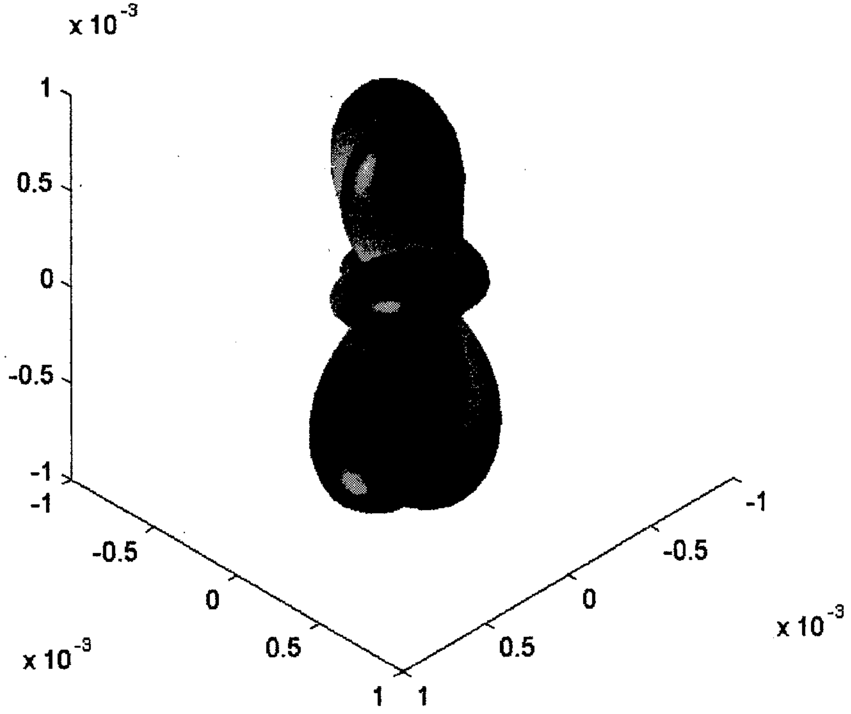
Y_{22}

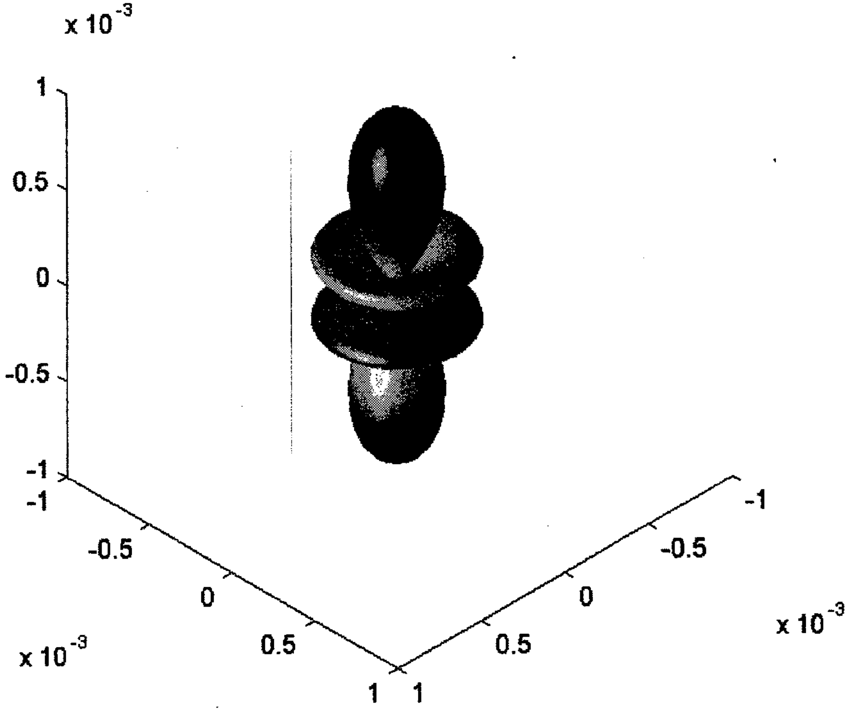
"planar" Hall effect


x 10^-3
2
1
0
-1
-2
-2
-1
0
1
2
x 10^-3
2
1
0
-1
-2
x 10^-3

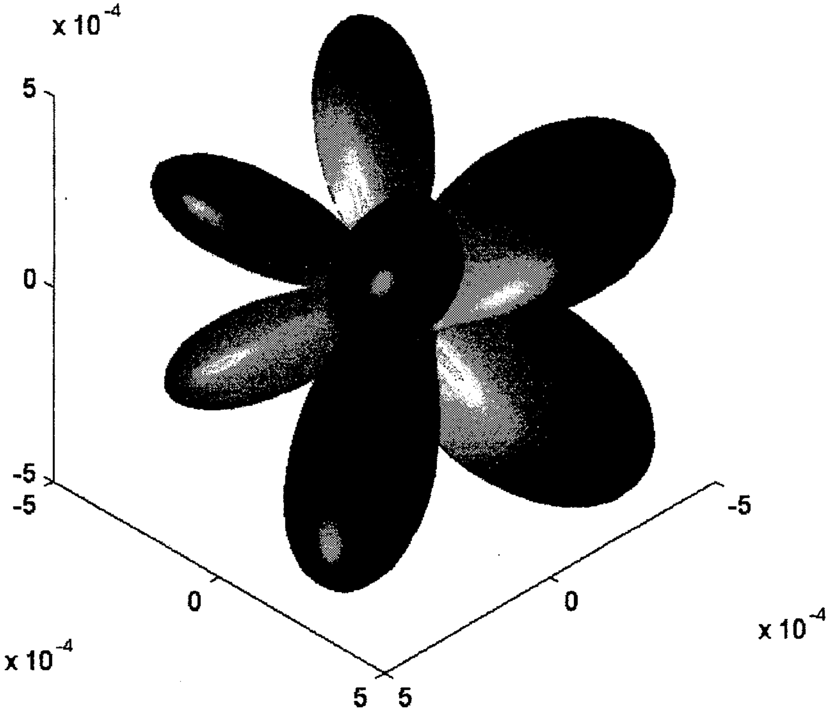

x 10^-3
2
1
0
-1
-2
-2
-1
0
1
2
x 10^-3
2
1
0
-1
-2
x 10^-3

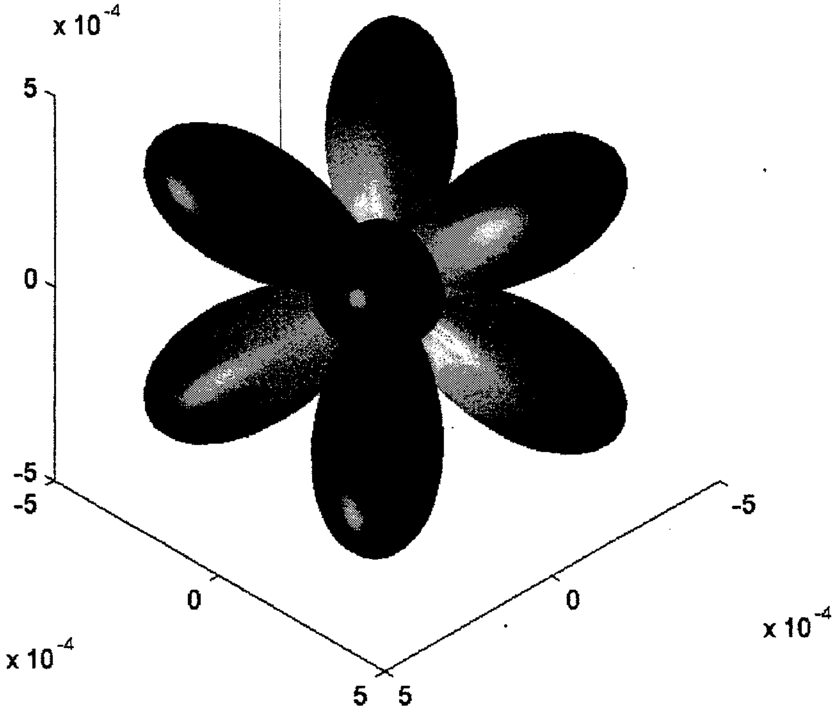
Y_{00}


x 10^-3
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
x 10^-3
1
0.5
0
-0.5
-1
x 10^-3

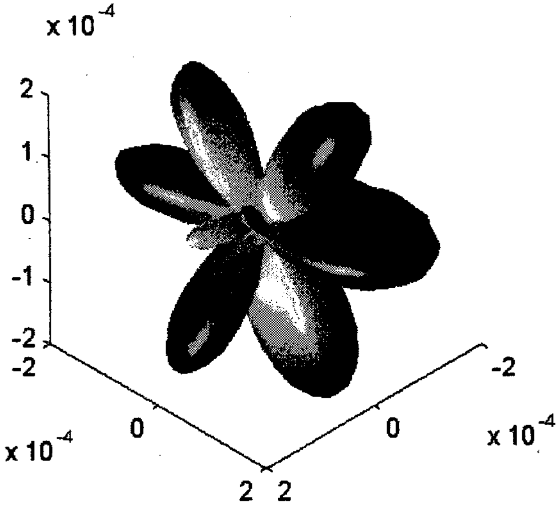

x 10^-3
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
x 10^-3
1
0.5
0
-0.5
-1
x 10^-3

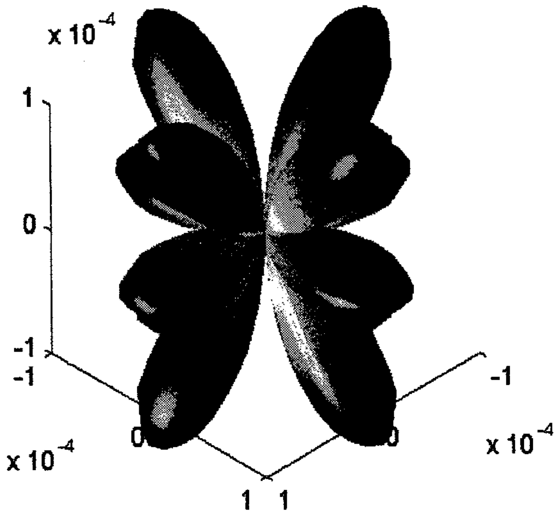
Y_{30}



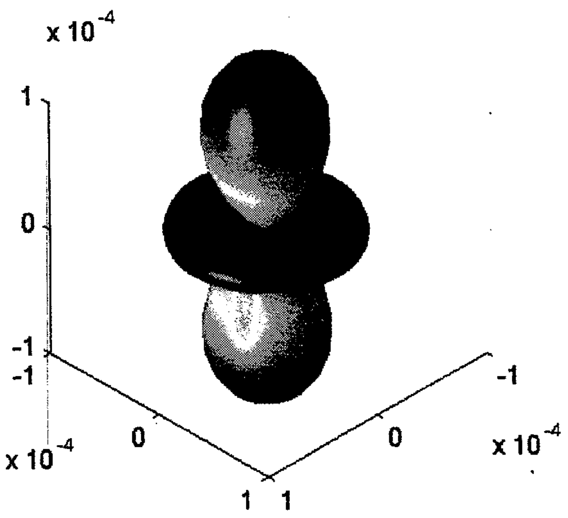


Y_{32}

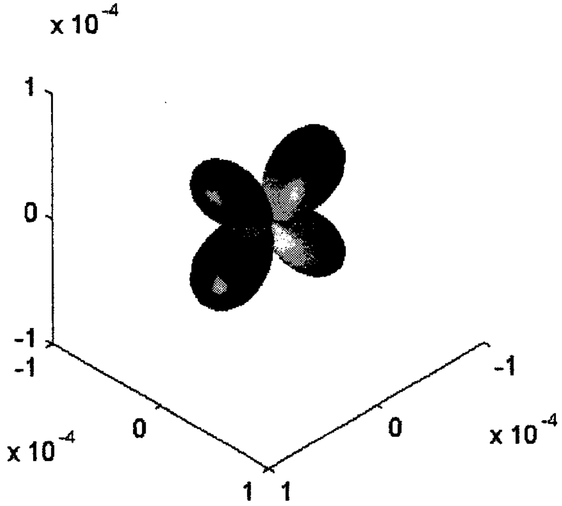




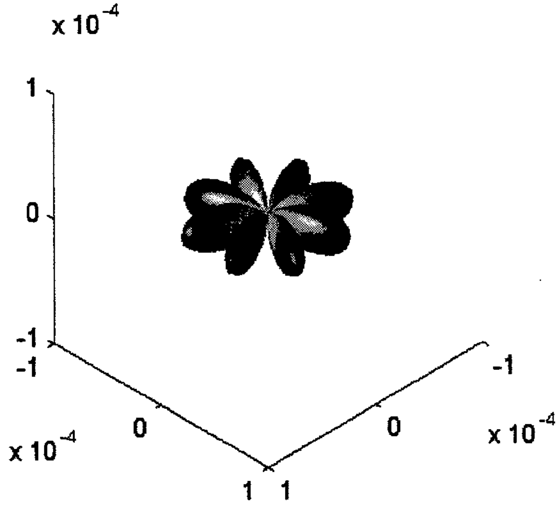
Y_{42}



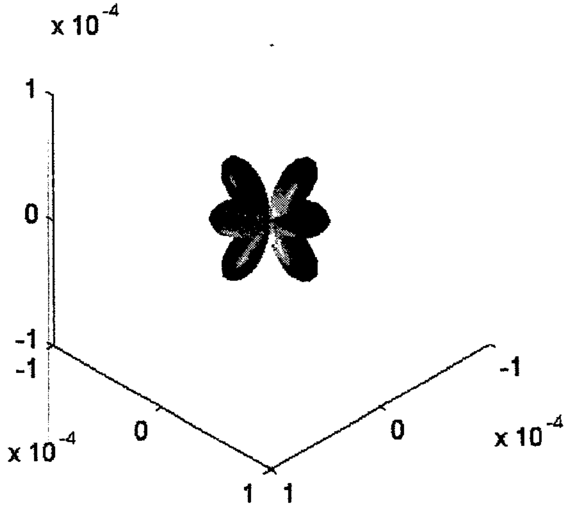
Y_{20}



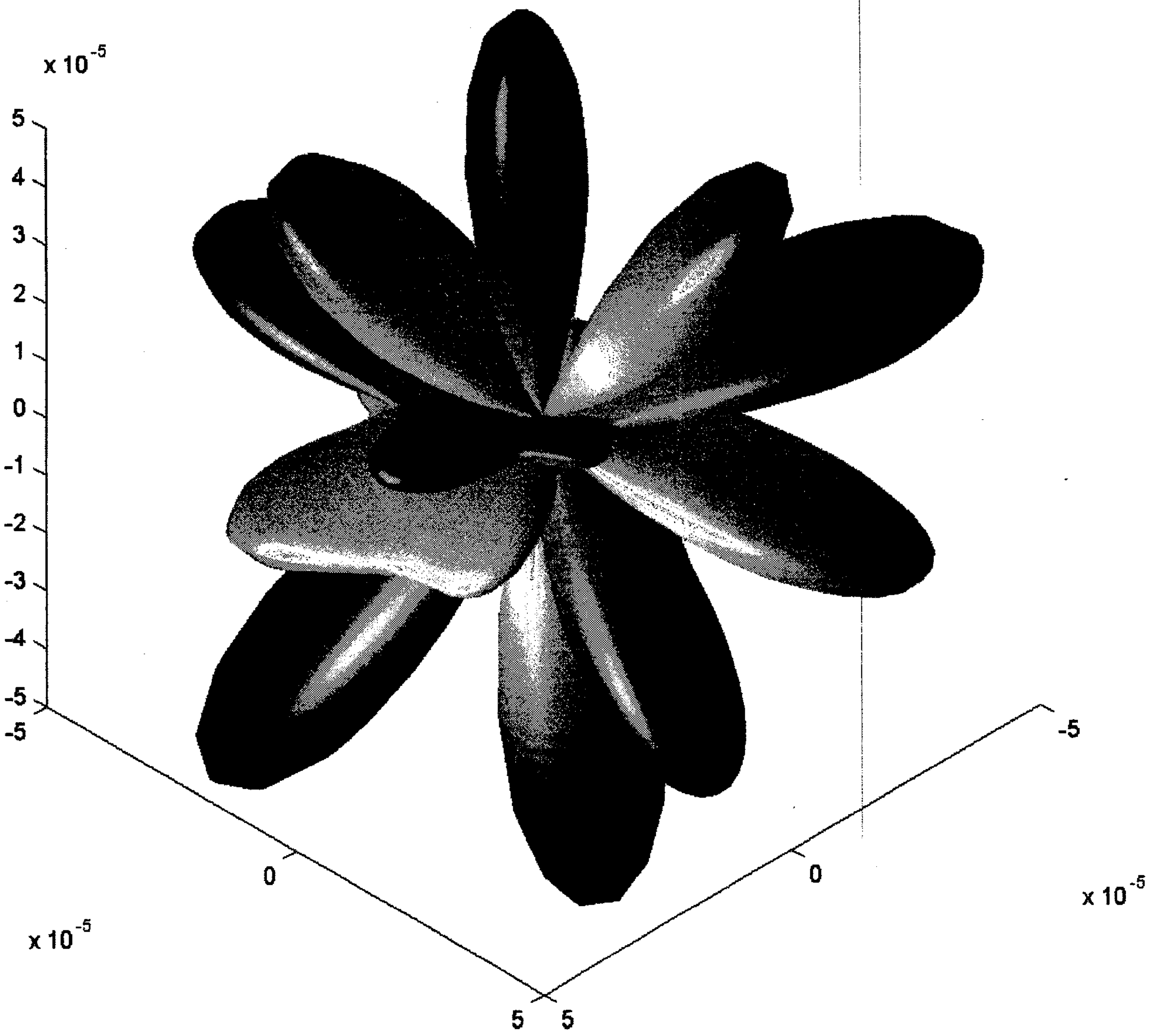
Y_{21}



Y_{44}



Y_{41}


x 10-5
5
4
3
2
1
0
-1
-2
-3
-4
-5
-5
0
x 10-5
5
5
0
-5
x 10-5

B reconstruction

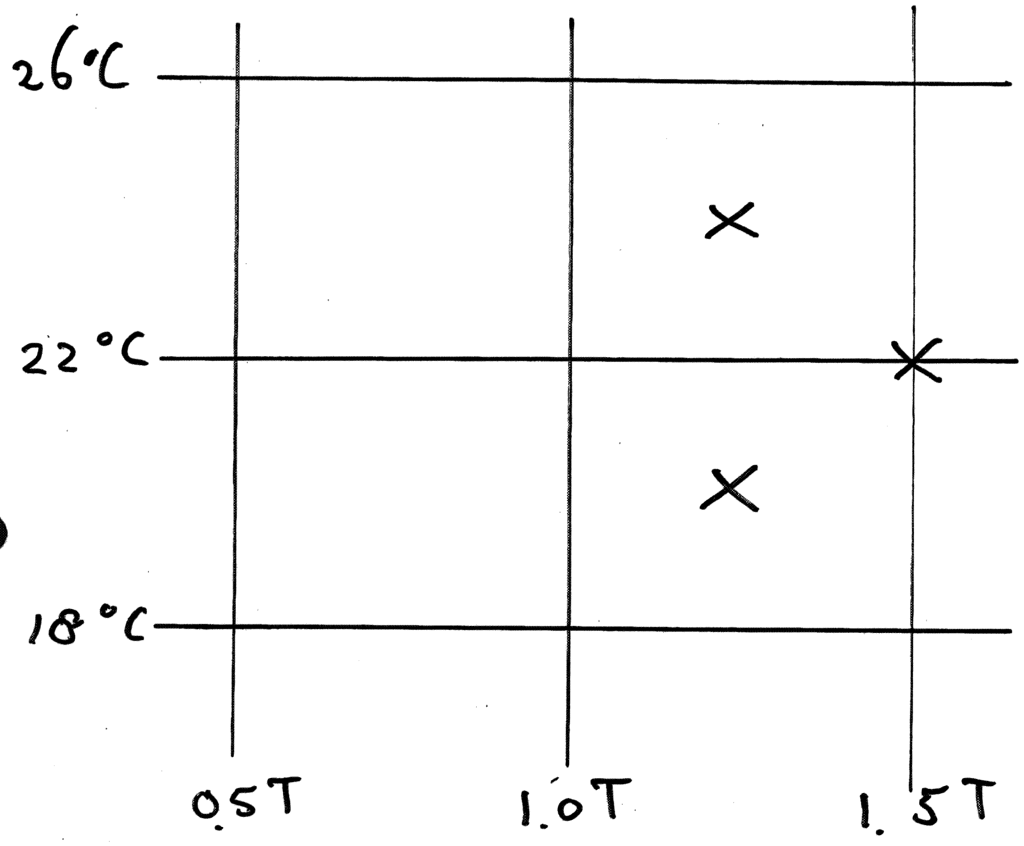
9 calibrations done @ 0.5 T, 1.0 T and 1.5T and

18 ^{0}C, 22 ^{0}C and 26 ^{0}C

interpolate to reconstruct B if

$0.5\ \mathrm{T} < B < 1.5\ \mathrm{T}$ and

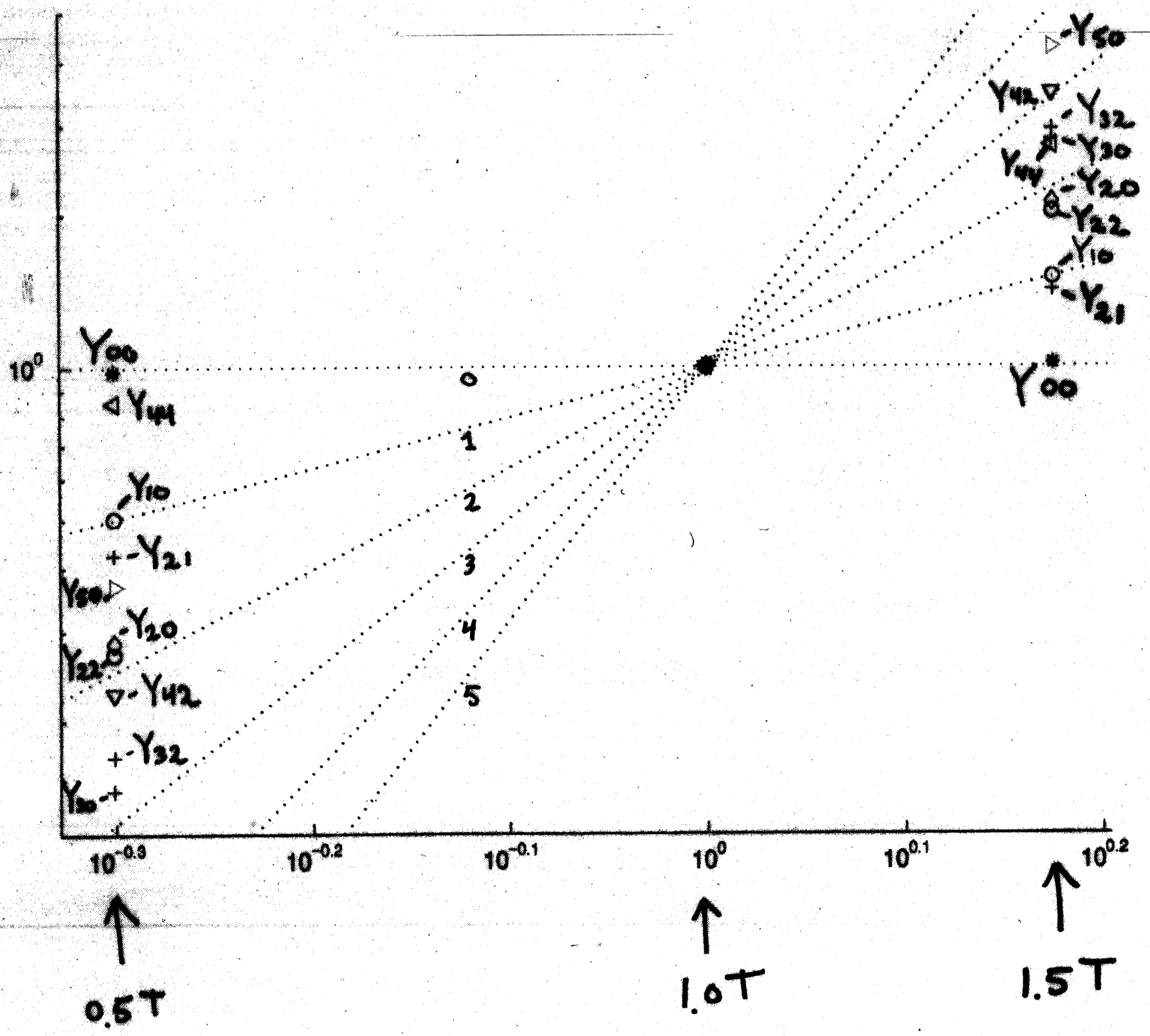
$18\ ^0\mathrm{C} < T < 26\ ^0\mathrm{C}$



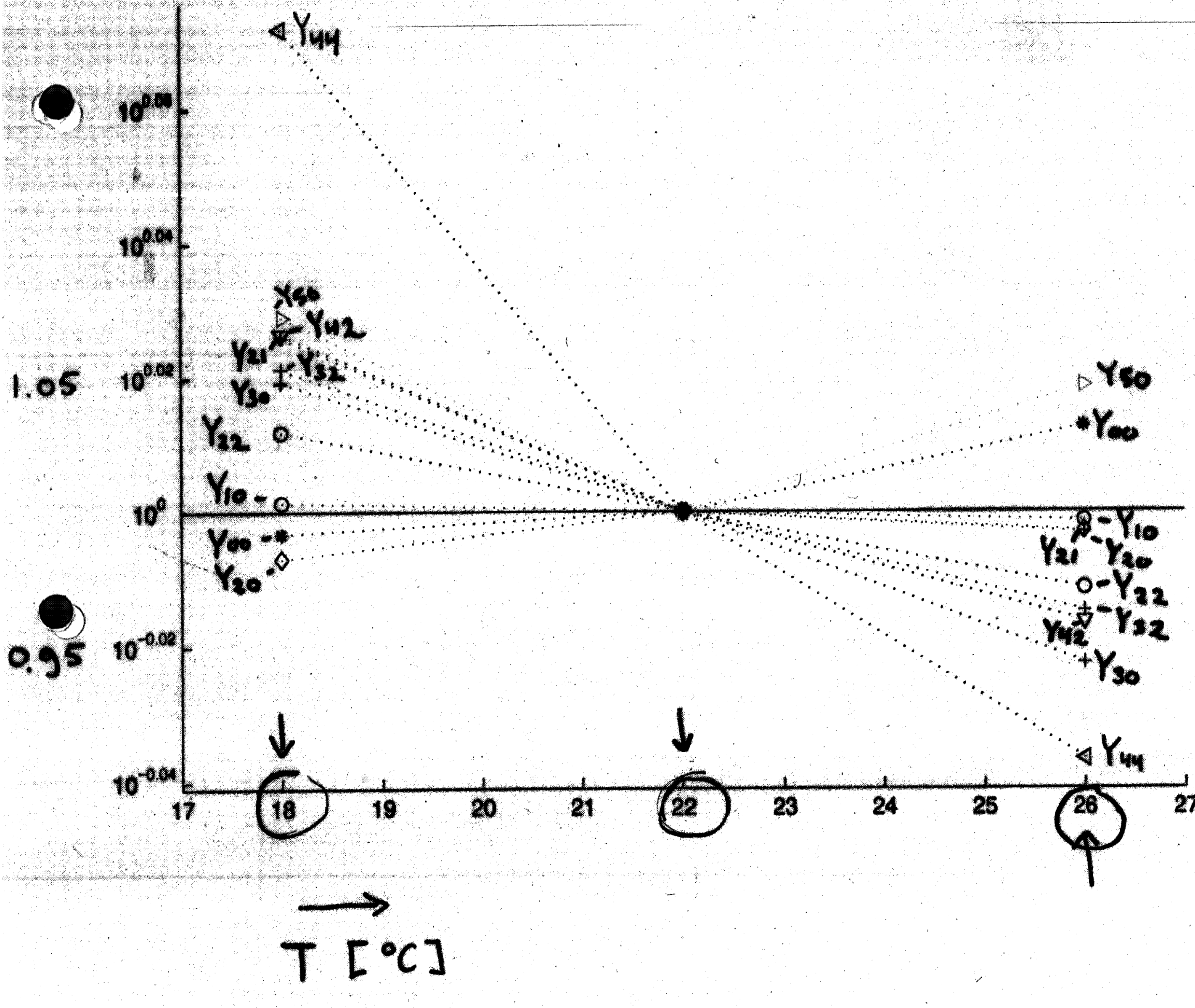
“ planar hall effect” Y_{22} doesn’t scale exactly with B^2

Spherical harmonics have complicated temperature behaviour

Y_{lm} vs $|B|$

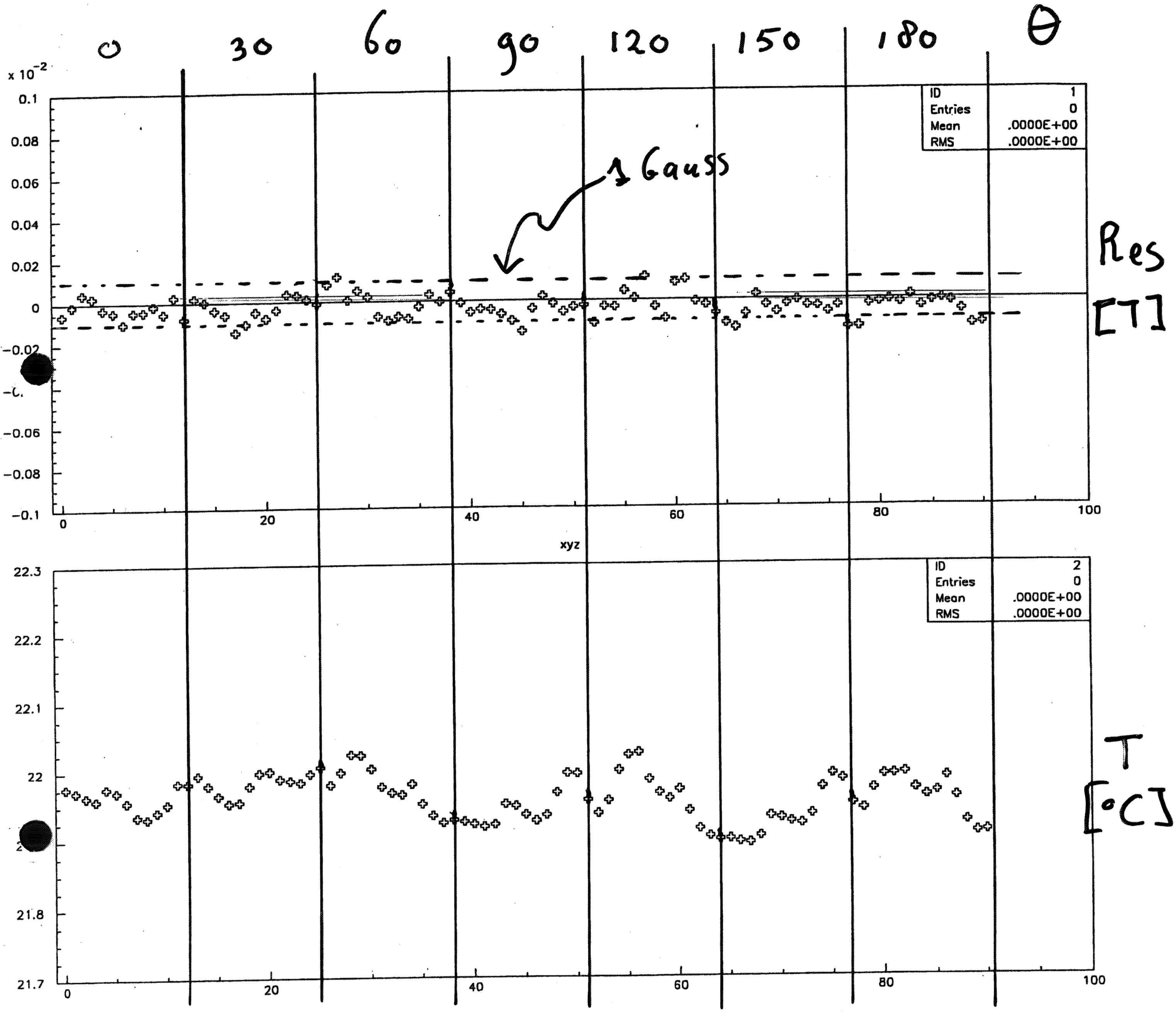

Y_{00}
10^0
Y_{44}
Y_{10}
Y_{21}
Y_{50}
Y_{20}
Y_{22}
Y_{42}
Y_{32}
Y_{30}
0
1
2
3
4
5
Y_{50}
Y_{42}
Y_{32}
Y_{30}
Y_{44}
Y_{20}
Y_{22}
Y_{10}
Y_{21}
Y_{00}
$10^{-0.3}$
$10^{-0.2}$
$10^{-0.1}$
10^0
$10^{0.1}$
$10^{0.2}$
0.5T
1.0T
1.5T

Y_{lm} vs Temp


Y44
Y50
Y42
Y21
Y32
Y30
Y22
Y10
Y00
Y20
Y50
Y00
Y10
Y21
Y20
Y22
Y42
Y32
Y30
Y44
1.05
0.95
$10^{0.06}$
$10^{0.04}$
$10^{0.02}$
10^{0}
$10^{-0.02}$
$10^{-0.04}$
17
18
19
20
21
22
23
24
25
26
27
T [°C]

1.5T 22°C

2 Reconstructed B

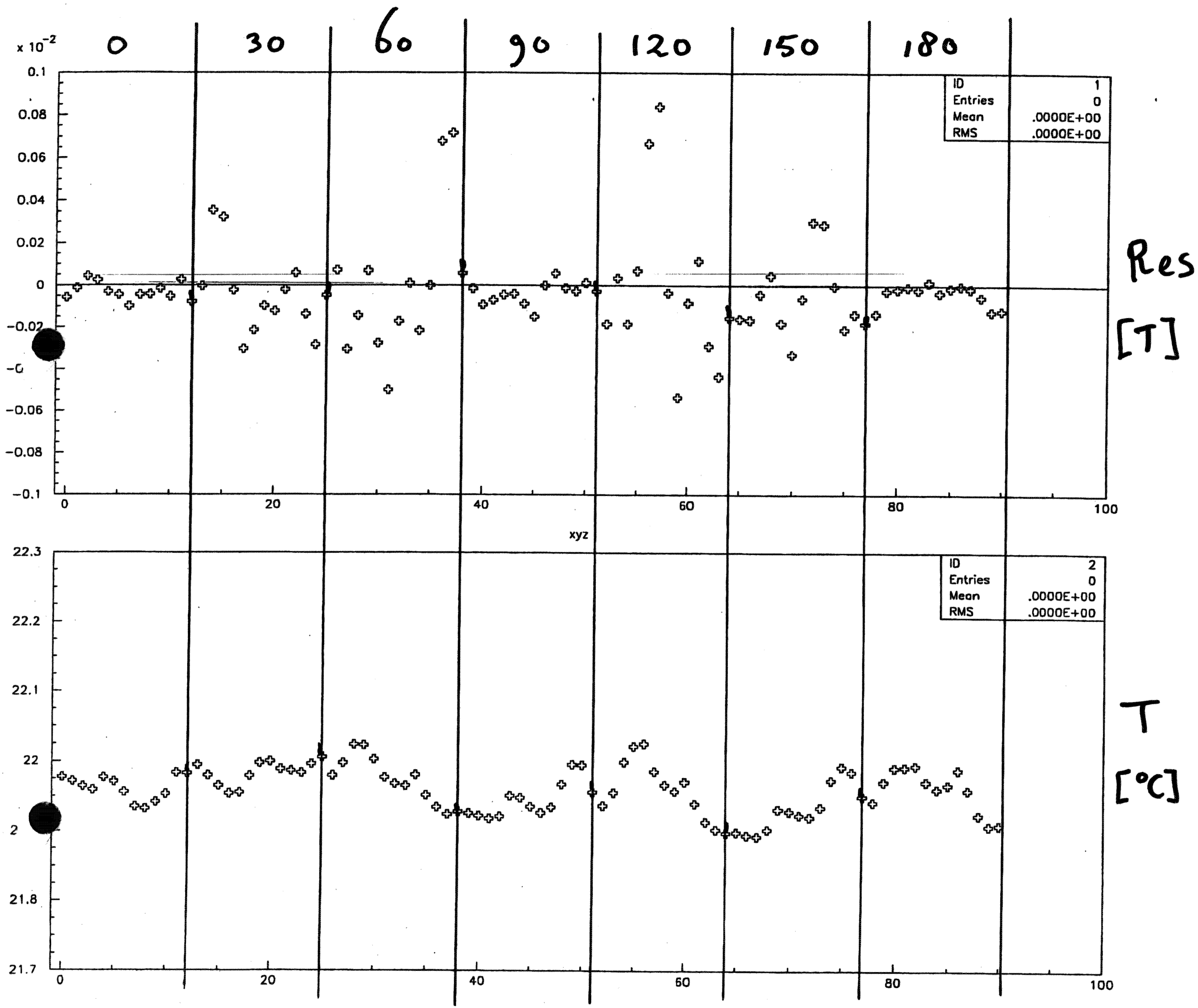


$0 < \varphi < 360°$ step 30°

2

1.5 T 22 °C

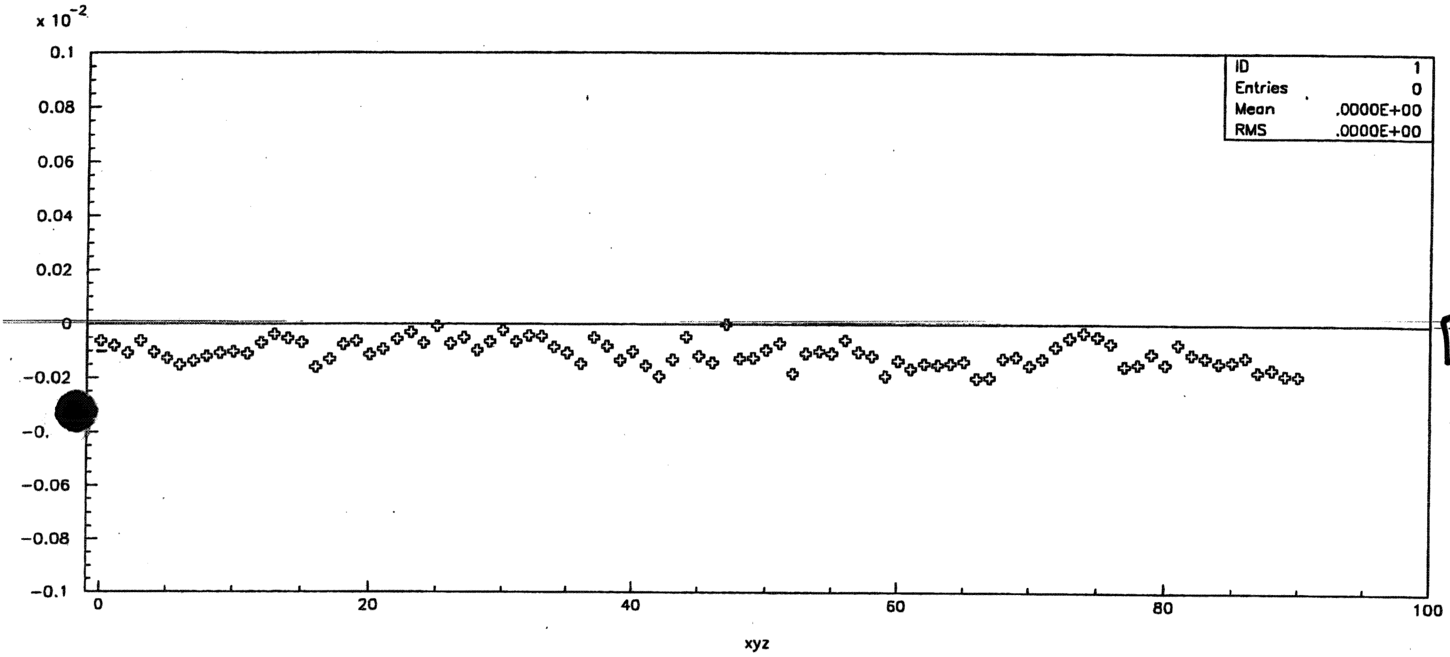
no Y_{32}



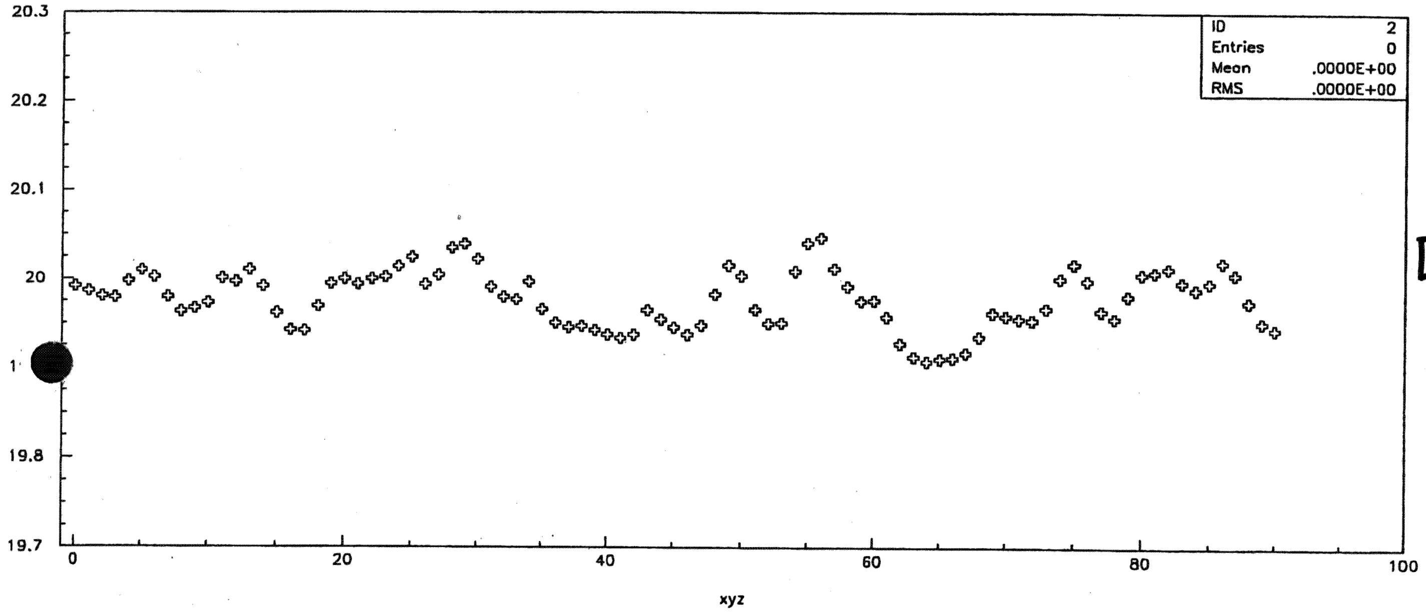
$0 < \varphi < 360°$ step 30°

2

1.25 T 20°C



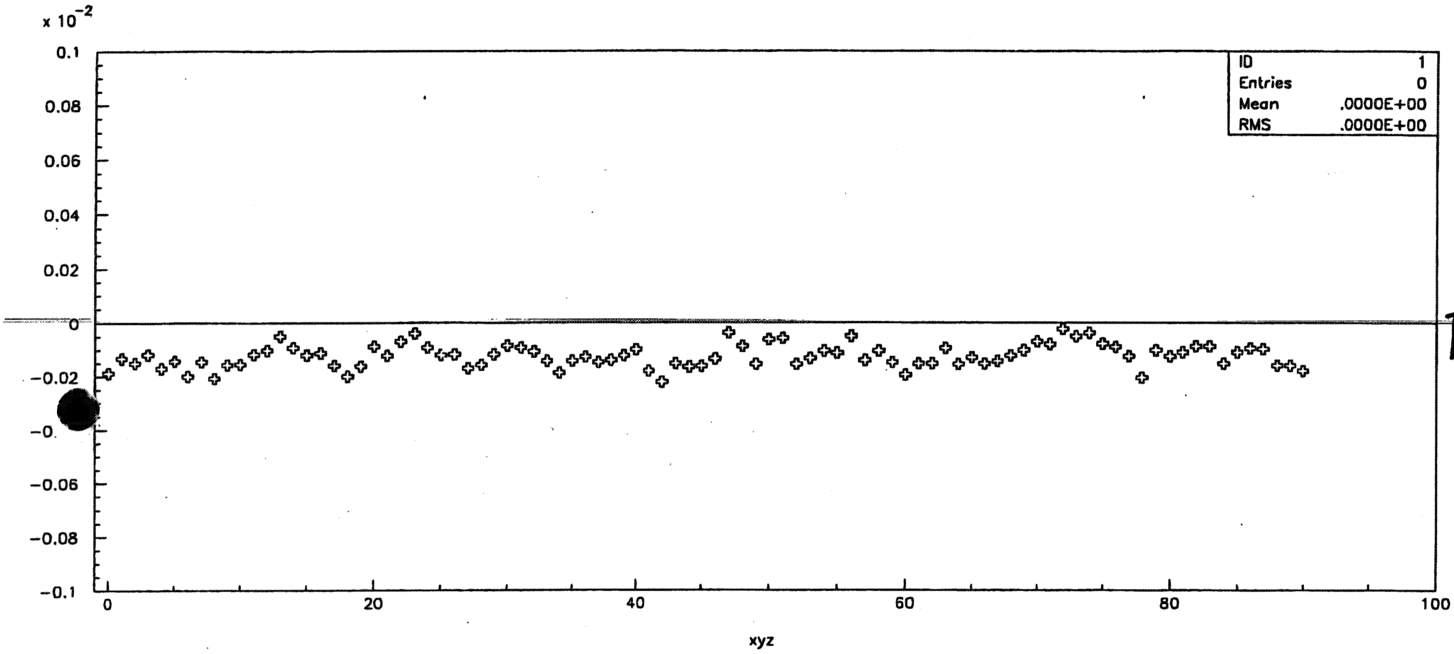
Res [T]



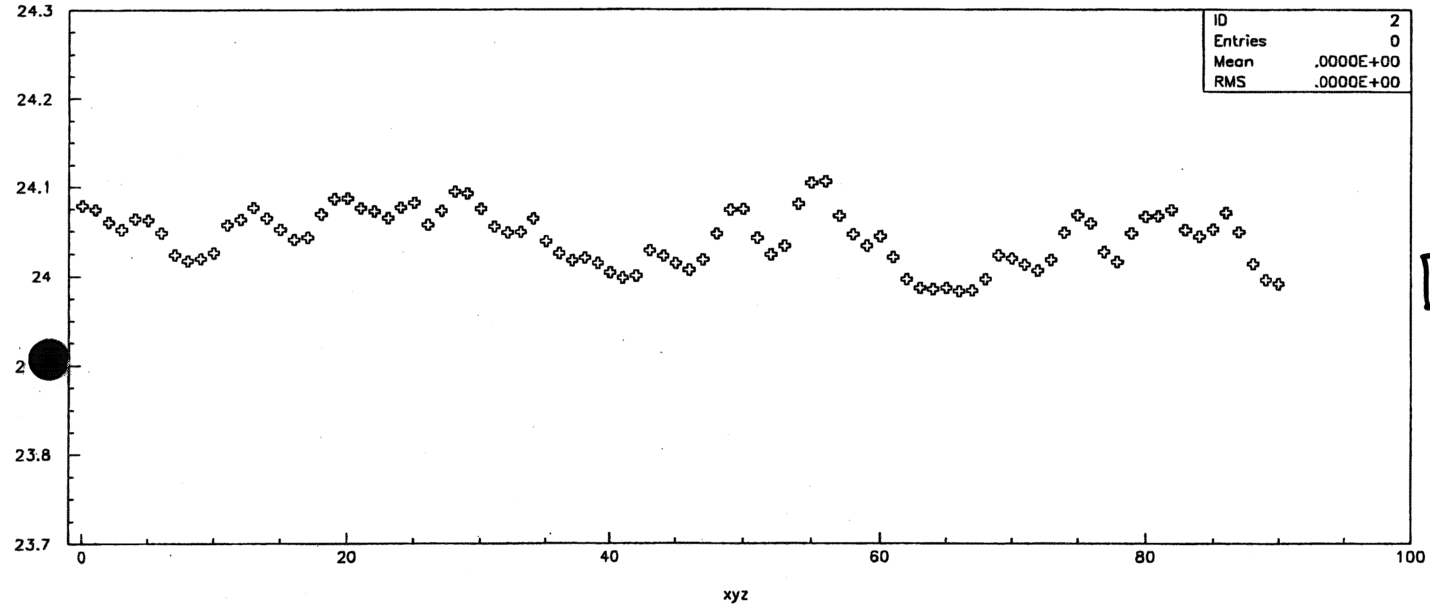
T [°C]

2

1.25 T 24°C



Res [T]



T [°C]

conclusions

precision of 10^{-4} seems achievable

improvements necessary:

temperature: better thermal contact of thermistor with

hall plates, thermal insulation

fixation of hall plates to pcb

interpolation: more points?

suppression of vibration: no stepper motors ?, damping ?

next

determine mean time between calibration

aging, radiation damage etc.

What happens at higher fields?

How does Y_{lm}-spectrum scale with hall-current?

Calibrate against 'mother' sensor card => faster

Optimize calibrator

etc.