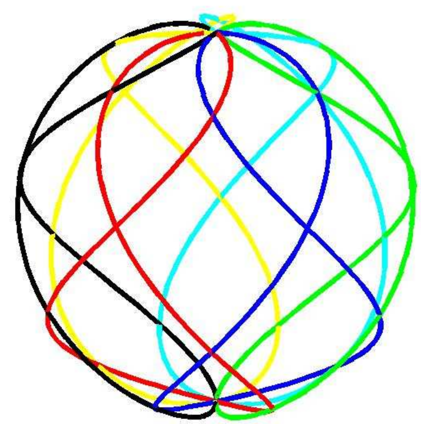
# 3D Hall probes applications

**IMMW15 FNAL USA**
AUGUST 21-24, 2007

F. Bergsma CERN



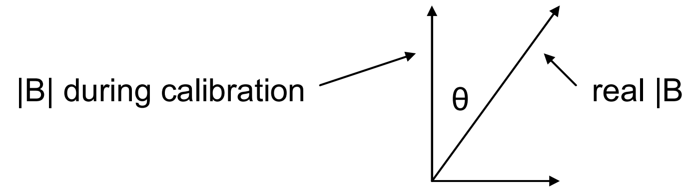
Why do we need 3D calibration?

3D Calibrator in dipole magnet

3D Calibrator in solenoid magnet

Applications of 3D B-sensors and performance

# Why do we need 3D calibration?



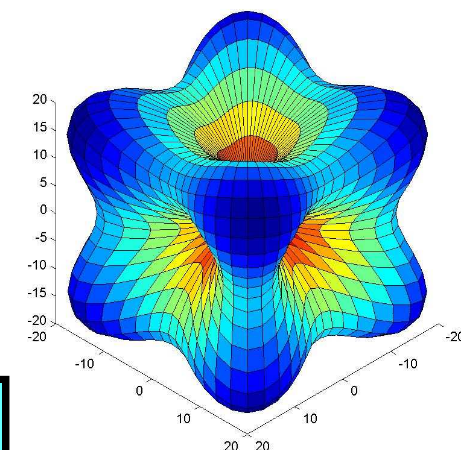

for example:

Ideal Hall probe:

$$\boxed{V = \text{constant } \ |B| \cos\theta}$$

More realistic Hall probe:

$$\boxed{V = (a + b|B| + c|B|^2 + d|B|^3 + \ldots..) \cos\theta}$$




2 ‰ error @ 1.5 T
Siemens KSY44

many reasons: material type, geometrical effects, magneto resistance, etc.        a,b,c,d… depend on temperature

=> You can not simply use 3 single axis calibrations in 3D

# Why do we need 3D calibration?

3D calibration = measuring the Hall voltage at many $\theta$ and $\varphi$ values and not only at $\theta \approx 0$

1 Rotational symmetric parts of Hall voltage depend on absolute value of B and not only on projection of B on one axis

2 Hall probes can not be mounted exactly orthogonal, small components influenced

$|B|\cos(\delta) = |B|\,(1 - \delta^2/2!\ \ldots..)$ $\qquad$ $|B| \cos(\pi/2 + \delta) = -|B|\,(\delta - \delta^2/2!\ \ldots)$

The orientation of the Hall probe should be very precisely known

3 there are non-symmetrical components which are zero on one or more main-axes: planar Hall effect ($Y_{22}$), 3D hall effect ($Y_{32}$), etc.

Hall voltage contains higher order terms

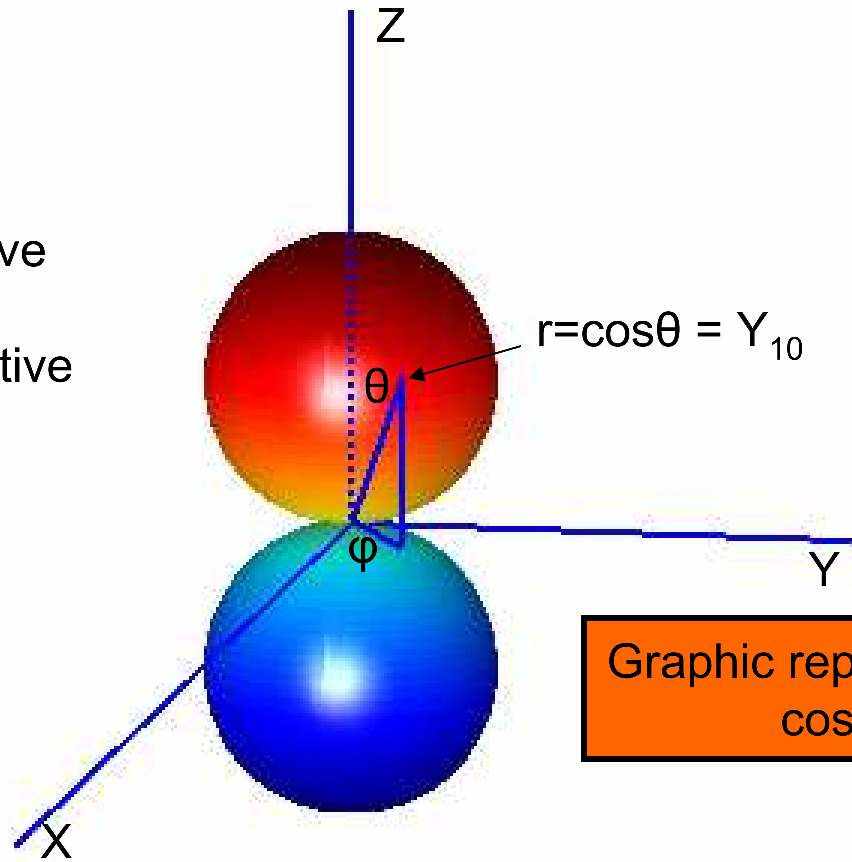
Planar Hall effect most known

**Let's look at a decomposition of a Siemens KSY44 at 1.5 Tesla**

Decomposition of Hall voltage in spherical harmonics

Red=positive

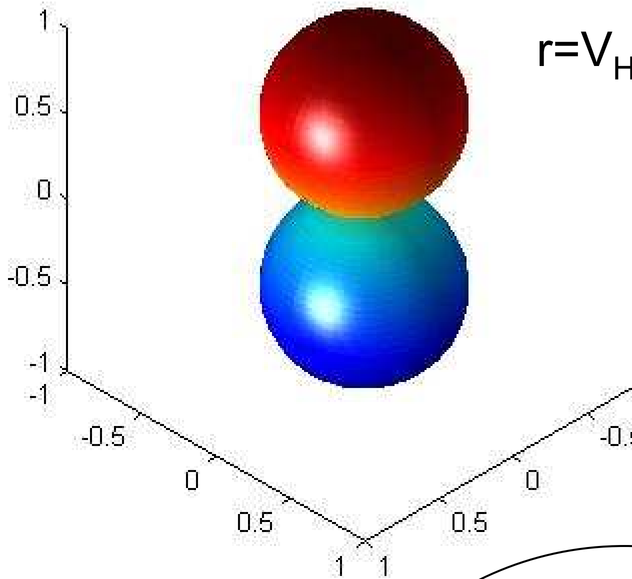
Blue=negative




Graphic representation of $\cos\theta = Y_{10}$

Normalized to 1

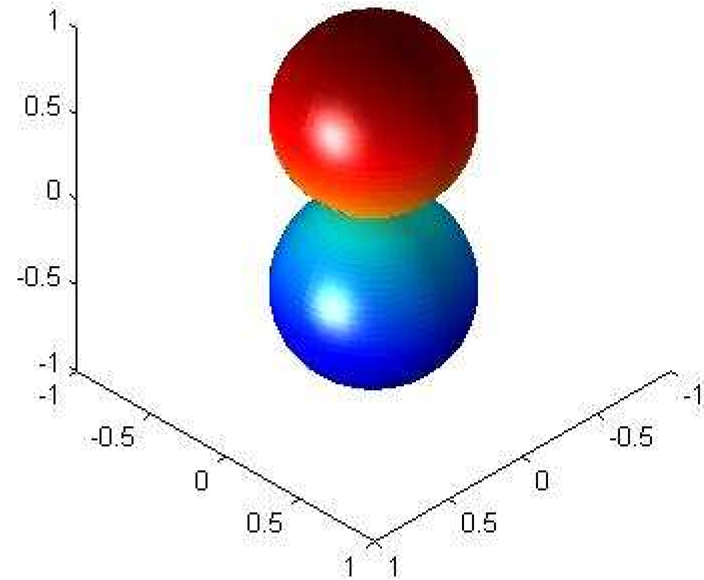
measured




$r = V_{Hall}$

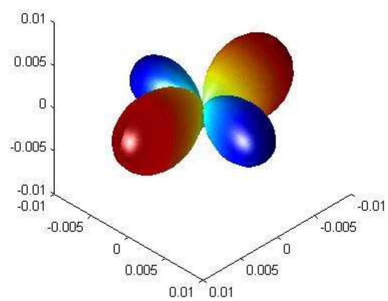
$-$

$Y_{10} = \cos\theta$

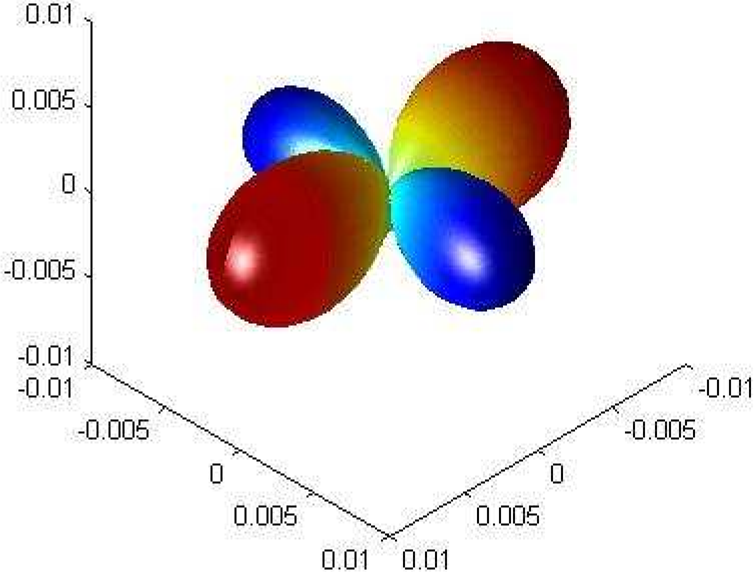



$=$

ZOOM 50 x



residue

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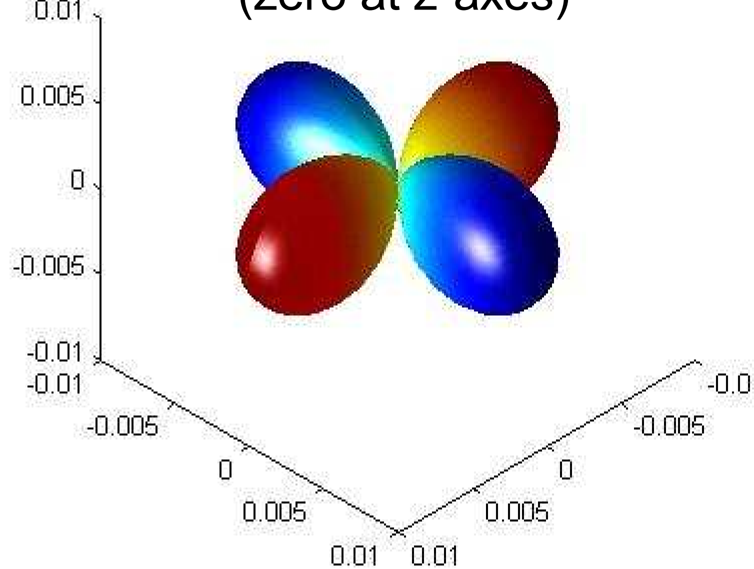
$Y_{22}$ planar Hall effect
(zero at z-axes)

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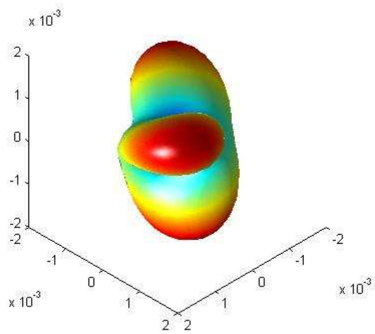
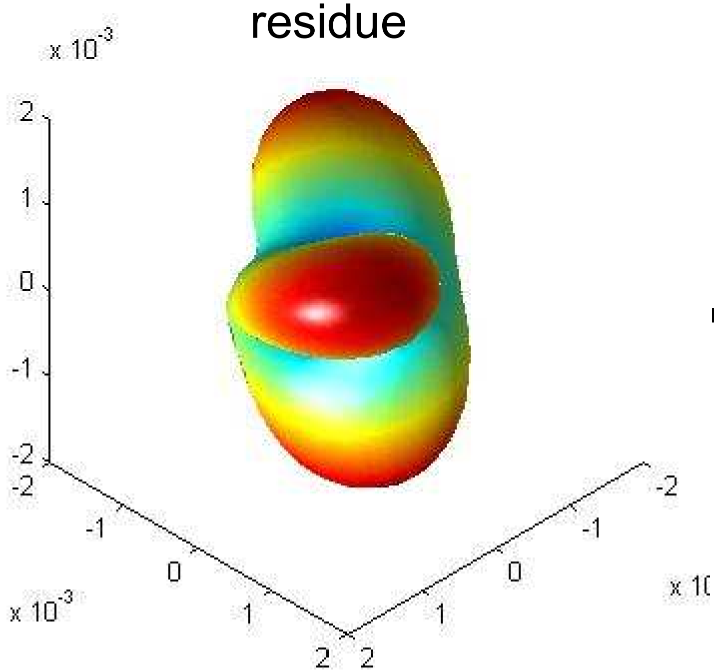
ZOOM 2.5 x



residue

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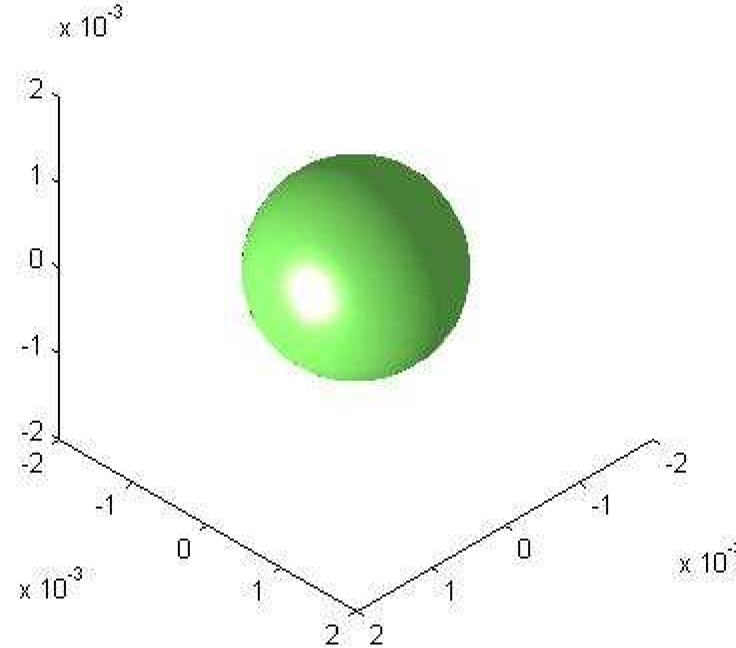
$Y_{00}$ offset

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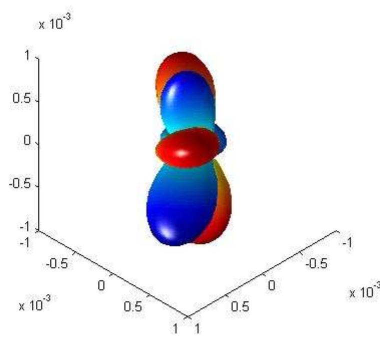
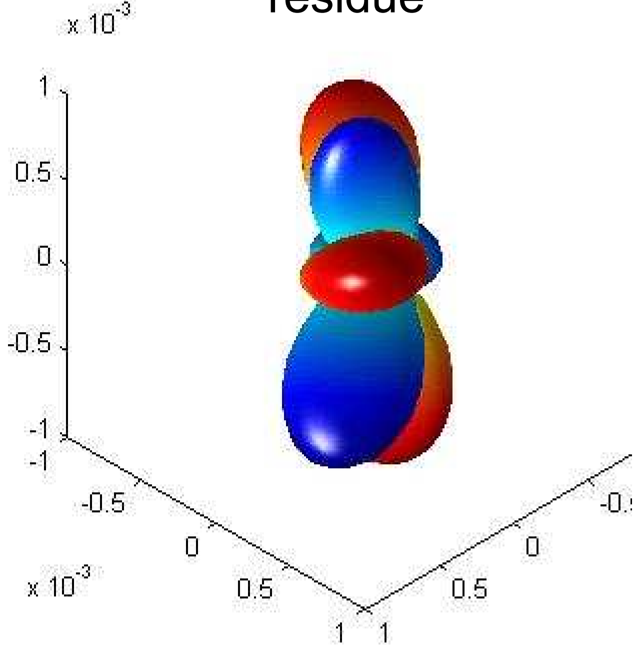


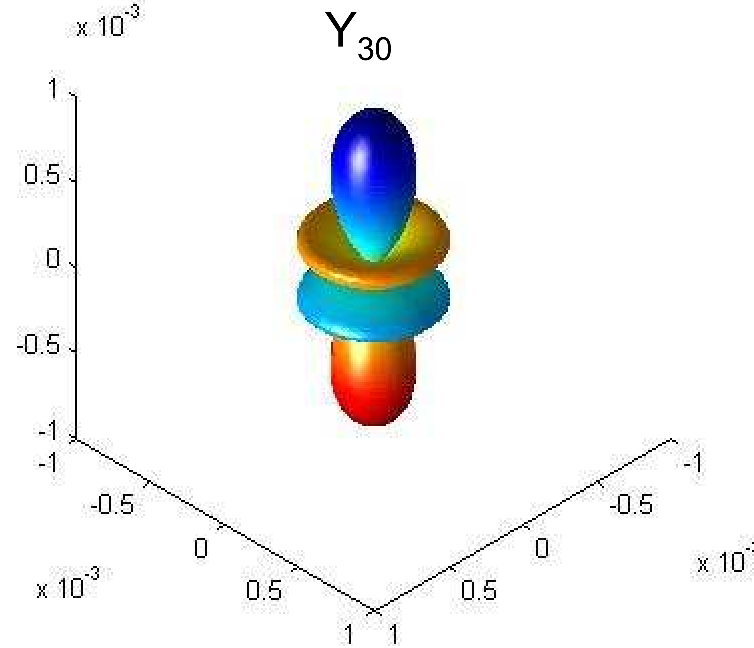
residue



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

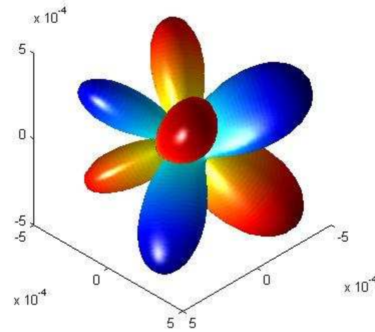

−

$Y_{30}$



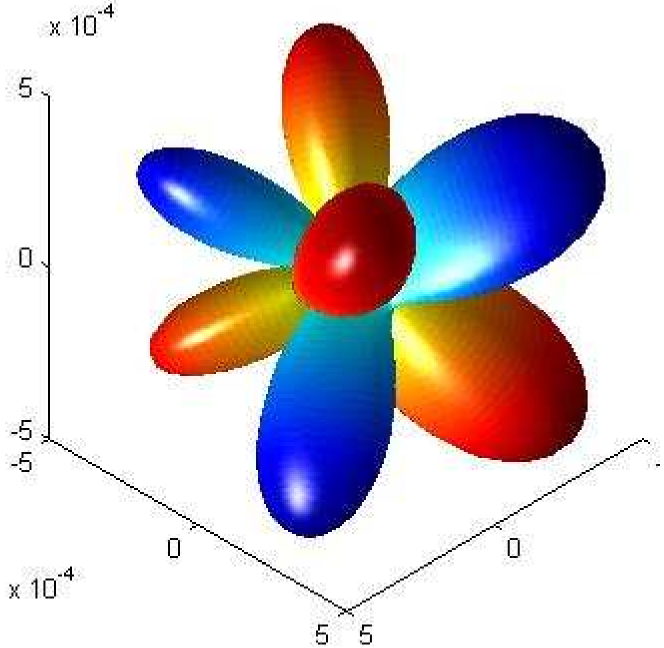
x 10^-3
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
x 10^-3
1
0.5
0
-0.5
-1
x 10^-3


=



x 10^-4
5
0
-5
-5
0
5
x 10^-4
5
0
-5
x 10^-4

residue

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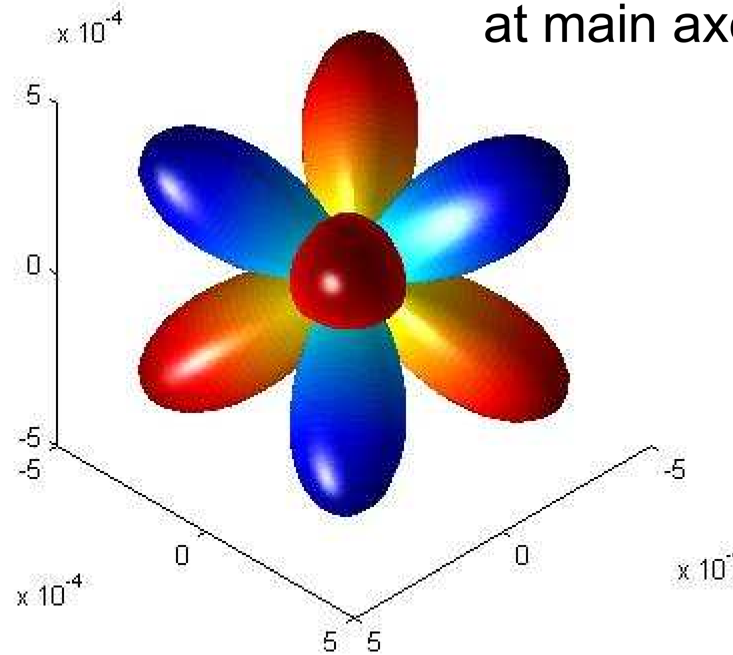
$Y_{32}$ 3D Hall effect, zero at main axes

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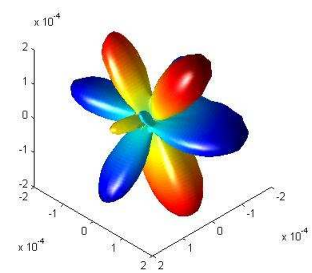
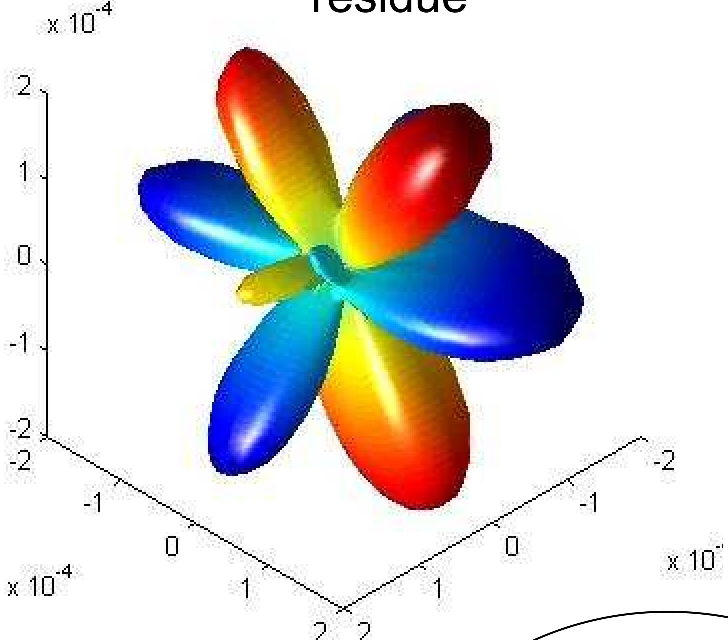


residue

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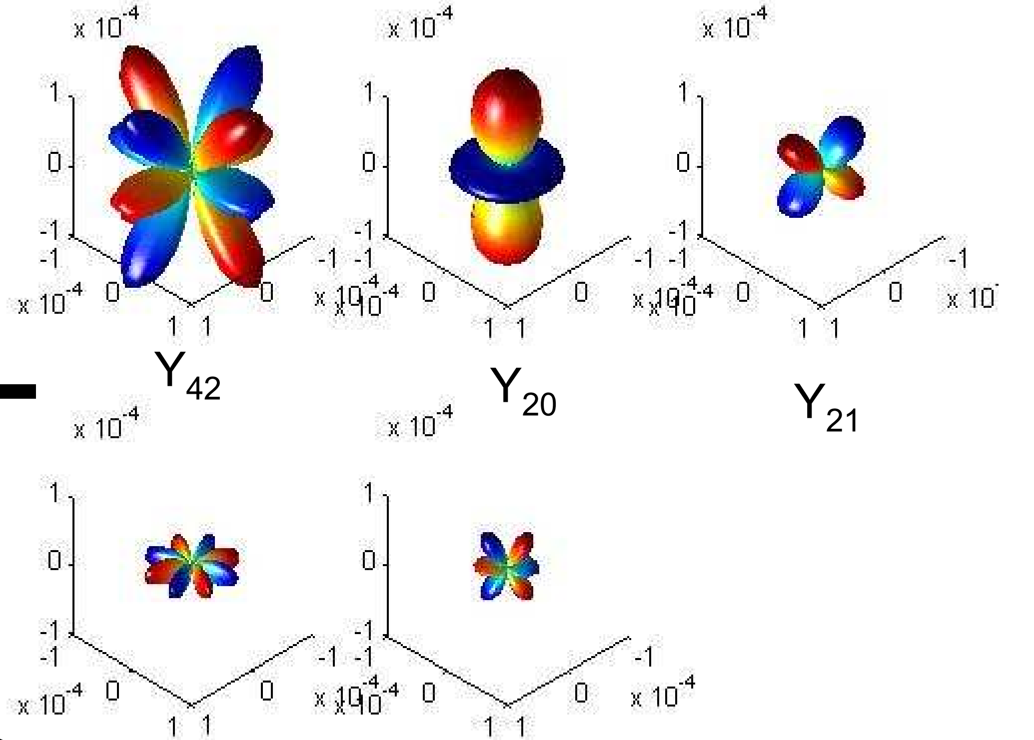


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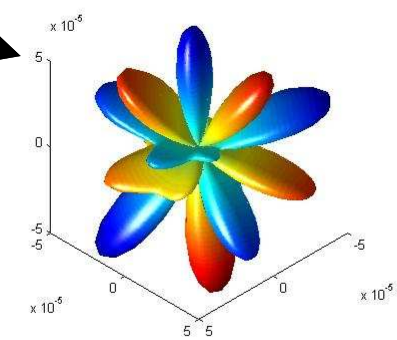
ZOOM 2 x

5 10-5



The components which are not symmetric around the Z-axis cannot be found with a calibration on main axis, because they are zero there

Hall voltage can be expressed in spherical harmonics ($Y_{lm}$) and Tchebychev polynomials ($T_n$) :

$$\boxed{V_H(|B|,t,\theta,\varphi) = \sum_k \sum_n \sum_l \sum_{m=0}^{l} c_{klm} T_k(B) d_{nlm} T_n(t)\ \ Y_{lm}(\theta,\varphi)}$$

$c_{klm}$ for |B|dependence, $d_{nlm}$ for temperature (t) dependence, need to be determined by a calibration. (with compression about 1 kb per B-sensor )

L ≠ 0 $C_k$'s rise roughly with $|B|^L$ => more important at higher fields

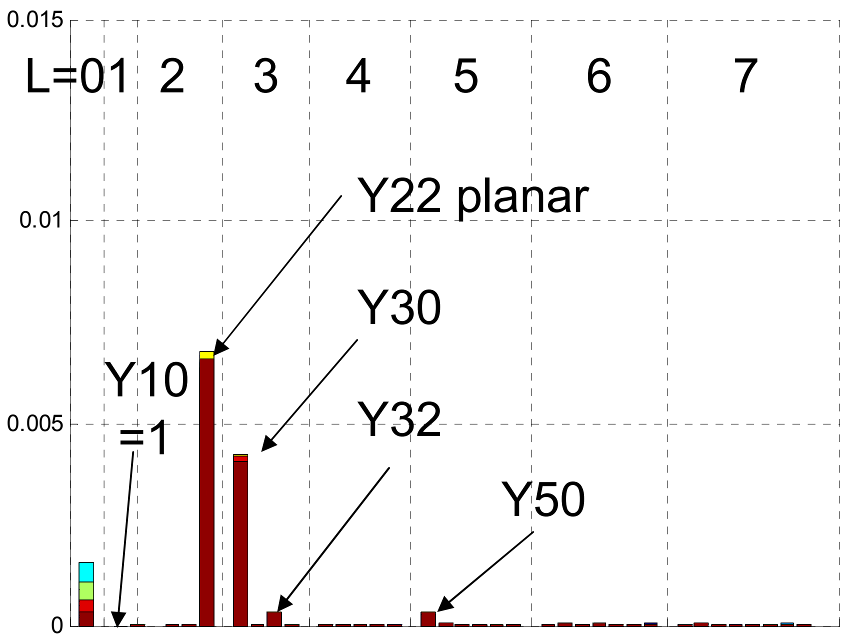
Errors > 50 % possible

3 Hall probes cannot be mounted perfectly orthogonal , can use symmetry axes of $Y_{lm}$'s as reference for their orientation

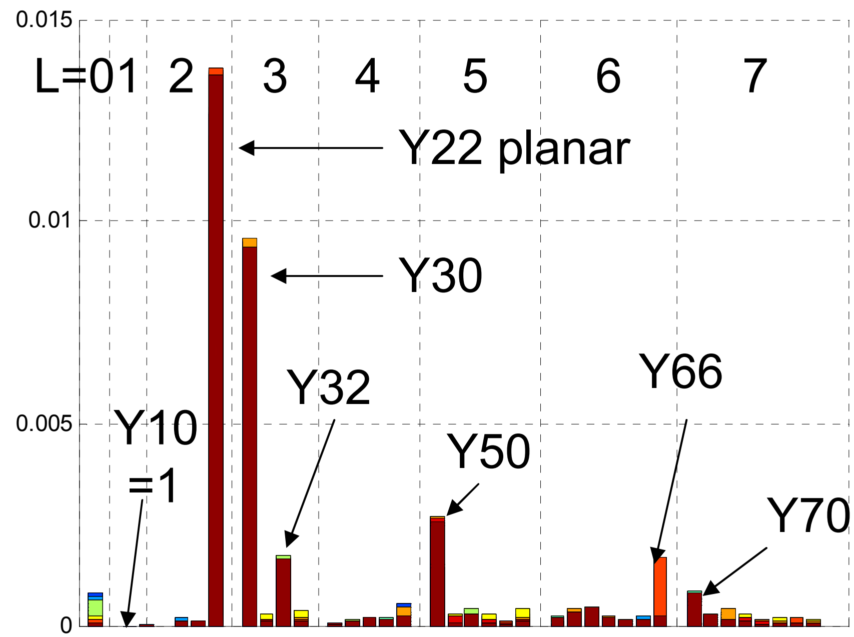
# Scaling of Ylm 's with |B|

$Y_{11}$ set to zero by rotation, $Y_{10}$ (z) set to one (not shown)

$Y_{22}$ should be 3.2 x bigger, $Y_{32}$ 10.3 x @ 4.5 Tesla according to $|B|^L$
In reality they are resp. 2 X and 5 x bigger



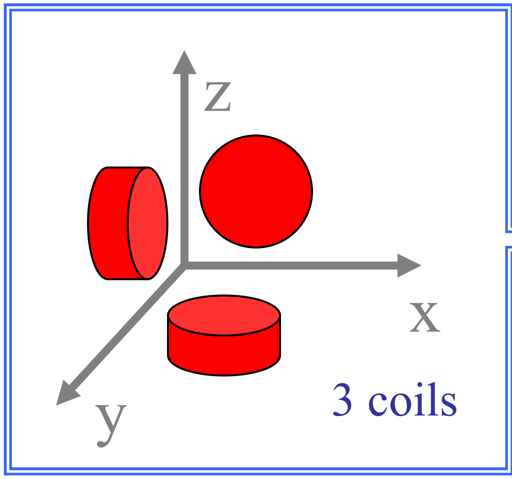

1.4 Tesla




4.5 Tesla

# How to do ?

Theta and phi must be very precisely known to be able to dig the small perturbations out of the large cos theta "background"




Rotate sensor continuous over two axes in constant homogeneous field , $\theta$ and $\varphi$ measured very precisely [0.02 mrad] by 3 small coils. |B| from NMR. Repeat for several field strengths and temperatures, find $c_{klm}$, $d_{nlm}$

For reconstruction solve inverse problem :

$Vhall_1$, $Vhall_2$, $Vhall_3$, T, $c_{klm}$, $d_{nlm}$ => $B_x$, $B_y$, $B_z$

For more details see IMMW13 -14 talks

Rotation must be slow and without vibration to not perturb the integration of the coil signal

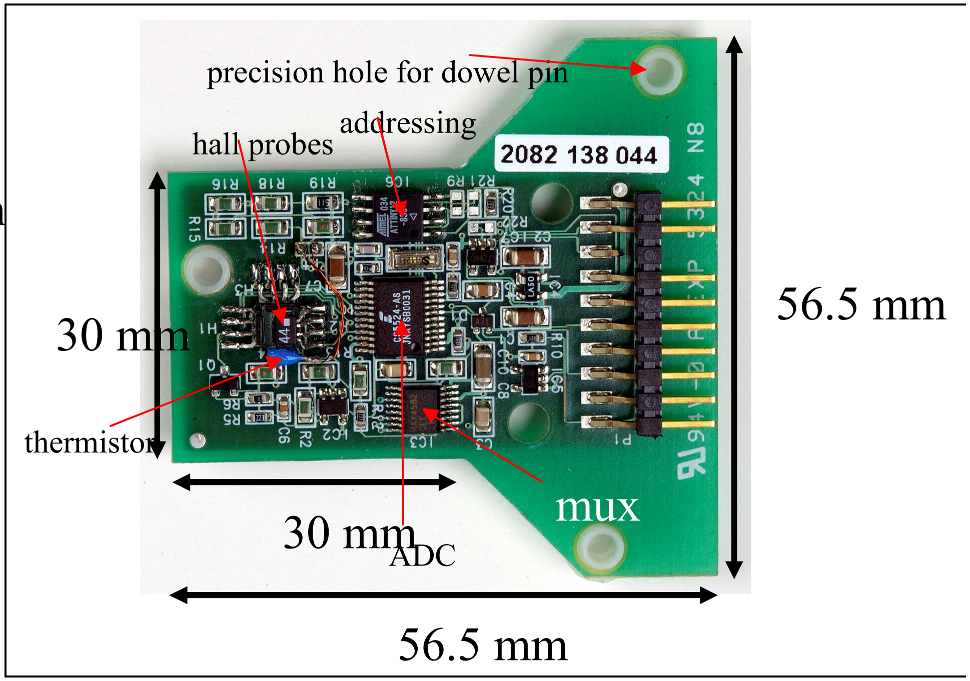
Need alignment procedure to find possible (small) rotation of coil reference frame with respect to sensor reference frame
(coils cannot be positioned with infinite precision)

# B-sensor card

• Small card containing all analog electronics $\Rightarrow$ electronics in same field as Hall probes, calibrated together

• 3x Siemens KSY44 glued on glass cube

• Hall current 230 μA $\Rightarrow$ small heat dissipation
( $I_{nom}$ = 5mA )




• ADC: 24-bits delta-sigma modulator

• Thermistor connected to cube, no thermostat

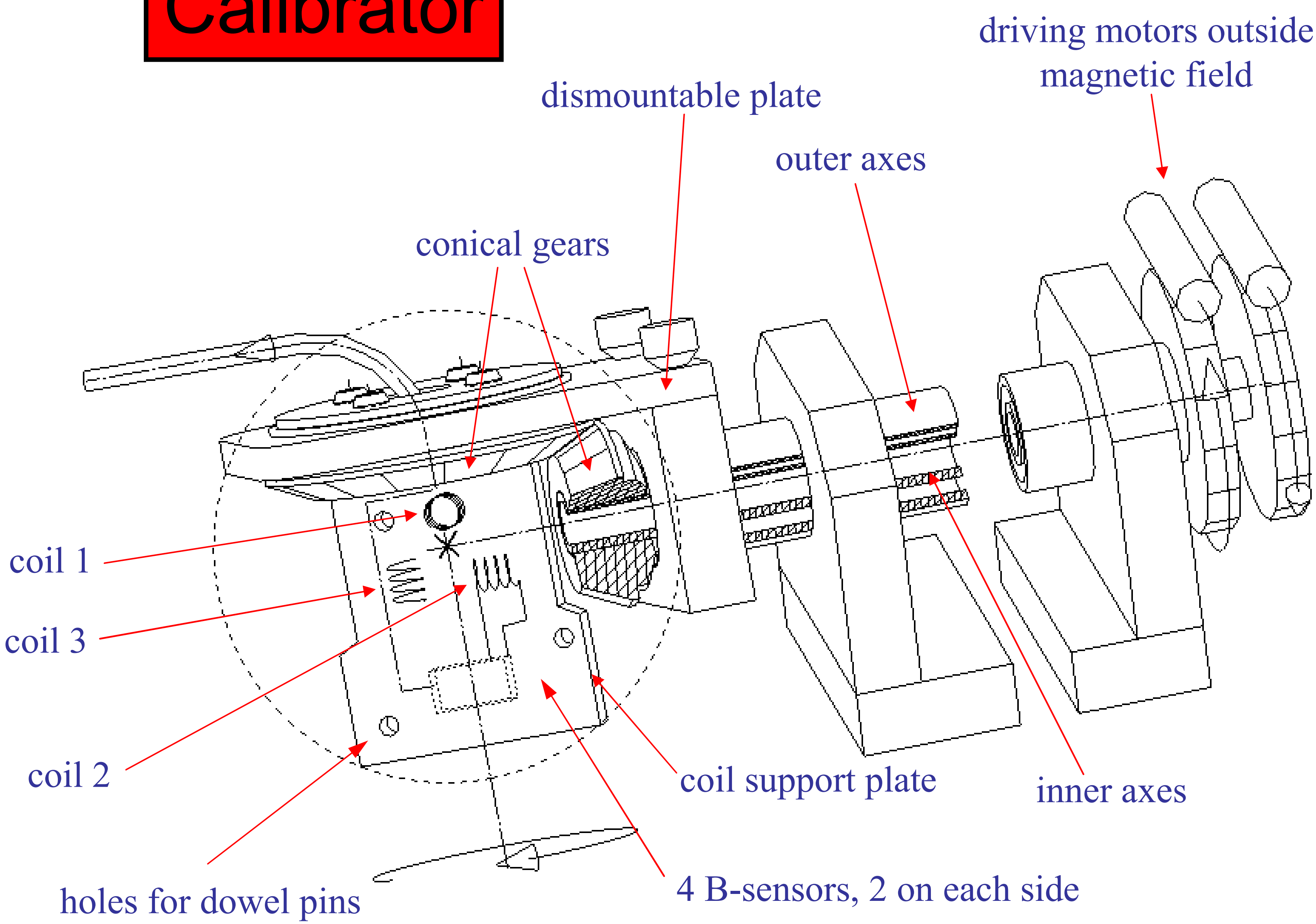
• Calibration circuit for thermistor

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

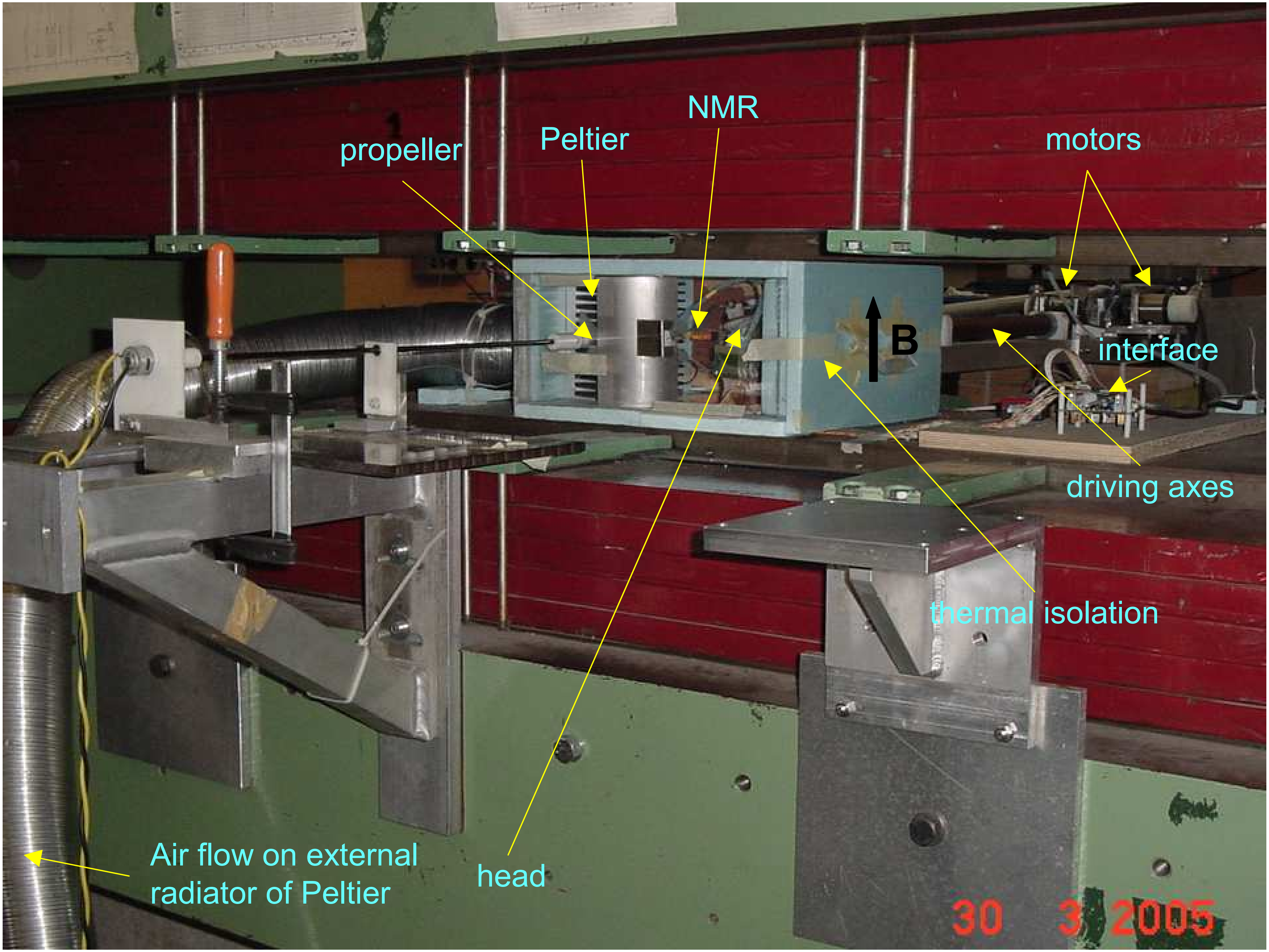
• Addressable: 254 cards on one serial bus, broadcast address

B-sensor development in collaboration with the Dutch scientific institute NIKHEF for the ATLAS detector at the CERN-LHC collider.
H. van ES, J. Kuijt, H. Boterenbrood

# Calibrator

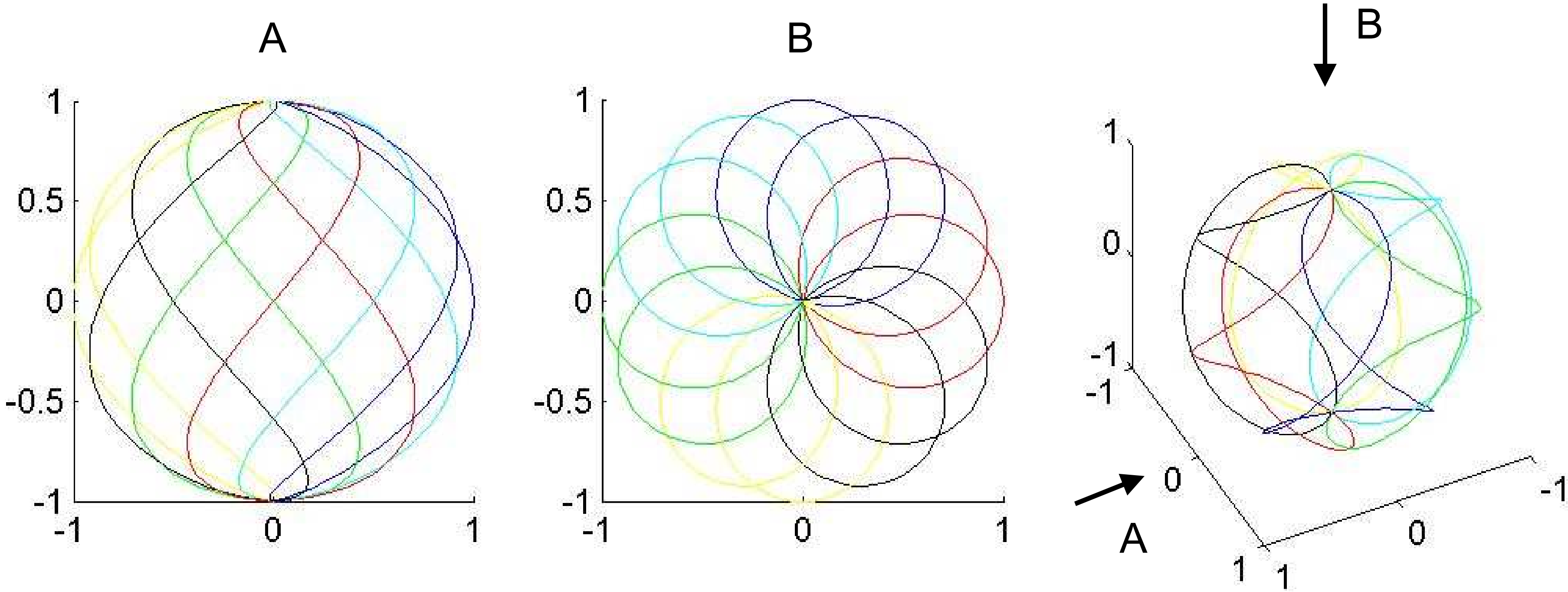



Long and heavy axes => damping of vibrations


NMR
propeller
Peltier
motors
B
interface
driving axes
thermal isolation
Air flow on external
radiator of Peltier
head
30 3 2005

**B**

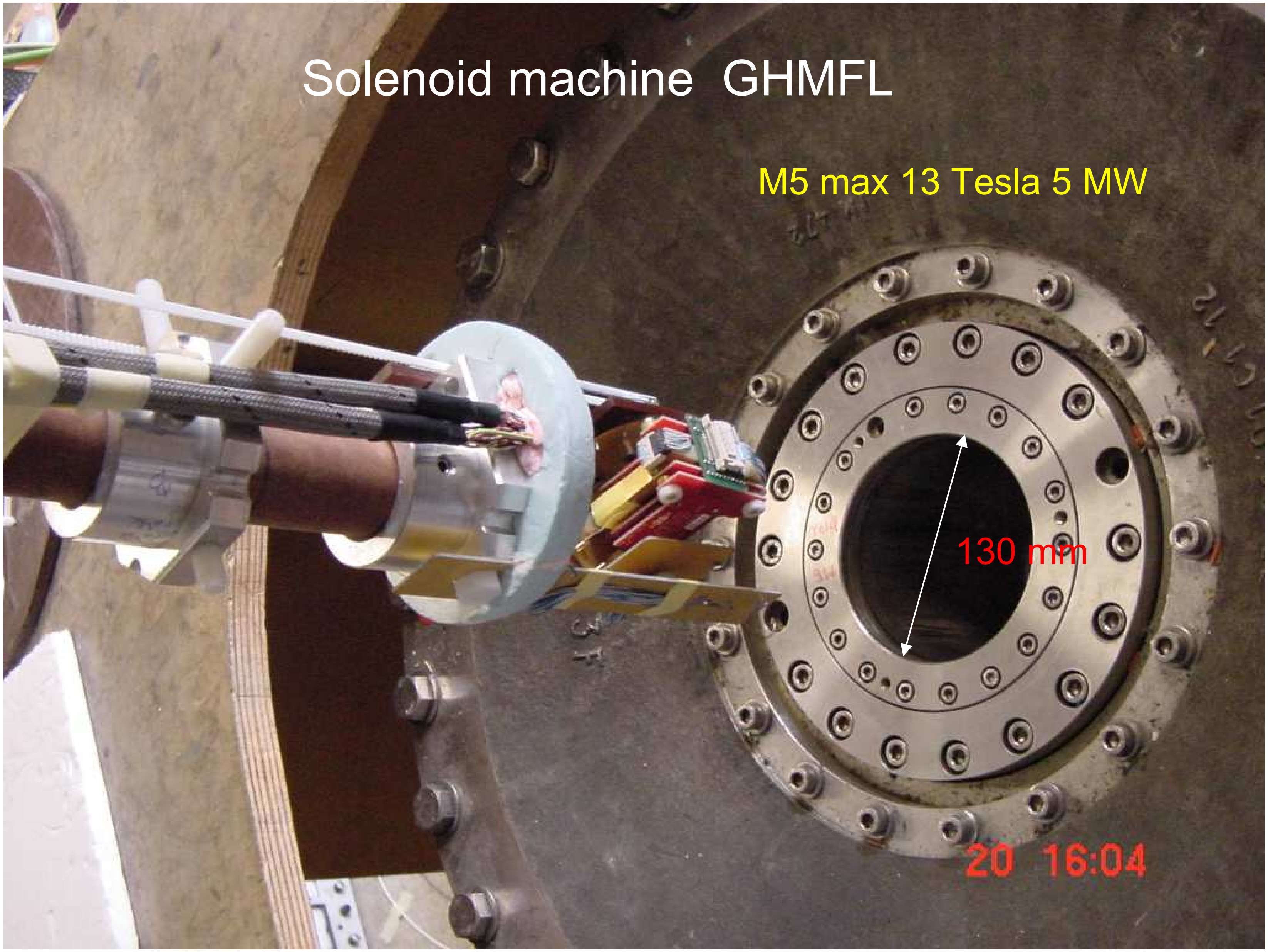
# Trajectory of B-vector on calibrator




Each 2 $\pi$ turn of main axes
has different color

Outer axes 6 turns
Inner axes 5 turns

Full coverage of unit sphere
Regular movement, no error build up


Solenoid machine  GHMFL
M5 max 13 Tesla 5 MW
130 mm
20 16:04

# GHMFL Grenoble

M5 max 13 Tesla 5 MW

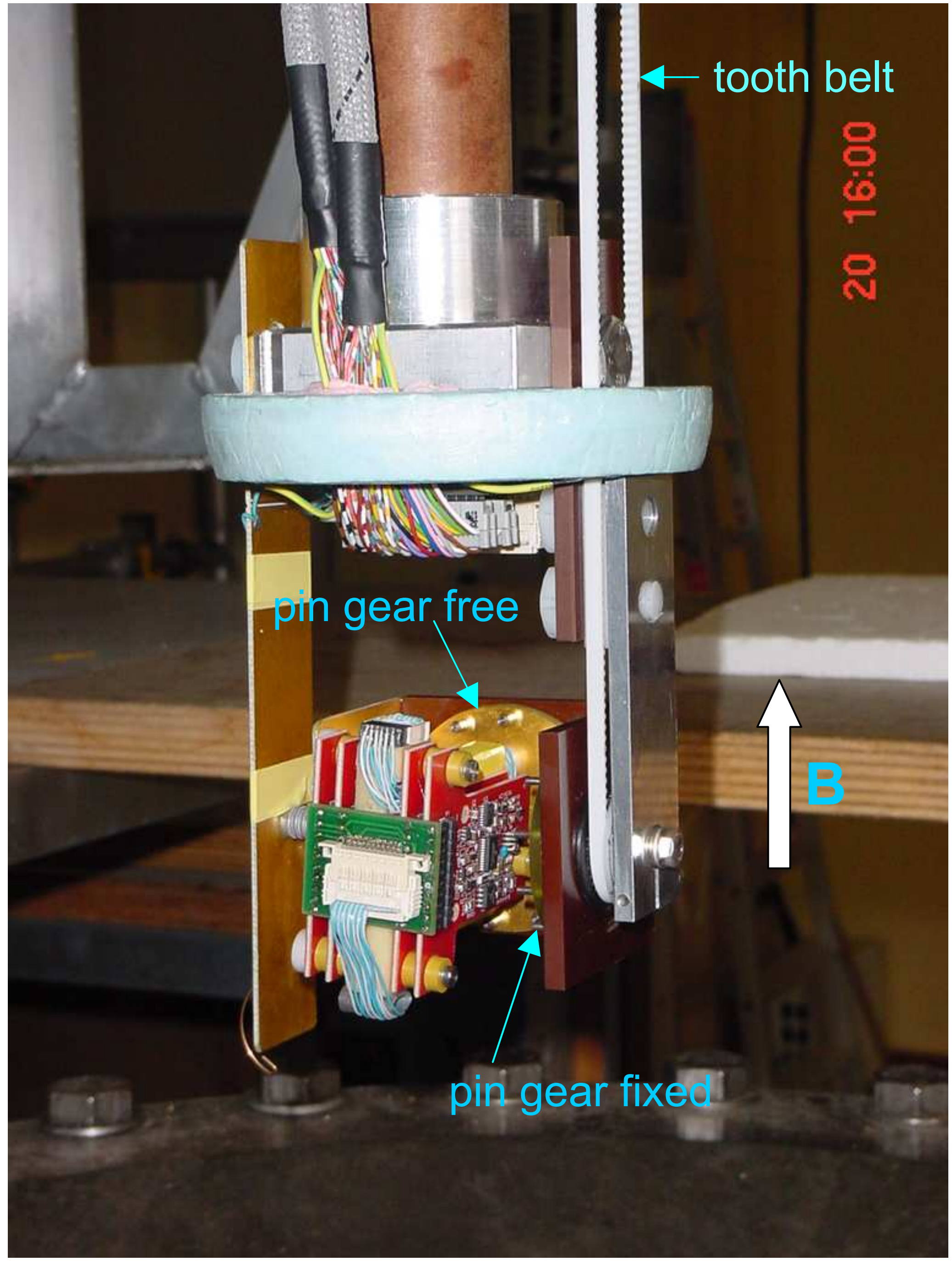
Homogeneous field region smaller than dipole machine
NMR only before and after Calibration
Use coil sensitivity

Only one belt drive
“pin” gears 10/12

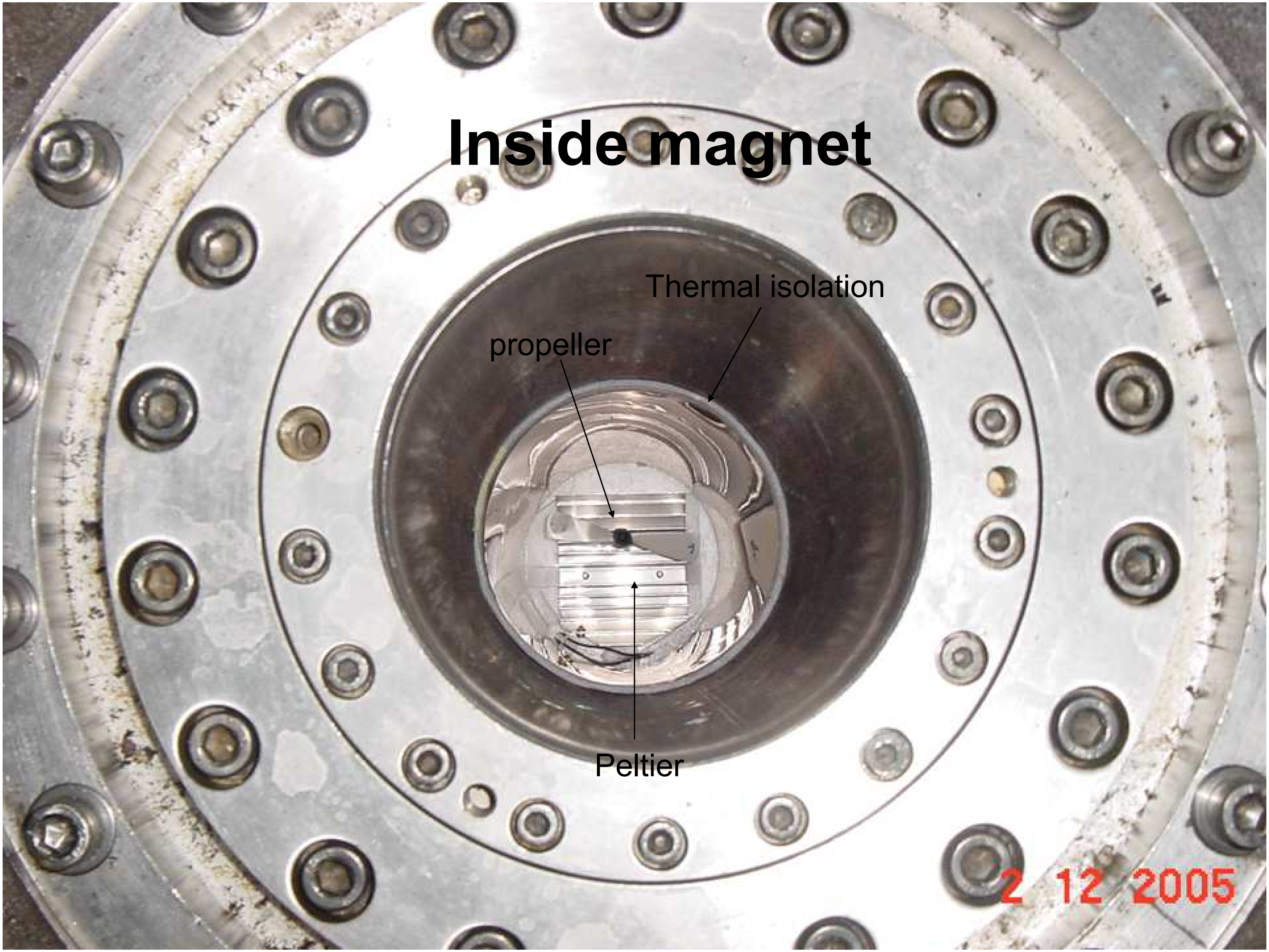
Vibrations damped by silicon grease

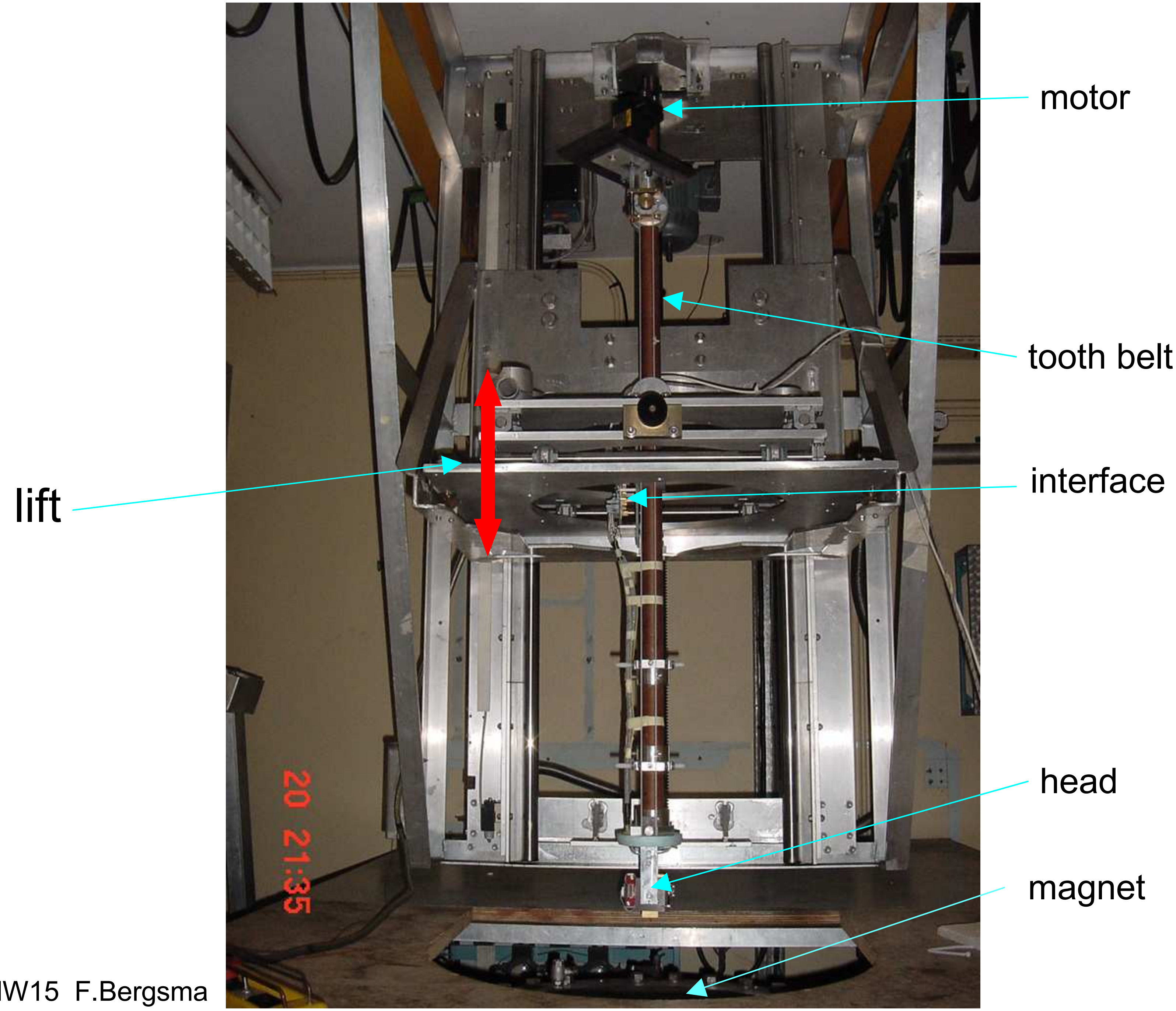
Field less stable as MNP24
$X^2$ 2 x MNP24

| | | |
|---|---|---|
| Used for: | CMS | 4.5 T |
| | ATLAS | 2.5 T |
| | MICE | 4.5 T |



# Inside magnet




motor
tooth belt
interface
lift
head
magnet
20 21:35

# System used by:

ATLAS fixed 1.4 T  1837 delivered on 1900

ATLAS solenoid mapper  48 2.5 T

CMS fixed   70   1.4T

CMS mapper + fixed  20  4.5 T

LHCb dipole mapper 60 1.4 T

ALICE dipole + solenoid mapper 60 + 20 1.4T

EUDET solenoid mapper 24 1.4 T

MICE   4.5 T   28  in progress

# performance

Long term stability (2 years):

|B| +/- 2 gauss for 1.4 Tesla sensors

stability hall probe position 0.3 mrad

“Absolute” angular precision 1.3 mrad, due to limited position reproducibility . The probes have to be positioned in the experiment exactly the same way as in the calibrator. To improve this number the feet have to be redesigned. To approach 0.3 mrad alignment in situ is necessary.

The initial problems with the addressing of the cards during LHCb and ALICE mapping are solved: during the ATLAS solenoid mapping with 4 chains of 12 addressable sensors no single read-out error occurred

The fixed cards of ATLAS and CMS have an 8 byte ID-chip (DS2401 Dallas) which is a great help to administrate large numbers of them

# Future plans

“Mass” production => simplify hardware and software
2.5 Tesla CERN PT9 magnet
13 Tesla GHMFL M5 magnet

Easy read-out daisy chaining, CAN USB

Miniaturization reduce amount of components on sensor card

Better fixation Hall probes, bare chips + bonding?

Better feet more precise, increase position reproducibility

Better alignment optical markers on card?

etc.

## Difference for 3x Siemens KSY44 at 1.5 T , 20 $^0$C in 3x single axes and 3D calibration

Single axes = only main axes calibration

$B \Rightarrow B_z$

New method = 3D scan

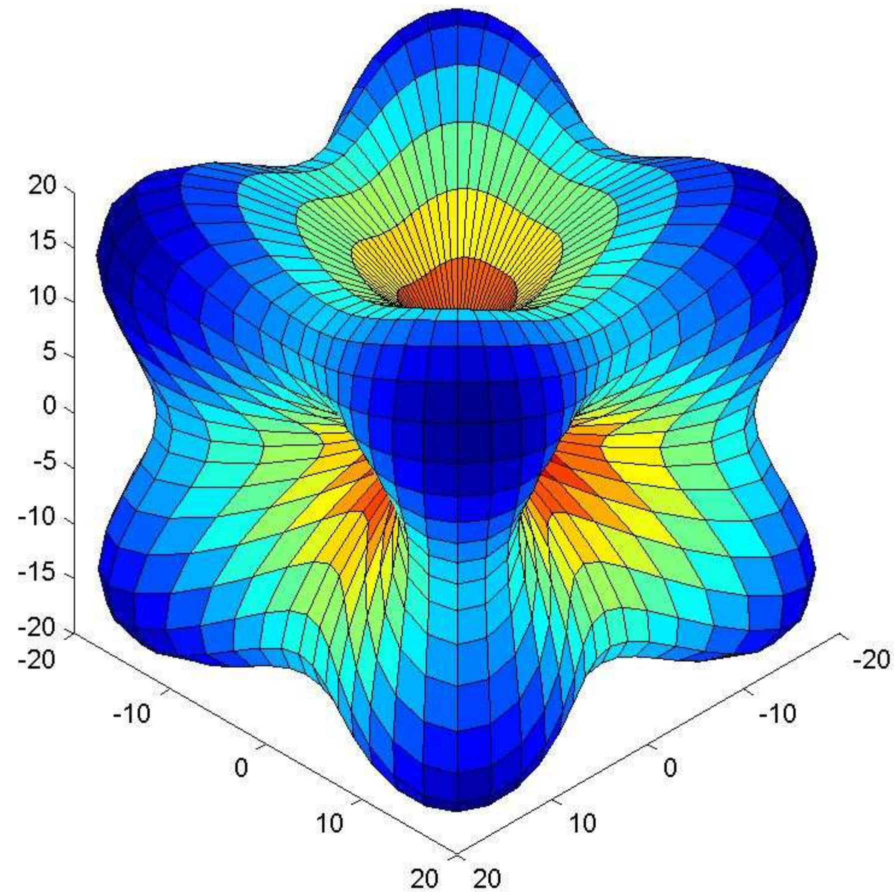
# Only symmetrical components $Y_{lm}$ m=0 => PHE off

no change of symmetry axes, simulated data with measured parameters

Plotted in figure: $|B_{old}-B_{new}|(\theta,\varphi)$
Color scale = $|B_{old}|-|B_{new}|$
Blue = -31 Gauss, red = 0

**At calibration axes error is zero, increases to 2 ‰ off axes.**

Difference at 1.5 Tesla




Scales in Gauss