Calibration of Hall sensors in three dimensions

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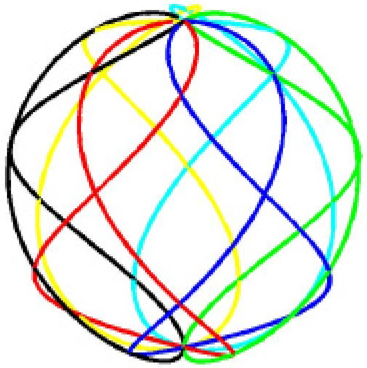

IMMW13
SLAC, May 19-22, 2003

Outline:

- Old methods not good enough for precision better than 10^{-3}
- Full 3D scan necessary
- Machine to do it
- 3D sensor with 10^{-4} precision
- Results
- Future developments

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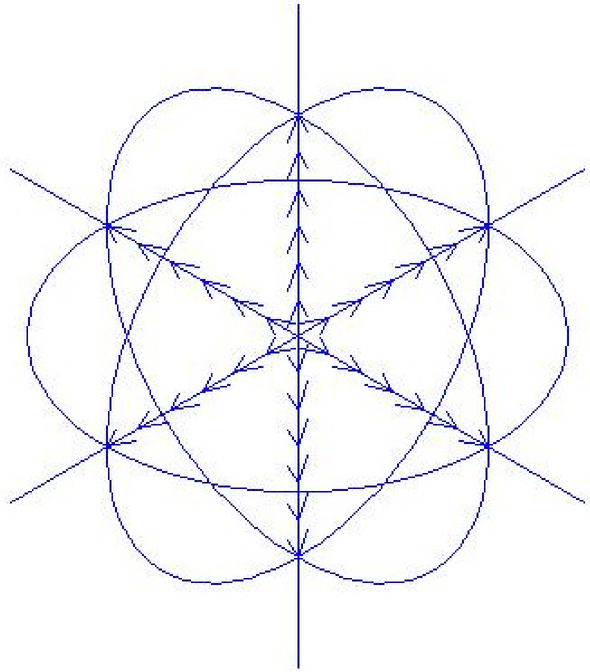
How to calibrate a 3D magnetic sensor with three more or less orthogonal Hall probes?

Correct for:

- Non-linearity
- Non-orthogonality
- Temperature dependence of sensitivity
- Planar Hall Effect (PHE)
- etc

Many tricks available:

- Main-axes calibration
- invert field: main signal changes sign, PHE not, prop. to $B^2 \sin 2\varphi$
- Rotate over xy, xz and yz axes : PHE + non-orthogonality
- Search for 0 Volt position with special balance
- Two hall probes back to back to cancel PHE
- etc



We tried: cubes with 6 hall probes

1. Main axes calibration for x, y and z,   -2.4 T to 2.4 T,   step 0.1 T
2. Rotation about xy, xz and yz axes at 0.5, 1.0 and 1.5 T,   step 15 deg

Result:

Measurements at arbitrary positions ⇒ max. error of order 10^{-3} in |B|

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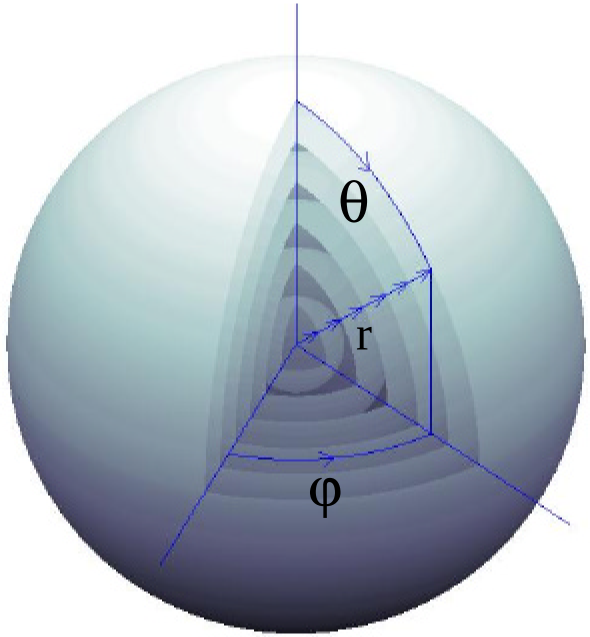

Solution = full 3D scan:

Rotate sensor over two orthogonal axes in constant homogeneous field , θ and φ should be measured very precisely

Repeat for several field strengths and temperatures, |B| and T should be measured very precisely

Decompose the Hall-voltage in orthogonal functions: spherical harmonics for θ and φ, Chebyshev polynomials for |B|.

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Spherical harmonics $Y_{lm}(\theta,\varphi)$

Rotation at constant |B|: $V_{Hall}(\theta,\varphi) = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} c_{lm} Y_{lm}(\theta,\varphi)$

$$c_{lm} = \int Y^*_{lm}(\theta,\varphi) V_{Hall}(\theta,\varphi)\, dO$$

$$\int_0^{2\pi} d\varphi \int_0^{\pi} \sin\theta\, d\theta \cdot Y^*_{l'm'}(\theta,\varphi) Y_{lm}(\theta,\varphi) = \delta_{l'l}\delta_{m'm} \qquad Y_{lm}(\theta,\varphi) = \sqrt{\frac{2l+1}{4\pi}\frac{(l-m)!}{(l+m)!}} P_l^m(\cos\theta) e^{im\varphi}$$

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

$l=0$

$$Y_{00} = \frac{1}{\sqrt{4\pi}}$$

$l=1$

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

$l=2$

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

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How do Y_{lm} scale from one |B| to another?

Solid harmonics $r^l Y_{lm}(\theta,\varphi)$

$$r^l Y_{lm}(\theta,\varphi) = \sqrt{\frac{2l+1}{4\pi}(l+m)!(l-m)!}\sum_{p,q,r}\frac{1}{p!q!r!}\left(-\frac{x+iy}{2}\right)^p\left(\frac{x-iy}{2}\right)^q z^r$$

$$p+q+r=l,\ p-q=m$$

is power series $\sum_{p,q,r} c_{pqr} x^p y^q z^r$

$r^1 Y_{10}(\theta,\varphi) = z$ Main component

$r^2 Y_{22}(\theta,\varphi) = xy, x^2 - y^2$ Planar Hall effect

$r^3 Y_{30}(\theta,\varphi) = 2z^3 - 3(x^2 + y^2)z$ Non-linearity

$r^3 Y_{32}(\theta,\varphi) = xyz, (x^2 - y^2)z$

In decomposition of Hall voltage Y_{lm} coefficients scale more or less with $|B|^l$

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$$V(r,\theta,\varphi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} c_{lm}(r) \quad r^l Y_{lm}(\theta,\varphi)$$

Decompose $c_{lm}(r)$ in Chebyshev polynomials

$$\int_{-1}^{+1} \frac{T_i(x) T_j(x)}{\sqrt{1-x^2}} dx = \begin{cases} 0 & i \neq j \\ \pi/2 & i = j \neq 0 \\ \pi & i = j = 0 \end{cases}$$

$$T_0(x) = 1 \qquad -1 \leq x \leq 1$$

$$T_1(x) = x$$

$$T_2(x) = 2x^2 - 1$$

$$T_3(x) = 4x^3 - 3x$$

$$T_4(x) = 8x^4 - 8x^2 + 1$$

...

$$T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x) \qquad n \geq 1$$

$$T_n(x) = 0 \quad at \quad x = \cos\left(\frac{\pi(k-\frac{1}{2})}{n}\right) \qquad k = 1,2,\ldots,n$$

Extremes: $T_n(x) = \pm 1 \;\; at \quad x = \cos\left(\frac{\pi k}{n}\right) \qquad k = 0,1,\ldots,n$

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Rotate Y_{lm} to symmetry axes of hall probe:
$Y_{11} = 0$ (only $Y_{10} = \cos\theta$) , $Y_{22} = \sin^2\theta \sin 2\varphi$ (PHE)

Parameters of calibration at fixed |B| and T per hall probe:

Y_{lm} coefficients in symmetry frame (64-3 for $l = 7$)
Direction of symmetry axes (2)
Rotation around symmetry axes (1)

Calibration at 0.25 - 0.5 - 0.75 - 1.0 - 1.25 - 1.5 Tesla
and 16 - 18 - 20 - 22 - 24 deg. Celsius

Interpolate with Chebyshev polynomials and reduce:
For $0.5 \cdot 10^{-4}$ precision is needed (3 x Siemens KSY44) :
about 40 +14 for Y_{lm} per hall probe (about 15 Y_{lm} per (B,T)-point)
36+3 for angles per sensor card
Total: ~ 200 parameters per sensor card
many are constant, common or dependend, can reduce more

Highest order Chebyshev needed: |B| = 5 →
T = 2

Maximum number of calibrations needed = 5B x 2T
3B x 2T realistic, 2B x 1T +1 simplified T maybe possible

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Difference for 3x Siemens KSY44 at 1.5 T , 20 ^{0}C in old method and new method

Old method = only main axes calibration
$B \Rightarrow B_z$

New method = 3D scan

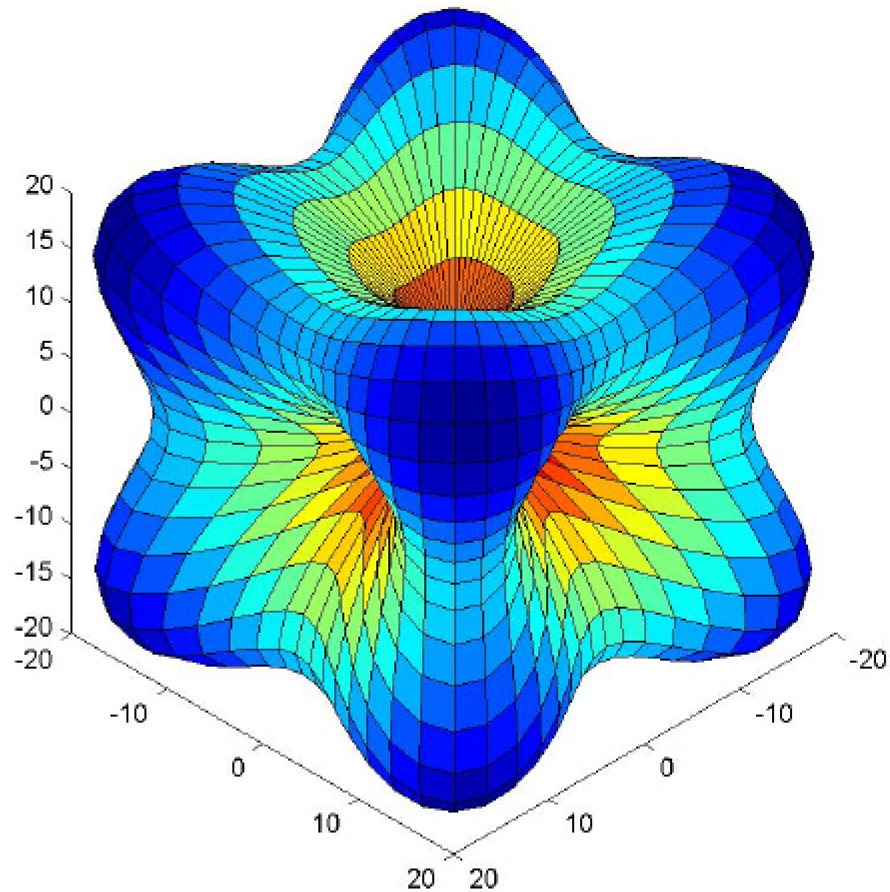
Only symmetrical components Y_{lm} m=0 => PHE off

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

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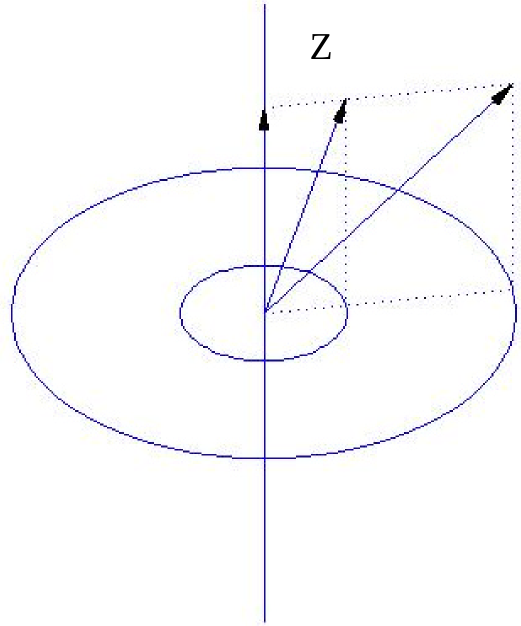
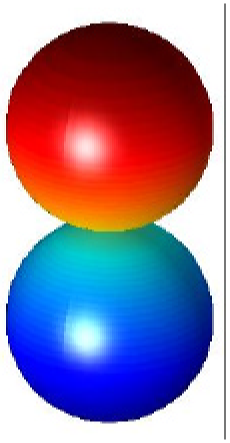
The sensitivity of a Hall probe depends not only on B_z, but also slightly on $|B|$
$B \Rightarrow B_z$ not allowed

Symmetry axes move with B and T

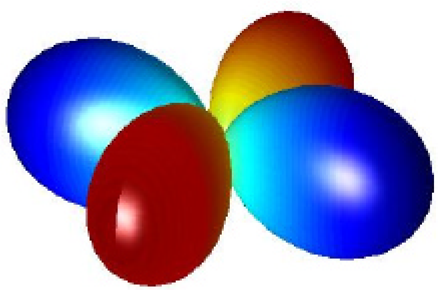
In addition there are $m \neq 0$ terms
Higher order terms increase with $\approx |B|^1$
Planar Hall effect not exactly ∞B^2



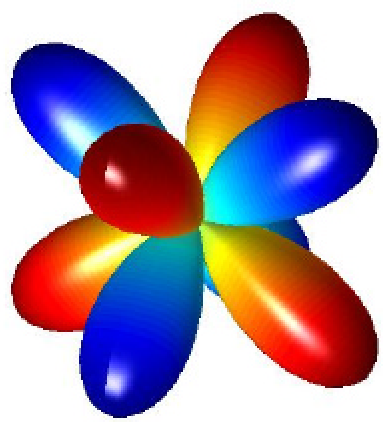
These B-vectors give all different Hall voltages.
Not to be confused with PHE, this effect is symmetrical around the z-axes



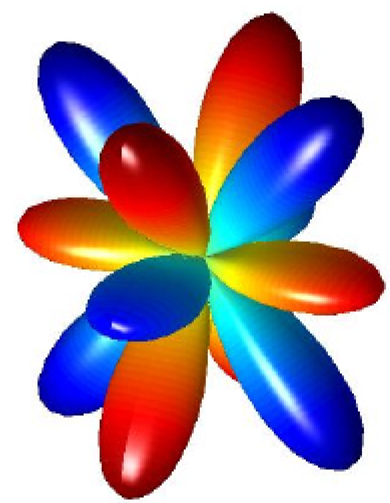
Y_{10}
Cos(θ)



Y_{22}
planar Hall effect



Y_{32}



Y_{42}

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Calibrator

Need θ and φ very precise < 10^{-4} on both
Difficult to realize with encoders

↓

Use three more or less orthogonal coils on rotating platform in constant homogeneous field
Sample coils with delta-sigma modulator
Continuous rotation on 2 axes, 2 rev/min on main axes, sample rate = 15 /sec

Adjust integrated coil signal to get $\sqrt{B_x^2 + B_y^2 + B_z^2} = 1$

Correct for:
Self-induction, non-orthogonality, offset ADC, start position, time constants
= 5 x 3 parameters

Method works because the integrated coil signal contains only Y_{lm} terms with $l \leq 1$
Not possible with Hall probes because of non-linearity, PHE, etc.

- Take mean of left and right turn against parasitic self-inductions
- # of turns of outer axes ≈ order of Y_{lm} extractable

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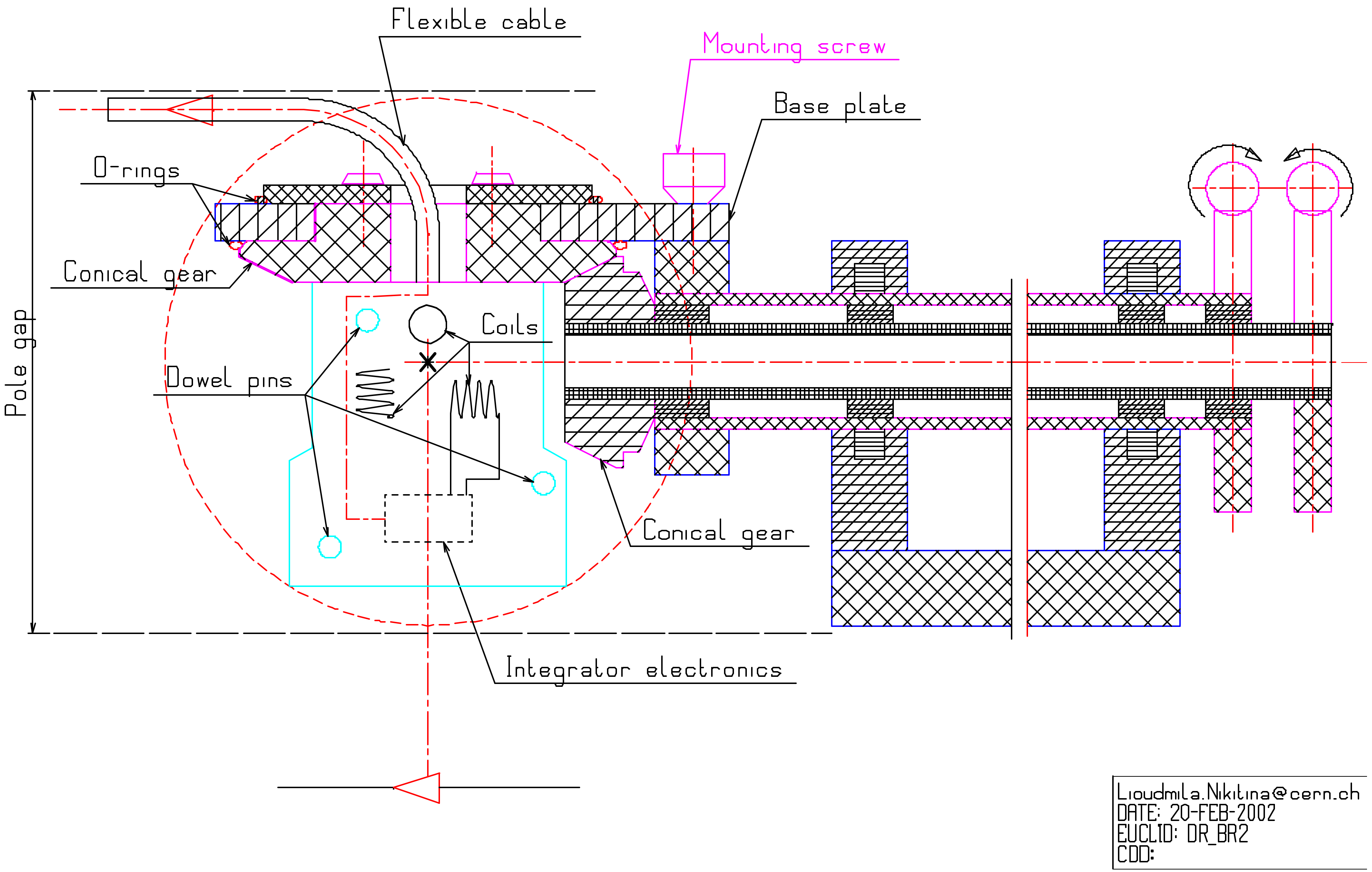
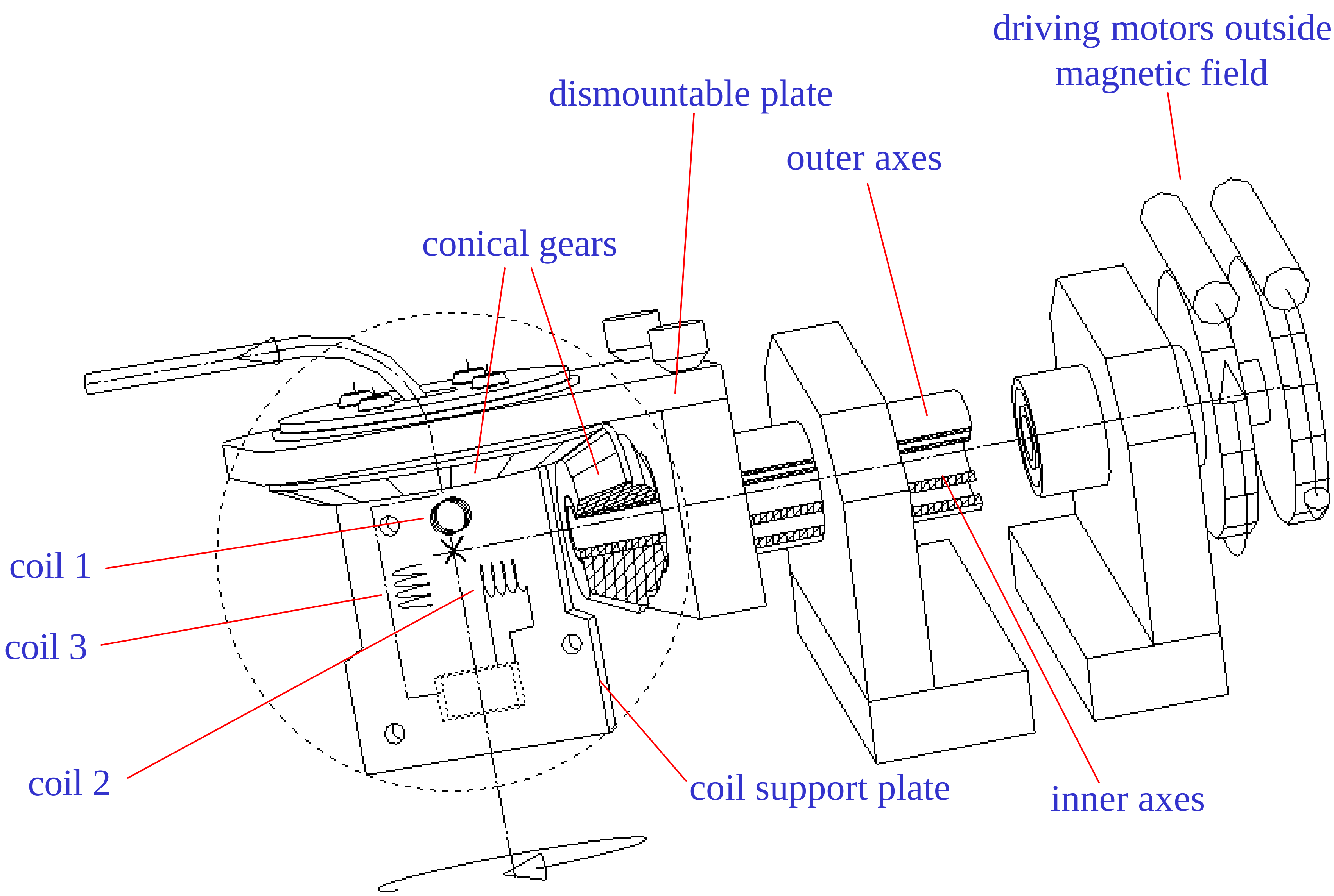
Calibrator

- With every coil (3x) sample also one Hall probe or thermistor is measured
- |B| measured by 2 NMR's at 10 and 25cm from center
- Temperature controlled by Peltier element + ventilator
  Temperature stability ±0.02 deg.C
- Support plate with coils and sensor cards easily removable from rest of the device
  Place for 4 sensor cards, fixed with dowel pins, precision ≈ 0.01 mm
- Cable winds by main axis, but unwinds by secondary axes:
  At end of calibration cable has made only one turn
- Typical calibration takes 6 turns of main axes = 3 min

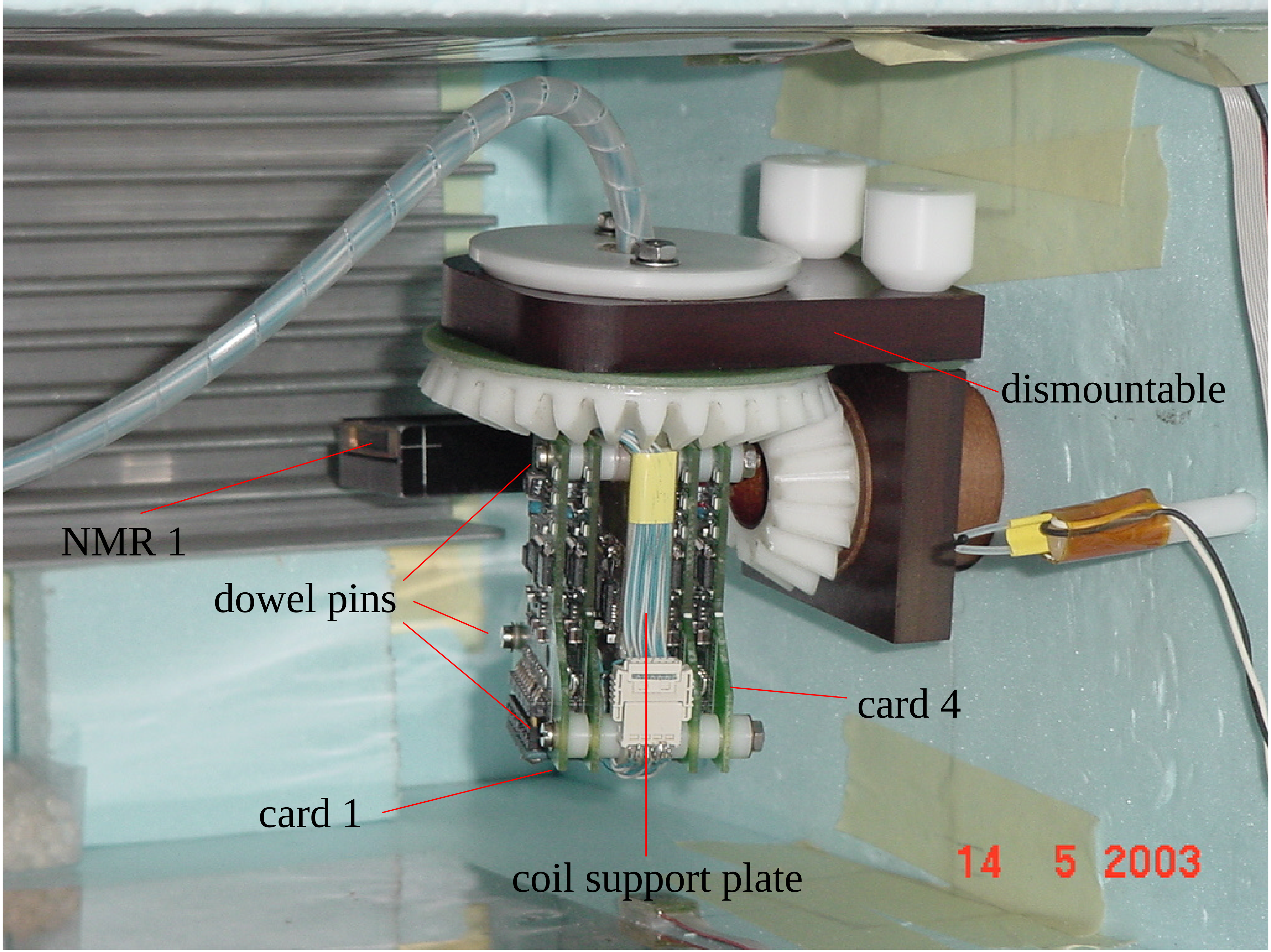
Simple and cheap device, vibrations point of care

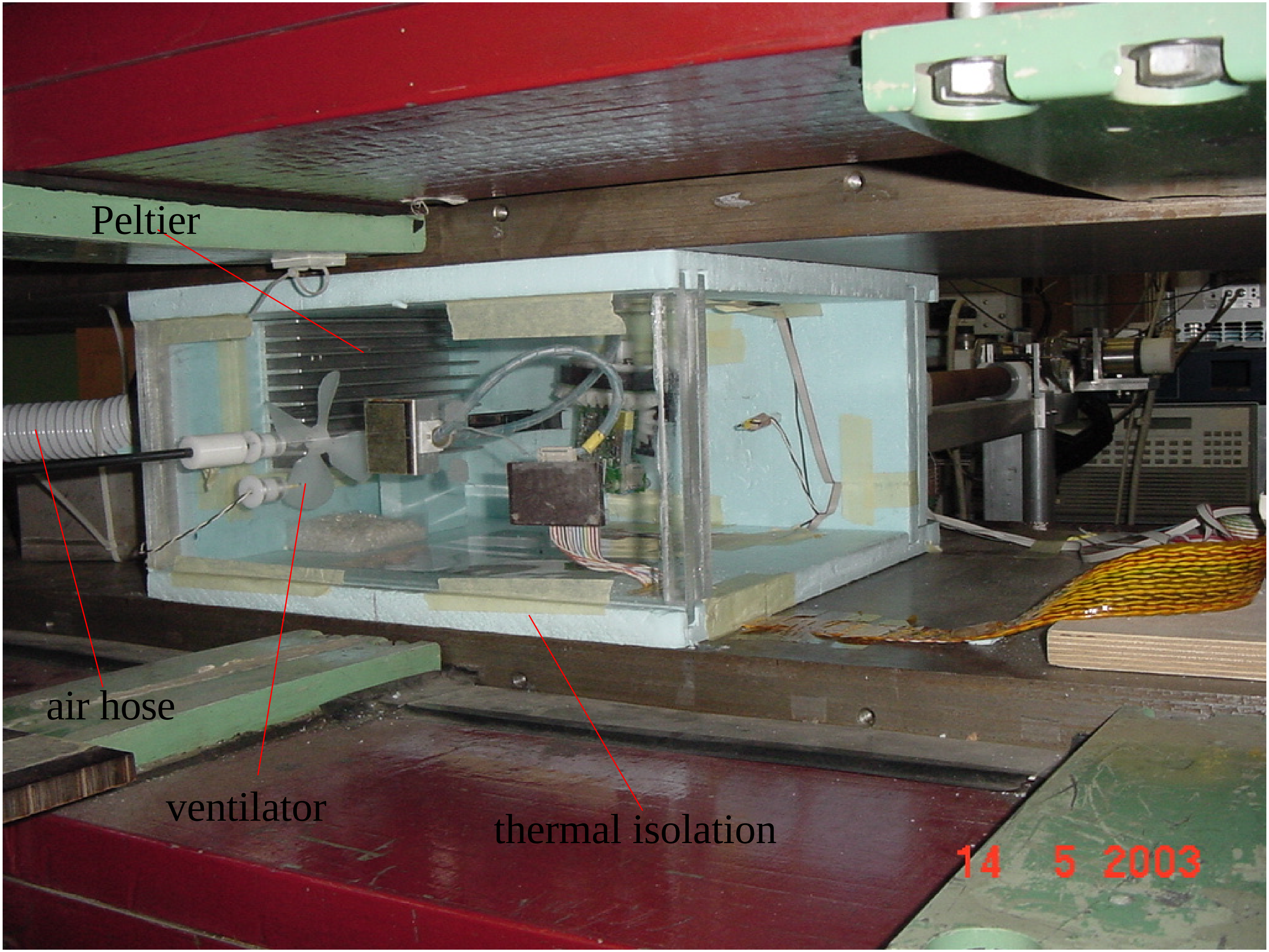

Flexible cable
Mounting screw
Base plate
O-rings
Conical gear
Pole gap
Coils
Dowel pins
Conical gear
Integrator electronics
Lioudmila.Nikitina@cern.ch
DATE: 20-FEB-2002
EUCLID: DR_BR2
CDD:

13


driving motors outside
magnetic field
dismountable plate
outer axes
conical gears
coil 1
coil 3
coil 2
coil support plate
inner axes

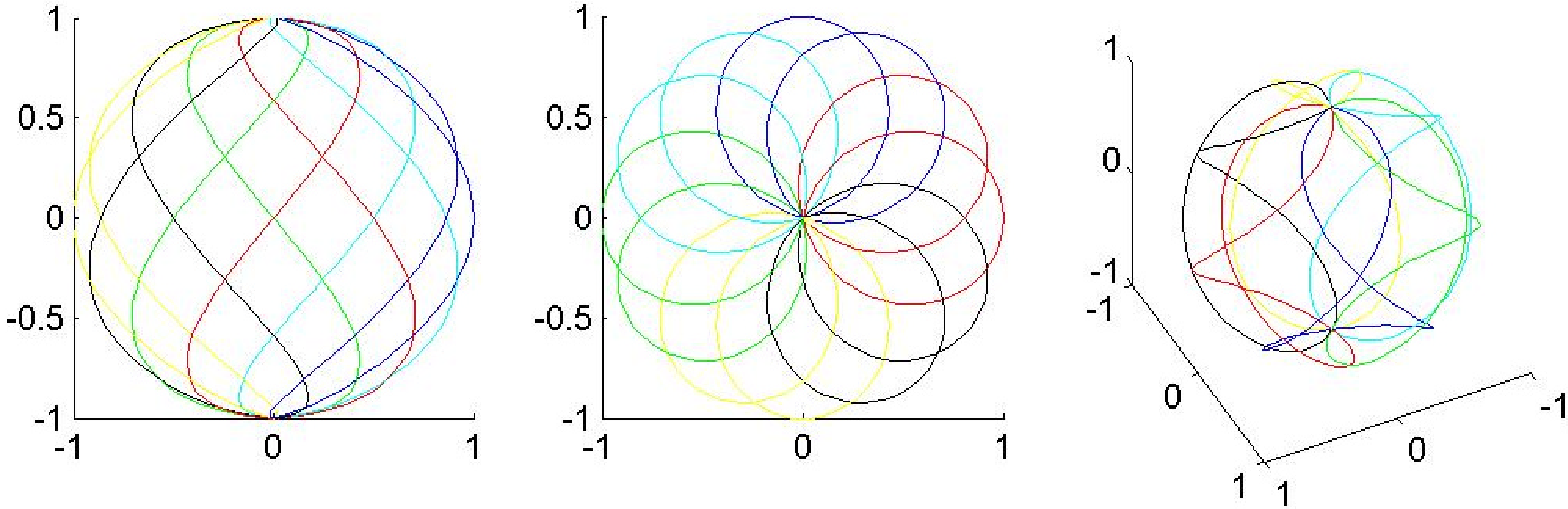
14


dismountable
NMR 1
dowel pins
card 4
card 1
coil support plate
14 5 2003


Peltier
air hose
ventilator
thermal isolation
14 5 2003


worms
stepper
motors
14 5 2003

Trajectory of B-vector on calibrator



Each 2 π 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

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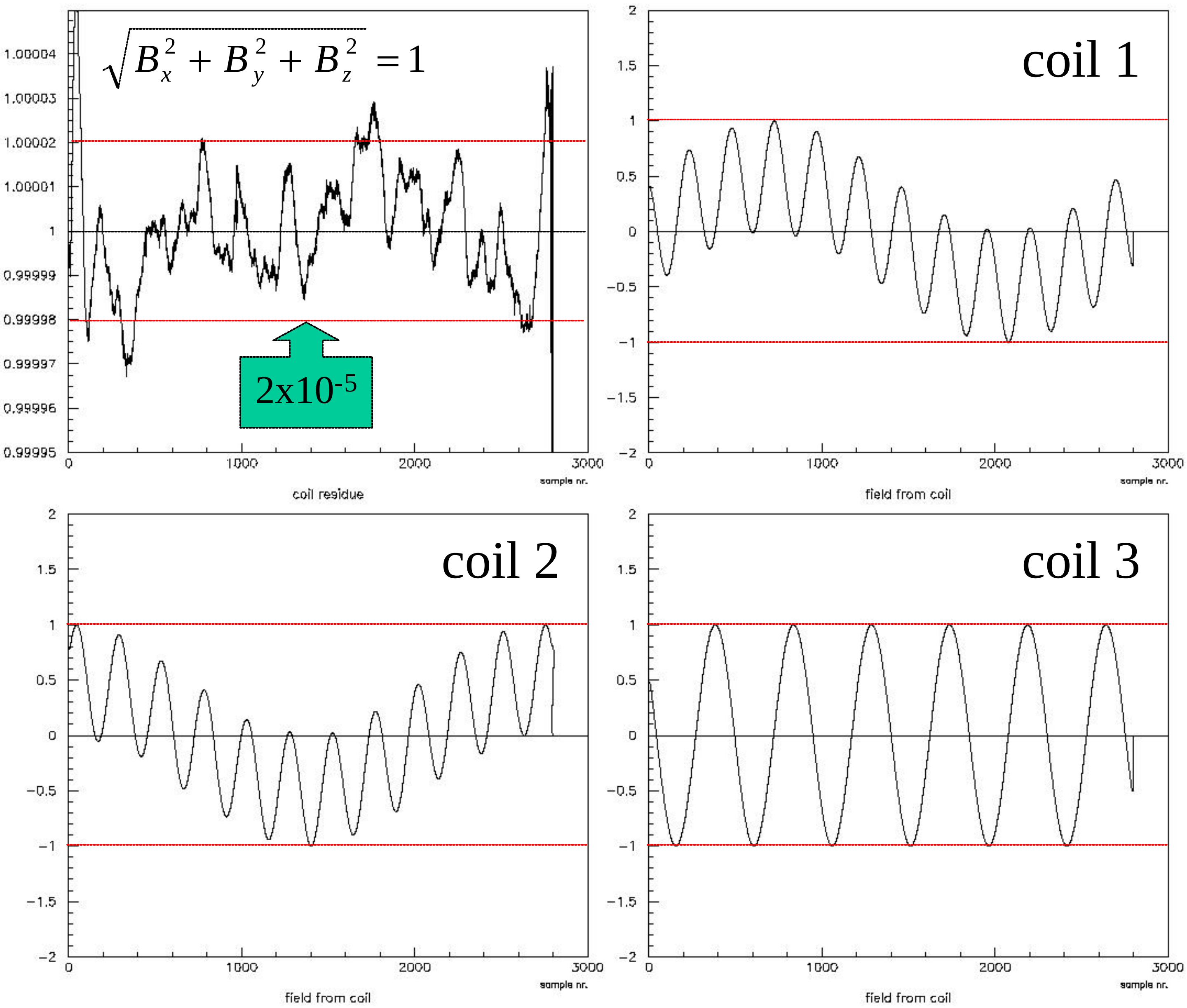
Results of coil fit



Horizontal scale = time in 1/15th sec.

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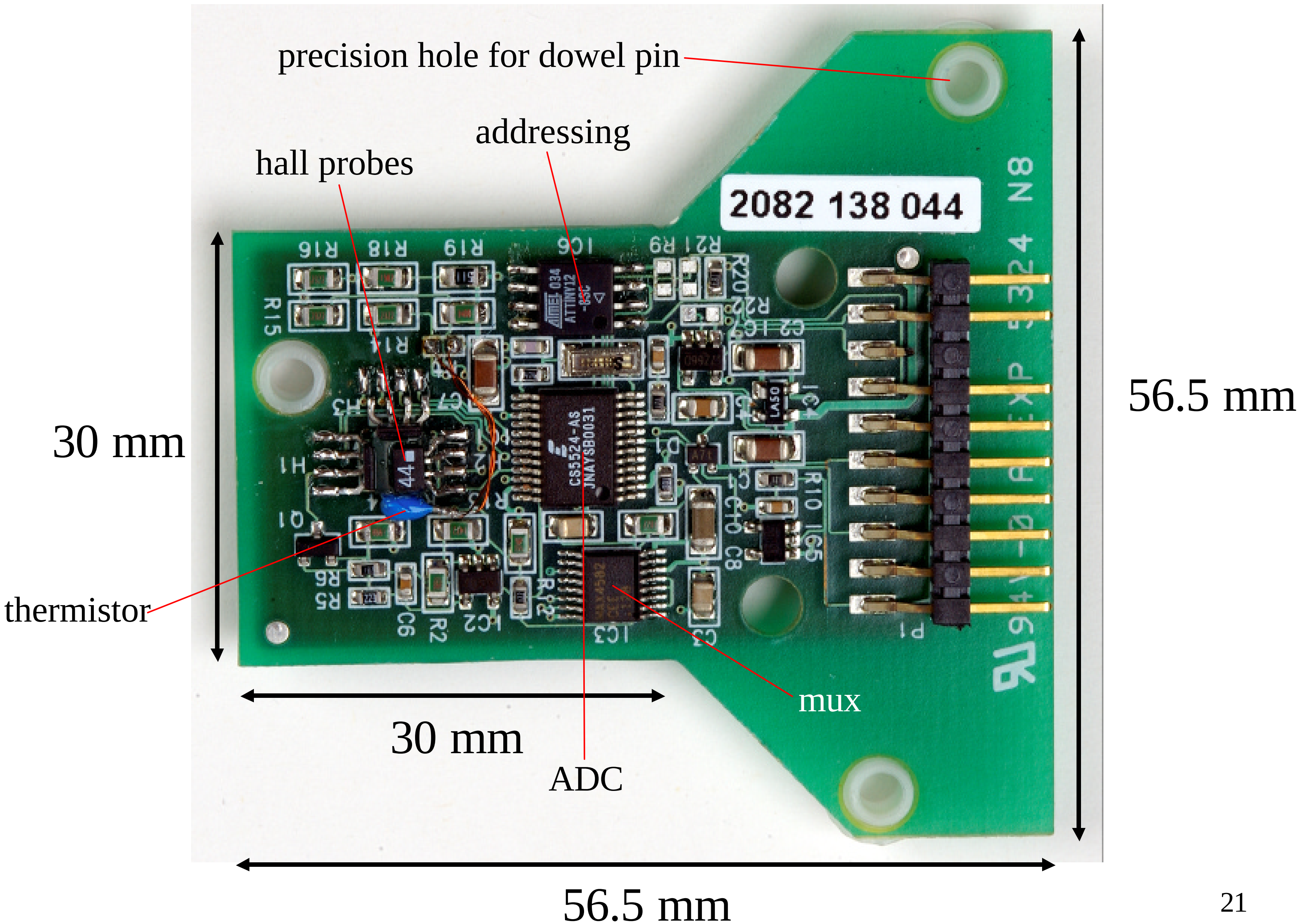
3D magnetic sensor card

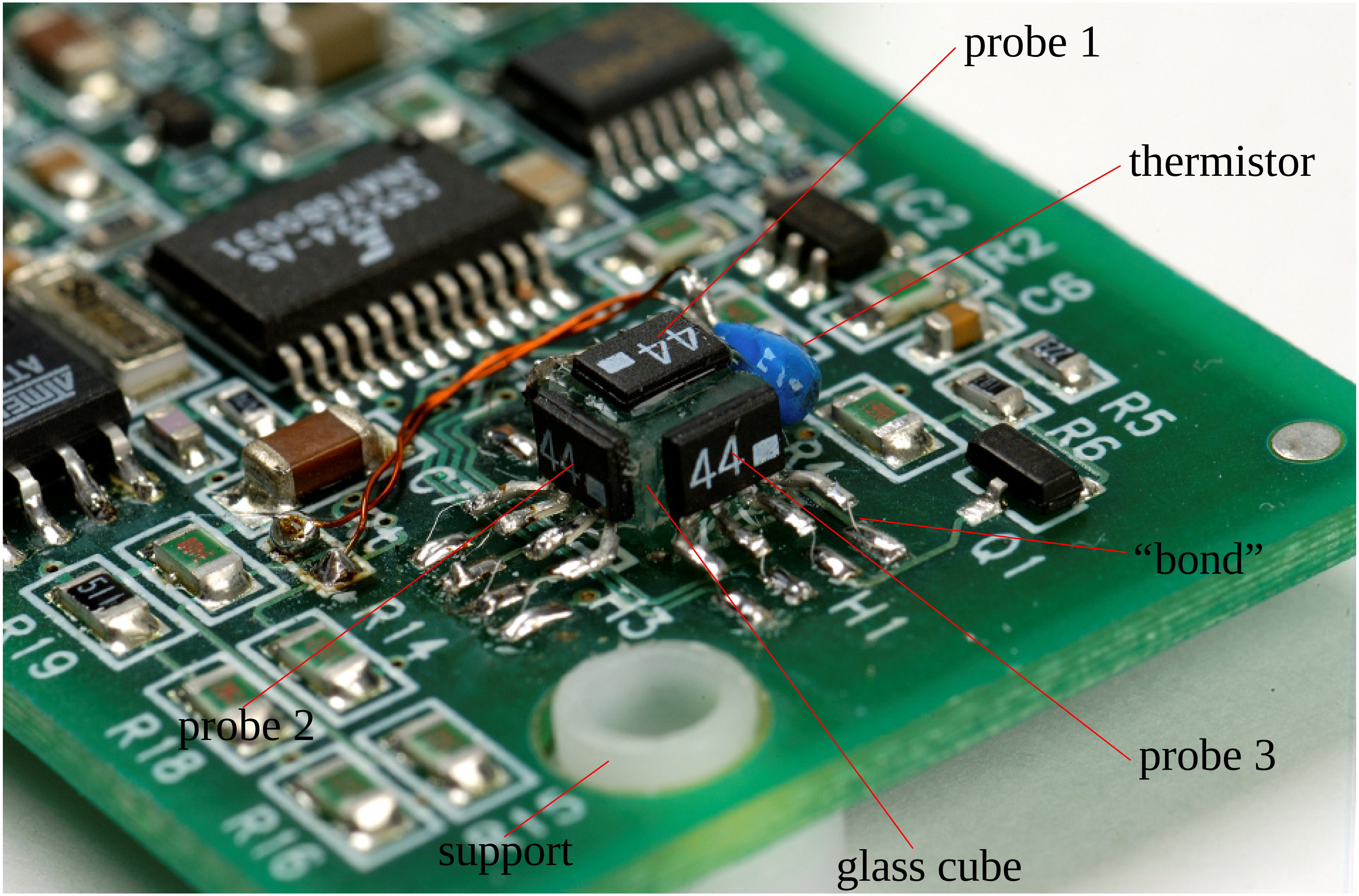
Prototype designed and build by NIKHEF Amsterdam for ATLAS detector at CERN-LHC p-p collider

J.T. van Es (design), J. Kuijt et al.

- Small card containing all analog electronics ⇒ electronics in same field as Hall probes, calibrated together
- 3x Siemens KSY44 glued on glass cube, 0.03 mm connection wires “bonds”
- Hall current 230 μA ⇒ small heat dissipation (I_{nom} = 5mA)
- ADC: 24-bits delta-sigma modulator
- Thermistor connected to cube, no thermostat
- Ref voltage ADC and hall current derived from same voltage source
  Offset cal + full scale cal ⇒ electronic sensitivity depends only on a few precision resistances
- Calibration circuit for thermistor
- Precision holes to fit on calibrator’s and experiment’s dowel pins
- Addressable: 127 cards on one serial bus


precision hole for dowel pin
addressing
hall probes
2082 138 044
30 mm
56.5 mm
thermistor
30 mm
ADC
mux
56.5 mm

21



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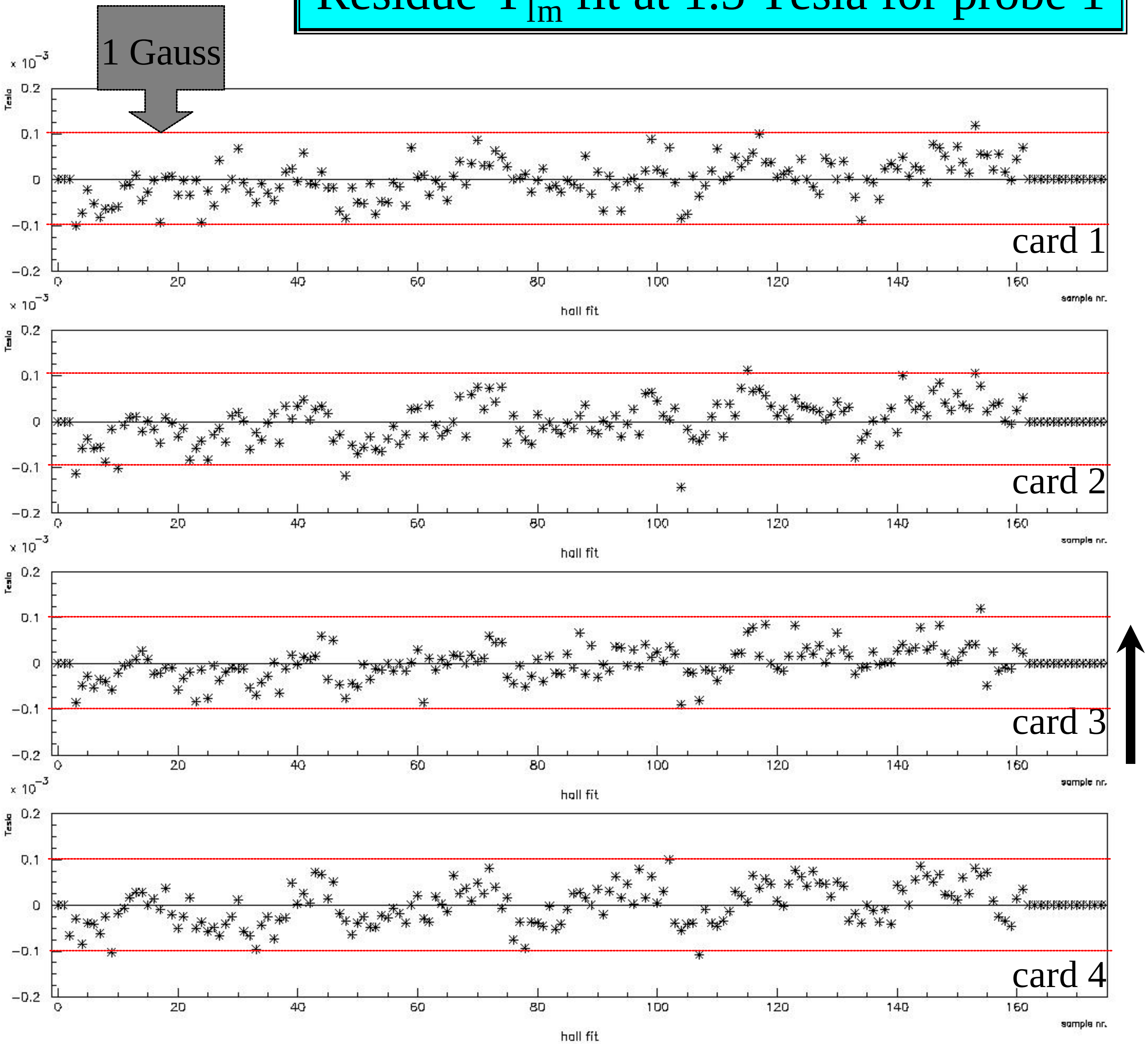
Residue Y_{lm} fit at 1.5 Tesla for probe 1



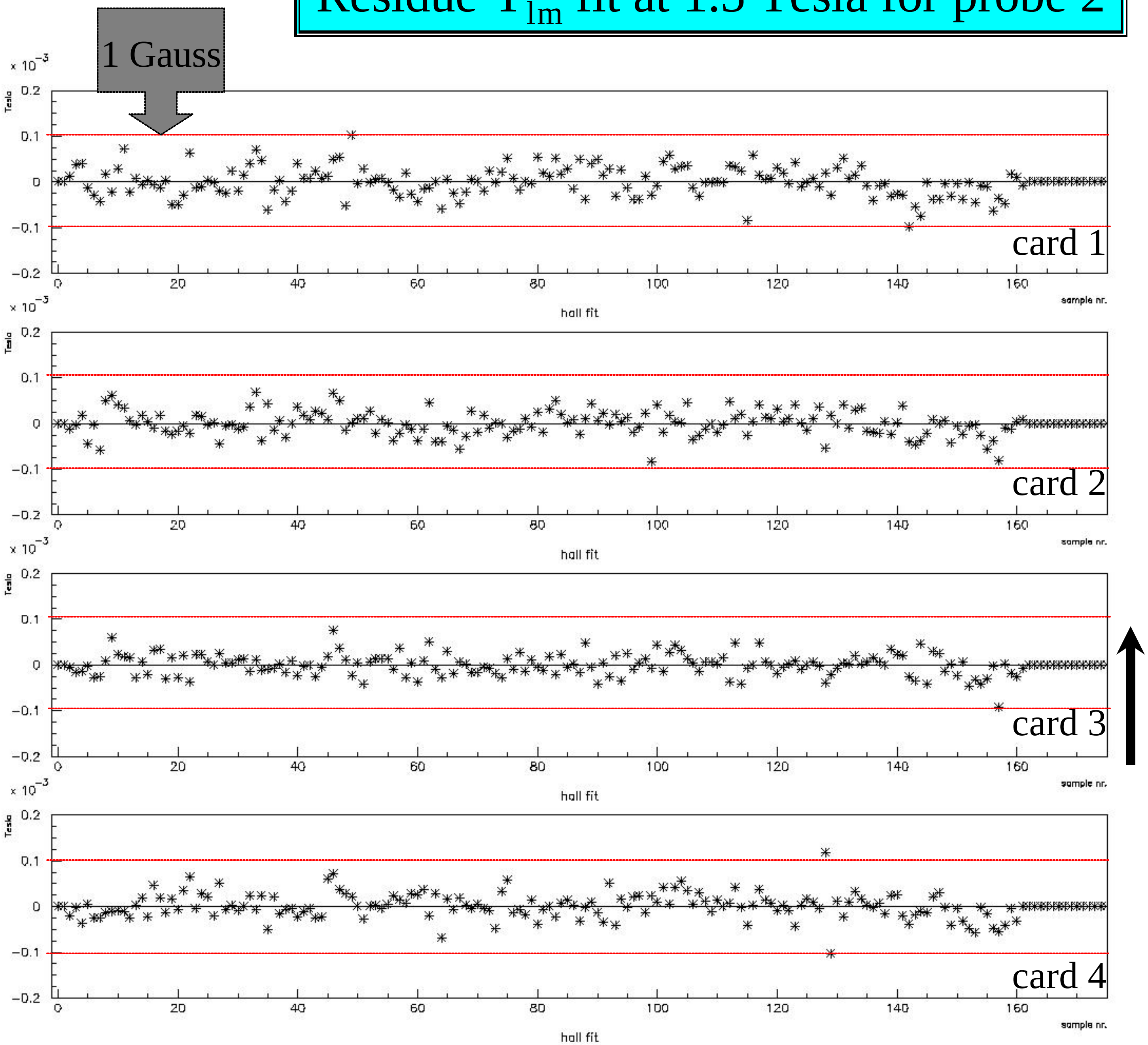
probe n sees same field as coil n

Horizontal scale = time in 16/15th sec.

Vertical scale = Tesla

23

Residue Y_{lm} fit at 1.5 Tesla for probe 2



probe n sees same field as coil n

Horizontal scale = time in 16/15th sec.

Vertical scale = Tesla

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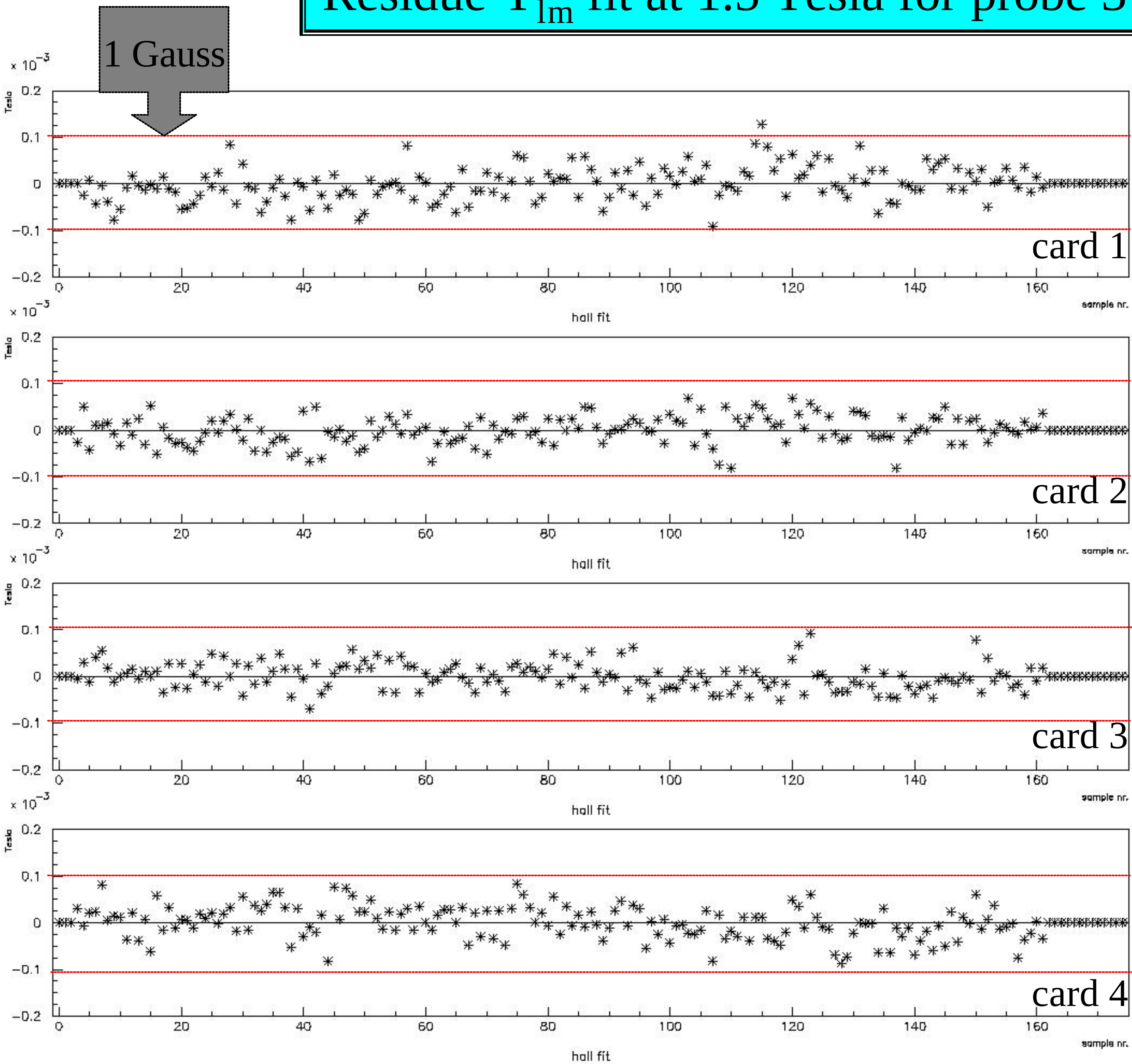
Residue Y_{lm} fit at 1.5 Tesla for probe 3



probe n sees same field as coil n

Horizontal scale = time in 16/15th sec.

Vertical scale = Tesla

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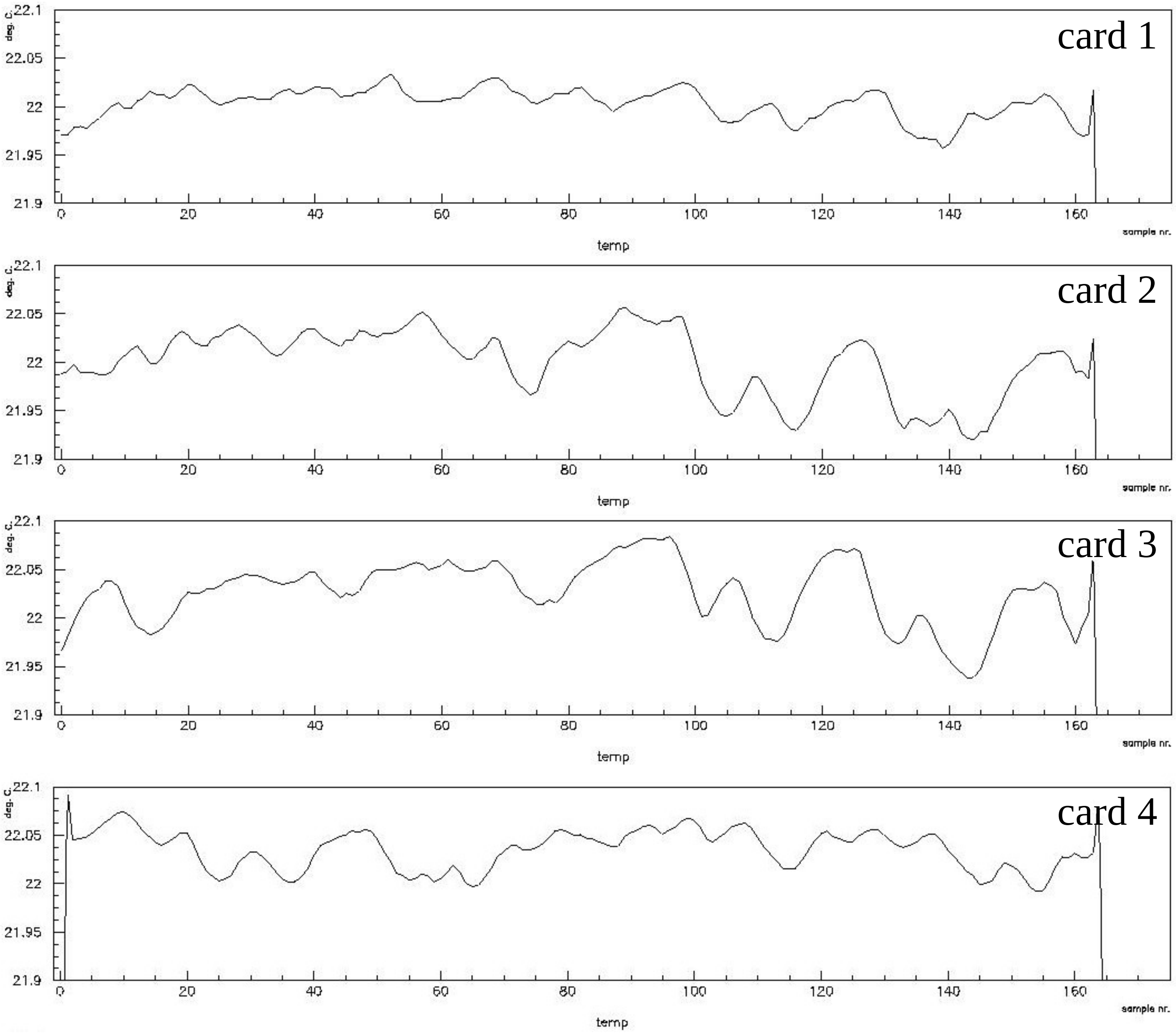
Temperature during calibration (not corrected for)



0.2 deg. C.

Horizontal scale = time in 16/15th sec.

Vertical scale = deg. Celsius

sensitivity of Hall probes changes with ~$3x10^{-4}$/deg.

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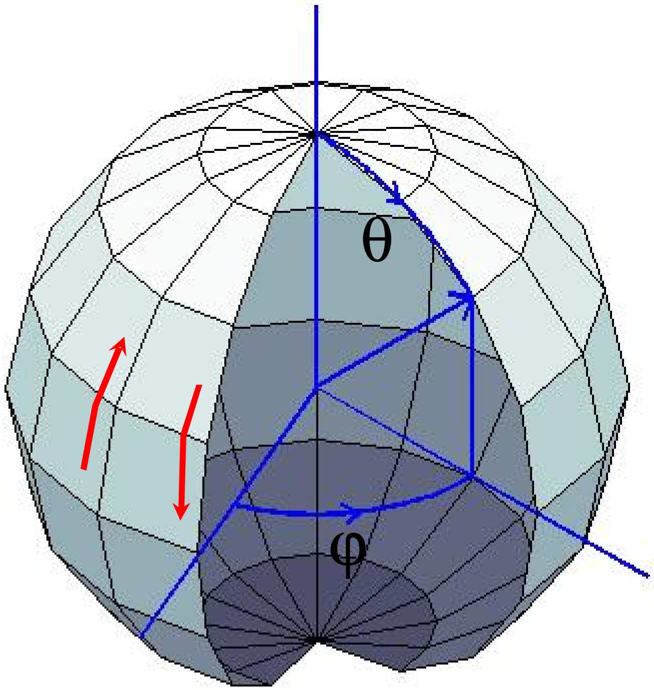
Reconstruction of B

Measurement of 3 x V_{hall} and
T at θ, φ = n x 22.5 degree
No movement during measurement
θ alternating in inner loop,
φ in outer loop



Reconstruction of B_x, B_y, B_z :
Solve 3 nonlinear equations
with 3 unknowns, using
parameterization of calibration data

Tests at several B and T

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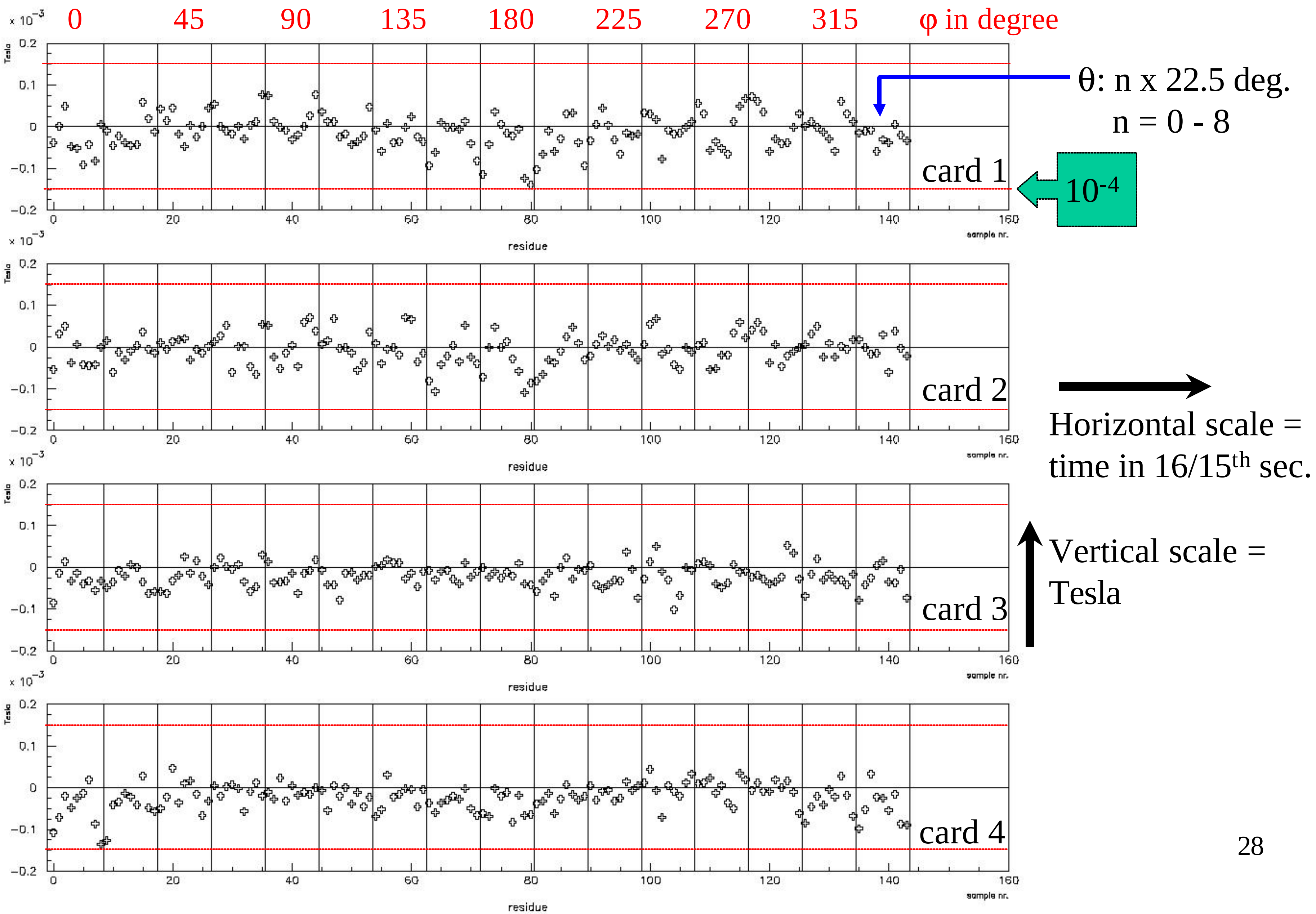
$|B|_{reconstructed} - |B|_{NMR}$ at 1.5 Tesla and 20 deg. C.



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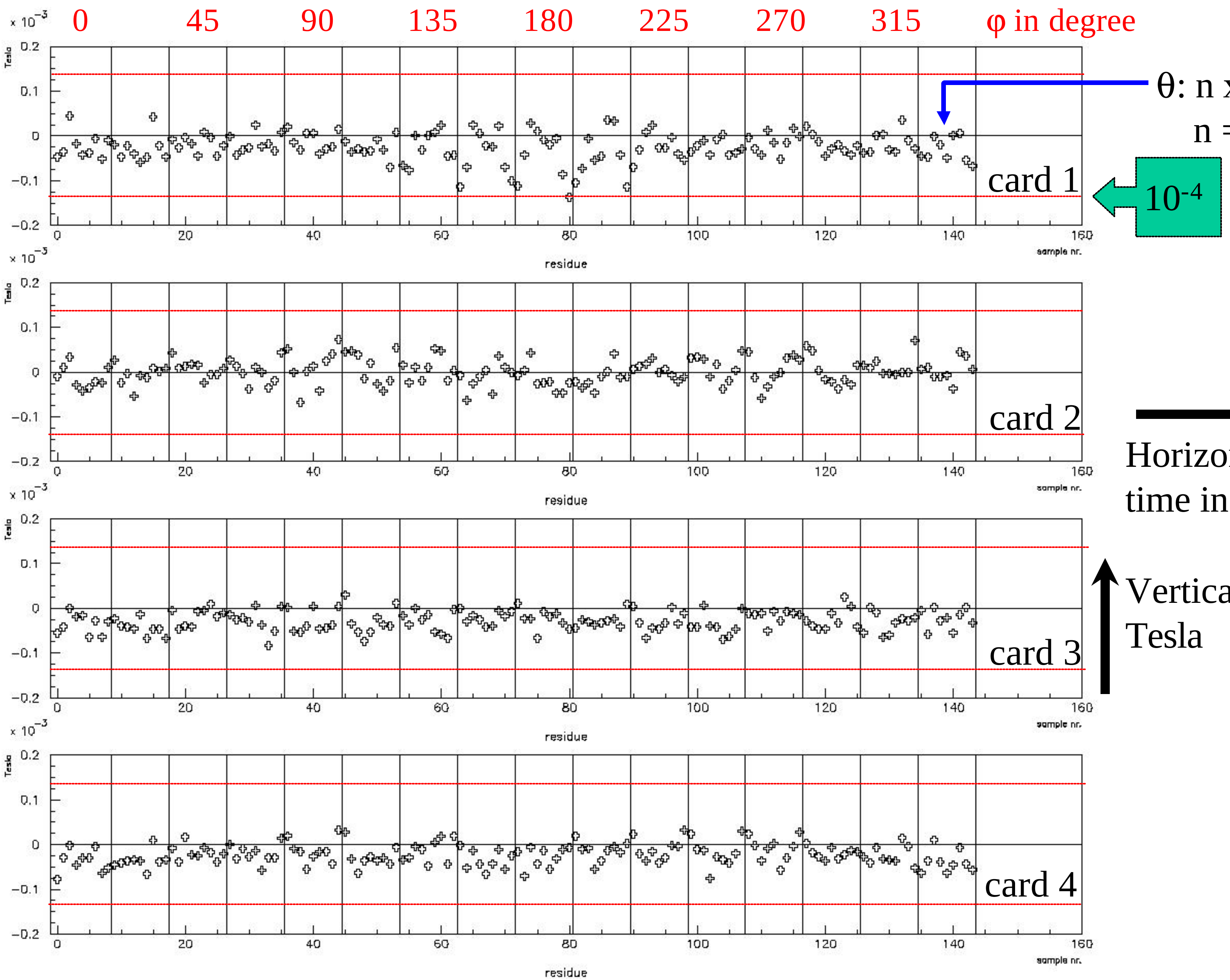
$|B|_{reconstructed} - |B|_{NMR}$ at 1.375 Tesla and 21 deg. C.

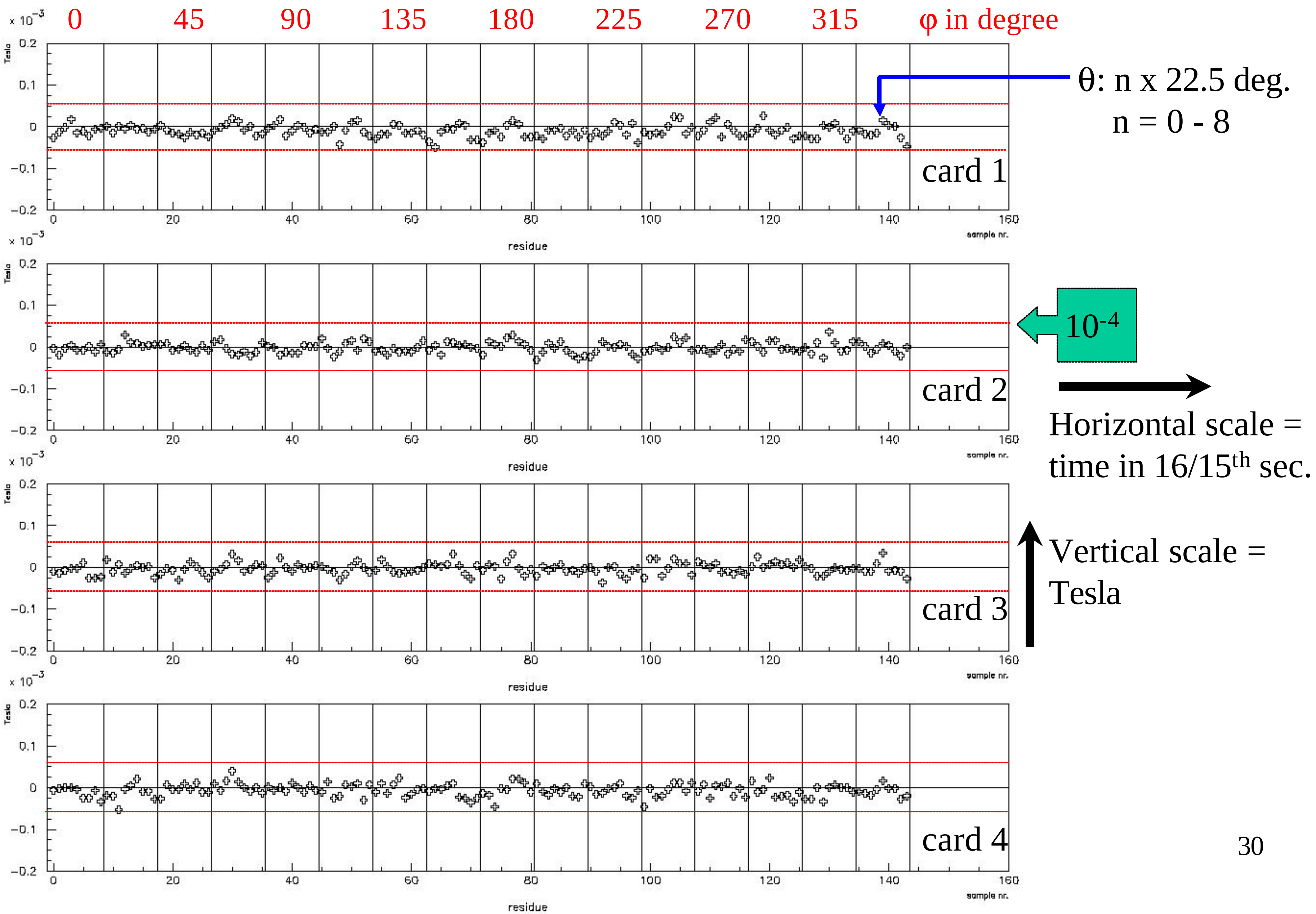


Horizontal scale = time in 16/15th sec.

Vertical scale = Tesla

29

$|B|_{reconstructed} - |B|_{NMR}$ at 0.625 Tesla and 21 deg. C.



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Analysis programs tested with simulated data:

Simulated calibration at fixed |B| and T:

Generate position of coil/Hall sensor, same trajectory as real calibration
coil signal = L dΦ/dt, hall signal from Y_{lm} decomposition of real calibration

↓

residue in coil fit $\sqrt{B_x^2 + B_y^2 + B_z^2} = 1$ of order of machine precision
find back same Y_{lm} decomposition within 0.5 x 10^{-5}

Simulated B reconstruction at arbitrary B and T :

Hall signal generated with parameterization of calibration

↓

Difference between generated and reconstructed data of order of machine precision

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Mean Time Between Calibrations (MTBC)

Main source of instability is a change in offset and angles between the Hall probes

Need "bonded" Hall probes glued on glass cubes

Offset and angles measured over 1 month period

→

For a precision of $\leq 10^{-4}$: MTBC $\geq$ 1 month, except for an offset calibration (zero field measurement) for some probes tests continue

Results wouldn't change with one collective rotation of Hall probes

→

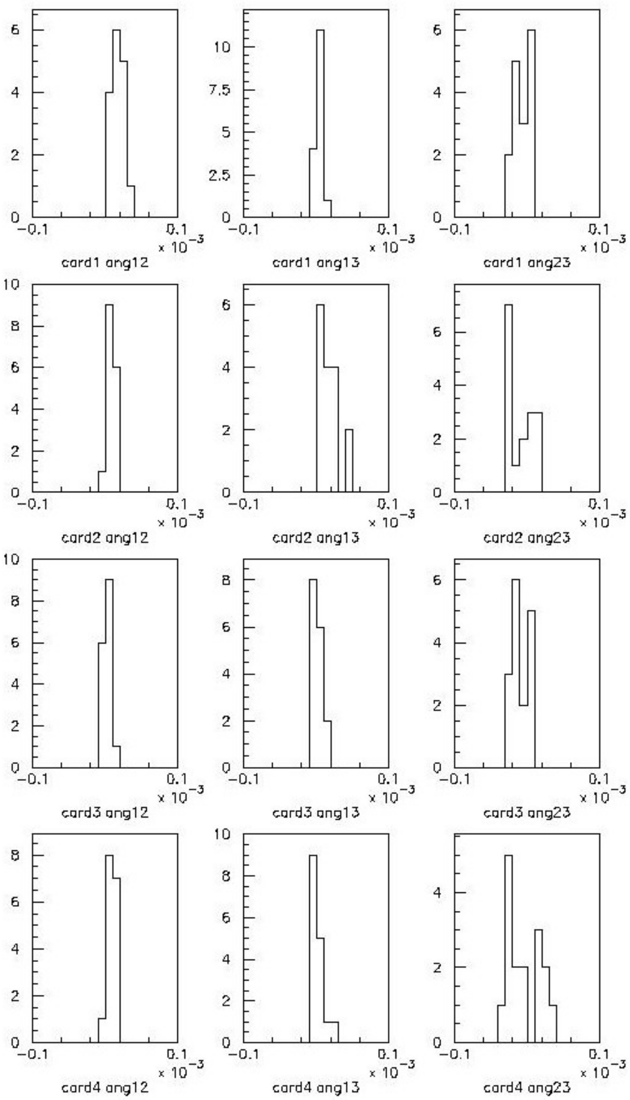
Need confirmation with an absolute measurement angles between probes

Period of one month

offset

1-2 1-3 2-3

uv / ca / uv / ca



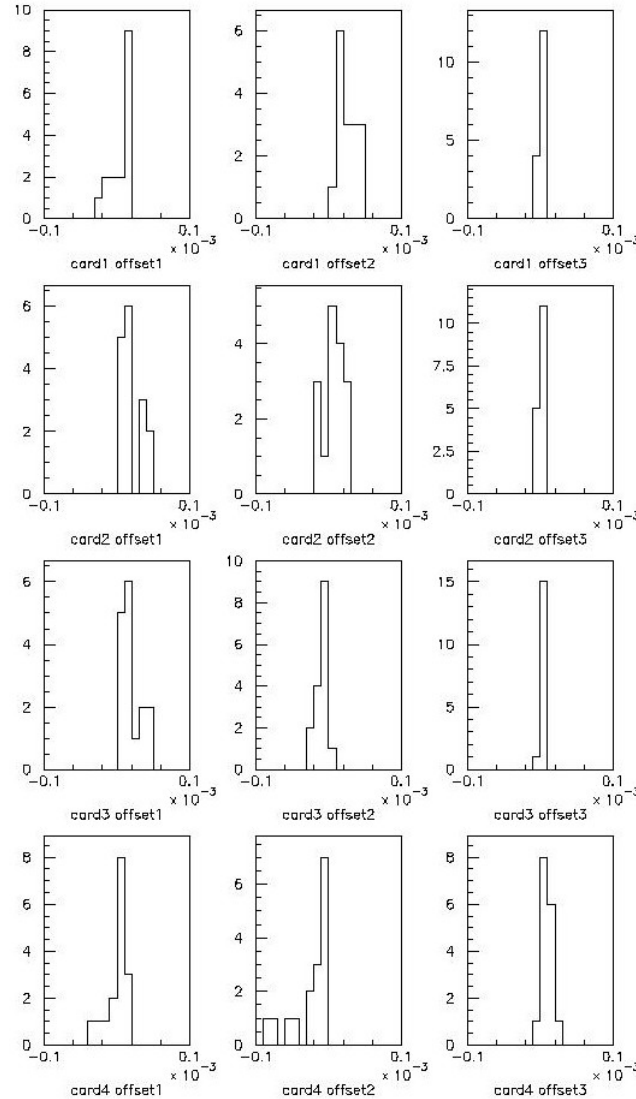
card 1

card 2

card 3

card 4

probe 1 probe 2 probe 3



horiz. full scale ± 10^{-4} rad

horiz.full scale equiv. of ± 1.5 Gauss

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Next

- Finish ATLAS 3D-sensor + calibrator for mass production. Make high (4T) field version — NIKHEF- Amsterdam

- Work on miniature version of calibrator for LHC magnet (40 mm diam.) for 9 Tesla

- Optimize calibrator (precision 10^{-5} seems possible)
  Do some absolute measurements

- 3D one-chip sensors:
  Small dimensions, almost point like measurements
  Decomposition of input V_{Hall} => direct temperature of chip
  Angles between x, y, z channels stable
  Spinning Hall current => offset more stable

- Research collaboration with industry sought

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