Magnetic Calibration System for Rotating-Coil-Based Measurement Instrumentation at CERN

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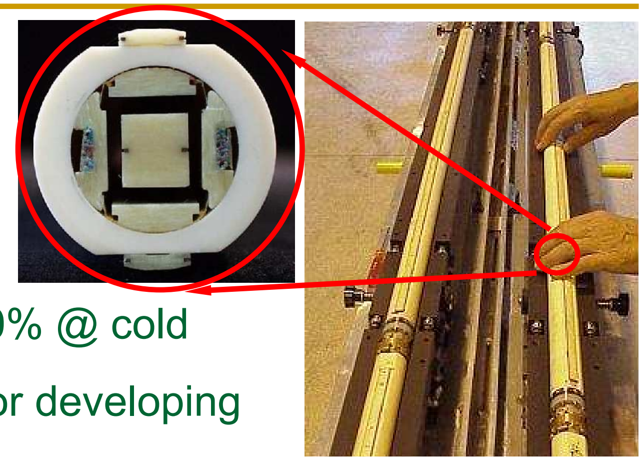
Thanks to: R. Beltron, M. Buzio, G. Deferne, L. Gaborit, P. Galbraith, J. Garcia-Perez, D. Giloteaux, N. Smirnov

Overview

- 1232 cryodipoles, ~500 quadrupole assemblies and ~6000 corrector magnets built for LHC
- Magnetic measurements on 100% @ warm and ~20% @ cold
- 4 years of measurement campaign, but a lot more for developing adequate measuring systems
- Multitude of field parameters to be measured
- Best adapted technique for most measurements: **Rotating Coils**
- Needs various types of instruments providing an accuracy in the range of 2–10x10^{-4} (all built in house)

→ Requires highly stable **Calibration System**



Dipole Long Shafts

Quadrupole Mole

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Three Tools for Coil Calibration:

Reference Dipole (in calibration lab)

- Magnet Aperture:
  L:2.5m, H:80mm, W:*300* mm
- Calibration Field:
  1Tesla @ 310 A (max: 350 A)
- Field angle:
  < 0.1 mrad w/r gravity

Used for Calibration of:
- **Coil area**
- **Parallelism of assembled heads**
- Abs. coil angle of moles

- Calibration of up to 5 coils simultaneously

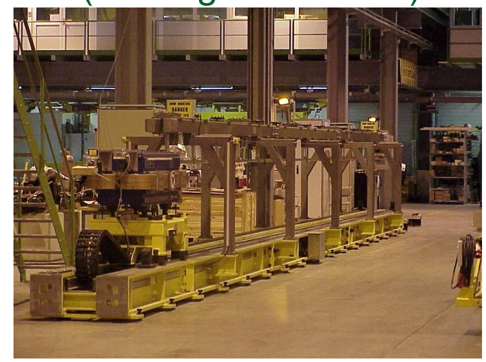
Reference Quadrupole (in calibration lab)

- Magnet Aperture:
  L:1.5m, Ø = 125mm
- Field Gradient:
  8.6 T/m (@ 480 A) (max: 480 A)

Used for Calibration of:
- **Coil Radius of assembled heads w/r rotation axis**

Calibration of up to 5 coils simultaneously

Long Shaft Calibration Bench (on magnet test site)



- Magnet Aperture:
  L:1.5m, W:*70* mm
- Calibration Field:
  0.51Tesla @ 200 A (max: 250 A)
- Bench Stroke: 17.25m

Used for:
- **Coil area check on long shafts before/after magnetic measurements**

Plugged-in shaft aligned w/r rails
Calibration of 1 coil/run

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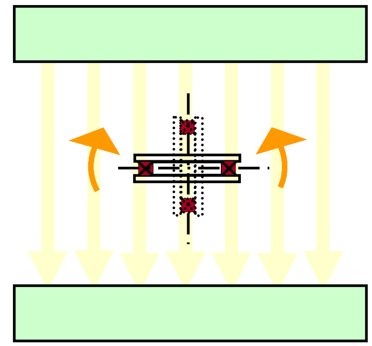
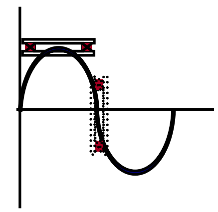
Method of Calibration in Reference Dipole:

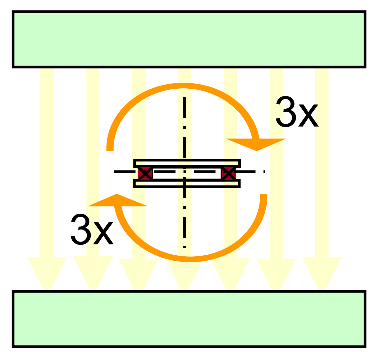
1. App. adjustment to max. (or 0) integrator signal





2. Start integrator → rotation 180° → stop integrator
   - Repeat 6 times
   - Observation of RMS
   - Average integrator signal
   - NMR-monitored field
   - Field correction factor

   } Coil Area



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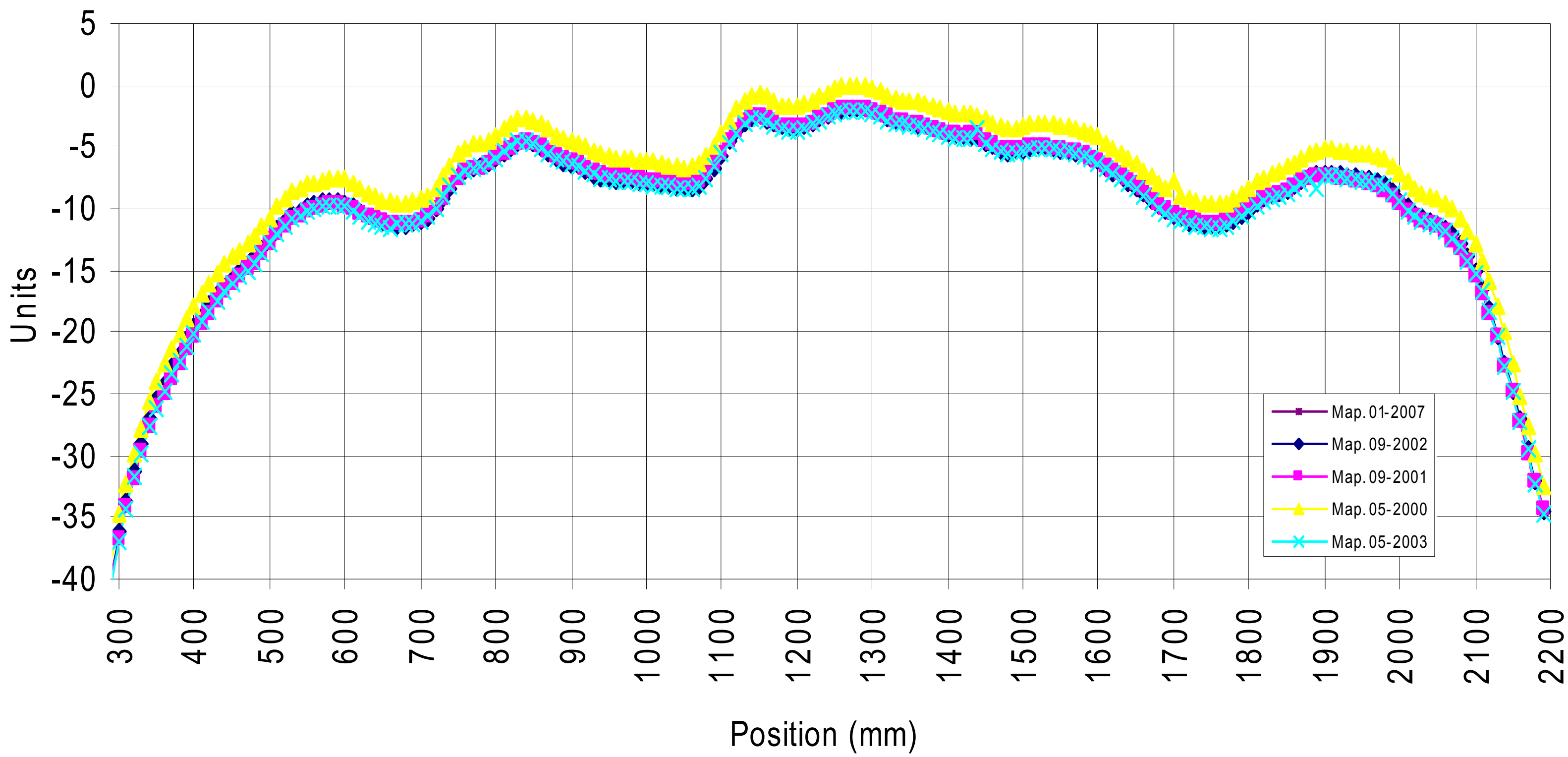
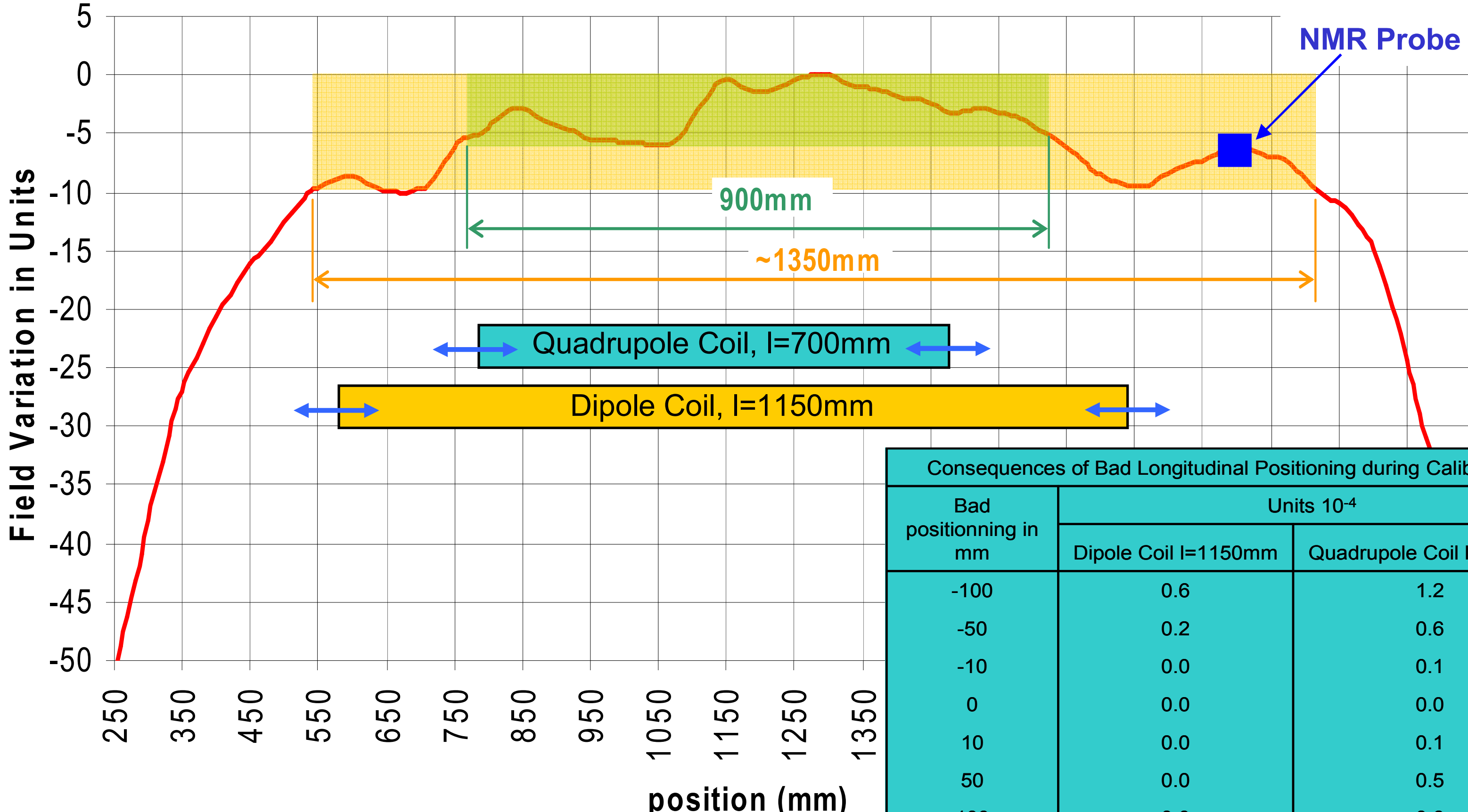
Reference Dipole:

- Field map shows field variation along centerline
- Periodical check to monitor long term stability
  → Good stability over years



Reference Dipole:

- Field homogenous within 6 units over ~900mm, within 10 units over ~1300mm
- Importance of longitudinal coil positioning for good reproducibility (in particular for shorter coils)



Consequences of Bad Longitudinal Positioning during Calibration		
Bad positioning in mm	Units 10^{-4}	
	Dipole Coil l=1150mm	Quadrupole Coil l=700mm
-100	0.6	1.2
-50	0.2	0.6
-10	0.0	0.1
0	0.0	0.0
10	0.0	0.1
50	0.0	0.5
100	0.0	0.6

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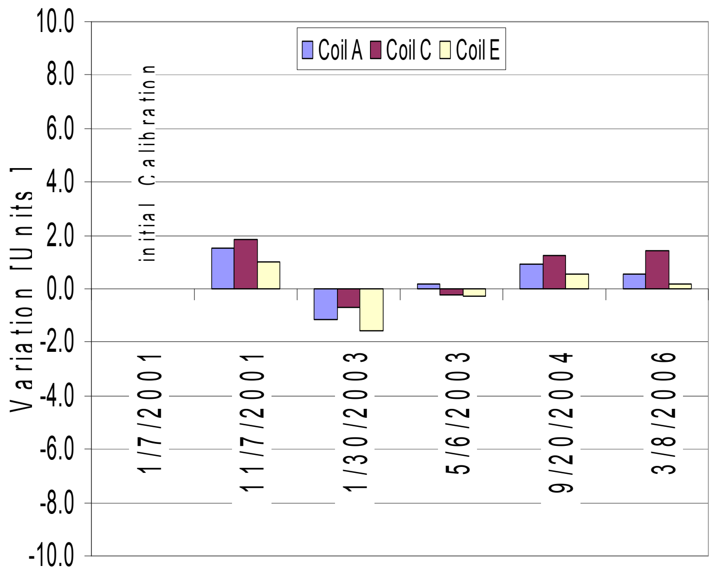
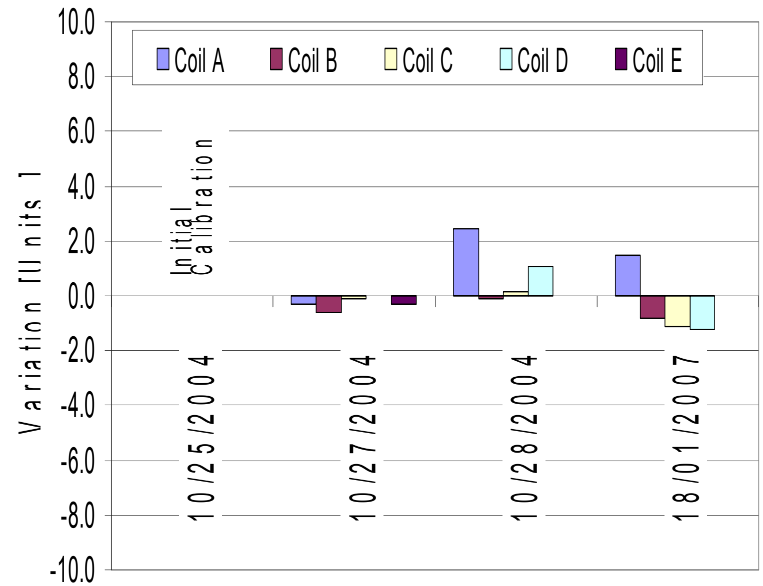
Reference Dipole:

-Good stability of coils (and reference magnet) over years

→ Coil area variation of ~2 units for various calibrations over 5 years



Industrial « DIMM » Mole No. 9
Calibrations 2001-2006



Quadrupole Long Shaft Segment No. 19
Calibrations 2004-2007

Three Tools for Coil Calibration:

Reference Dipole
(in calibration lab)

- Magnet Aperture:
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- Calibration Field:
  1Tesla @ 310 A (max: 350 A)
- Field angle:
  < 0.1 mrad w/r gravity

Used for Calibration of:
- **Coil area**
- **Parallelism of assembled heads**
- Abs. coil angle of assembled heads

Calibration of up to 5 coils simultaneously

Reference Quadrupole
(in calibration lab)

- Magnet Aperture:
  L:1.5m, Ø = 125mm
- Field Gradient:
  8.6 T/m (@ 480 A) (max: 480 A)

Used for Calibration of:
- **Coil Radius of assembled heads w/r rotation axis**

- Calibration of up to 5 coils simultaneously

Long Shaft Calibration Bench
(on magnet test site)

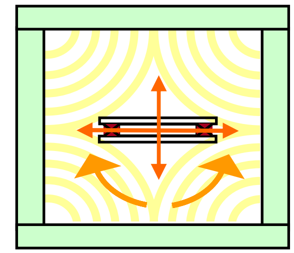
- Magnet Aperture:
  L:1.5m, W:*70* mm
- Calibration Field:
  0.51Tesla @ 200 A (max: 250 A)
- Bench Stroke: 17.25m

Used for:
- **Coil area check on long shafts before/after magnetic measurements**

Plugged-in shaft aligned w/r rails
Calibration of 1 coil/run

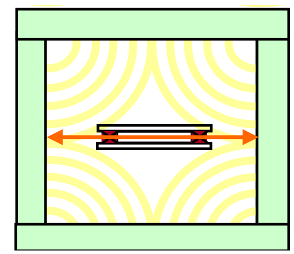
Method of Calibration in Reference Quadrupole:

1. Horizontal, vertical and angular adjustment of coil(s) w/r to central field (using integrator signal).



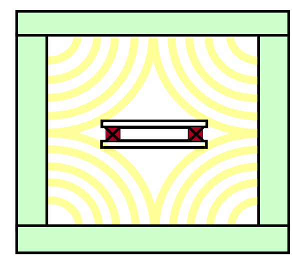
2. Measurement of field gradient by lateral displacement of coil(s) relying on previously calibrated coil sensitivity.
   - Precisely controlled lateral displacement (Heidenhain Sensor, 10^{-3}mm)
   - Gradient measurement with 2 diff. strokes (±10mm and ±15mm)

- Requires <u>Stable Field</u> during the entire procedure !!



3. Measurement of radius by rotation in reading coil sensitivity to B_2
   - Start integrator → rotation 90º → stop integrator
   - 4x counterclockwise, 4x clockwise
   - Observation of RMS
   - Previously measured gradient
   - Average integrator signal
   - Previously calibrated coil area

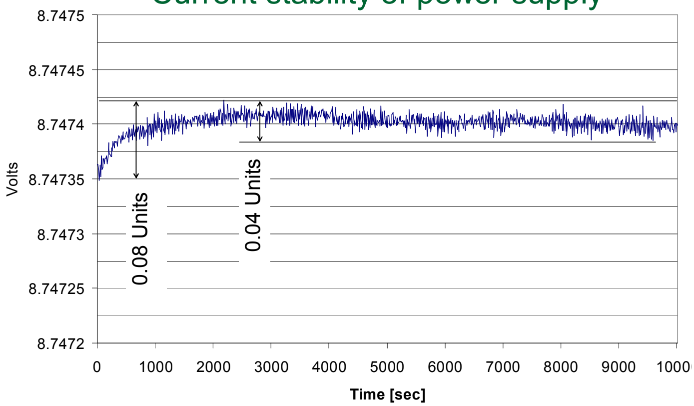
   } Coil Radius



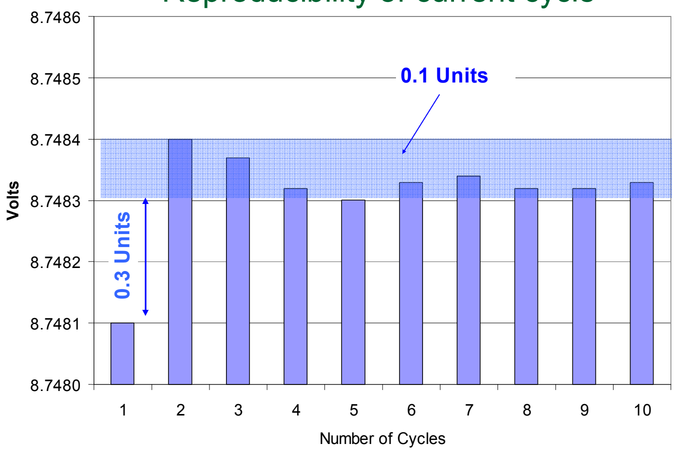
- No need to know exact gradient (provided it is stable!)
- Method relies entirely on coil sensitivity

Reference Quadrupole:

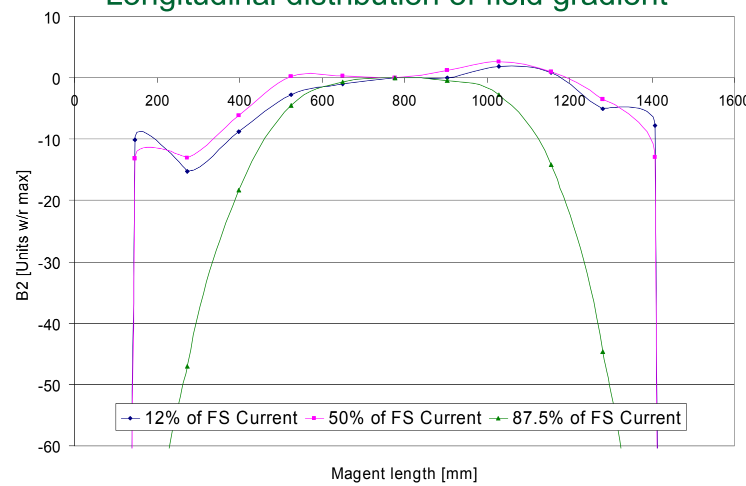
Current stability of power supply



Reproducibility of current cycle



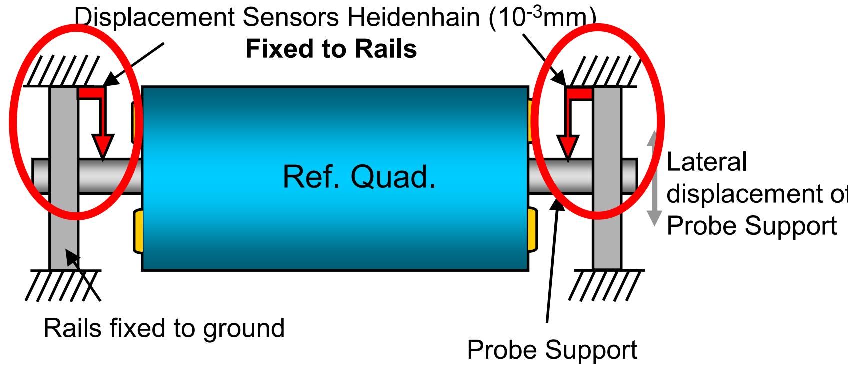
Longitudinal distribution of field gradient



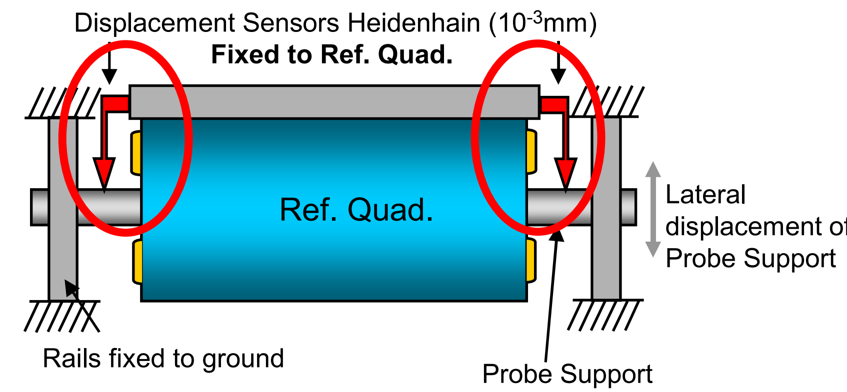
- Good stability and reproducibility of power supply
- But relatively short uniform region at nominal current
- Exact longitudinal positioning is important for absolute measurements

Reference Quadrupole:

Problem:
Large spread of gradient/radius measurements. (Too much for LHC requirements)
Reason:
Small, random movements of guiding rails support during lateral displacement (~20-50 μm)
→ Wrong measurement of lateral displacement of the probe

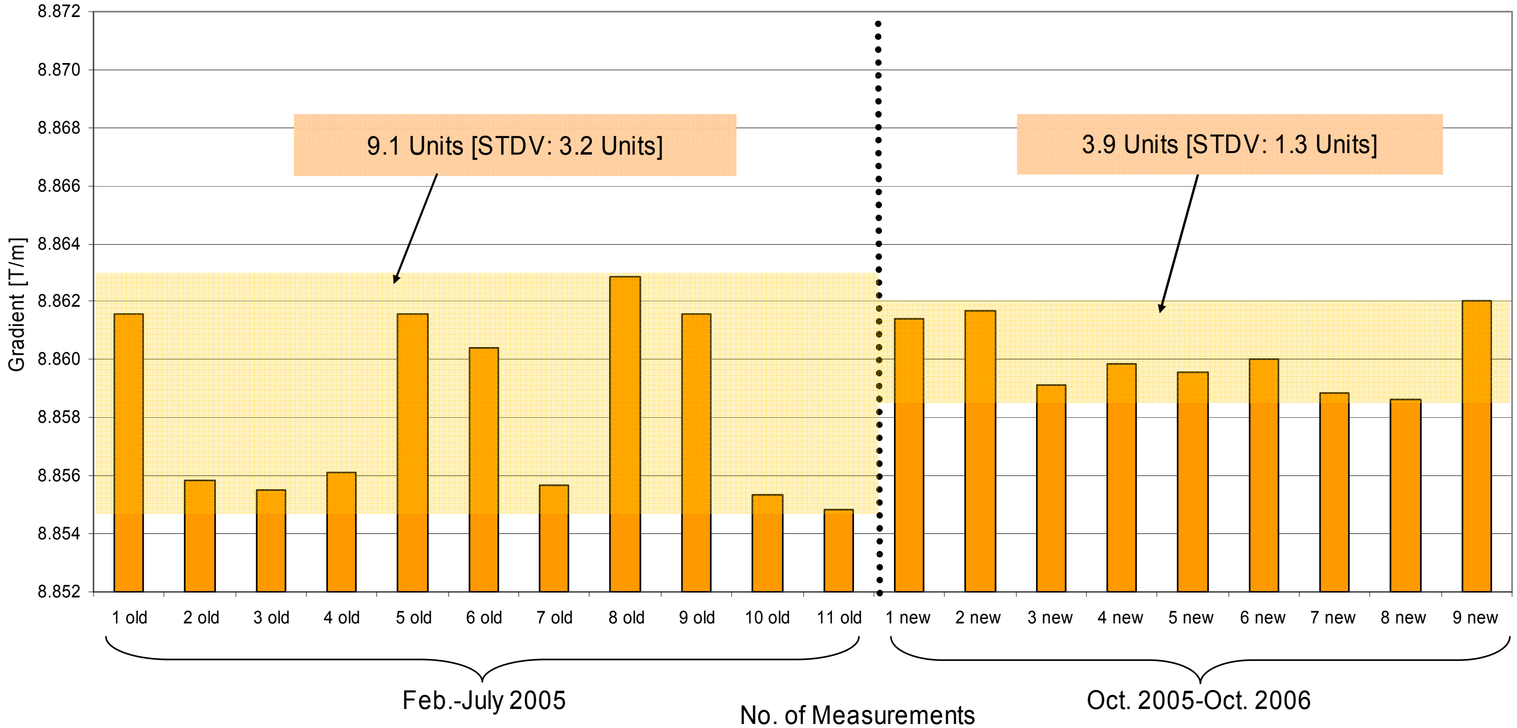


Solution:
Modification of Heidenhain Support to fix it directly to the reference magnet
Result:
Reproducibility of gradient/radius measurements increased by a factor of 2



Reference Quadrupole:

- Improvements of field gradient calibration after modification of displacement sensor
  → > 2x less dispersion of gradient / radius measurements



All measurements with the same head.

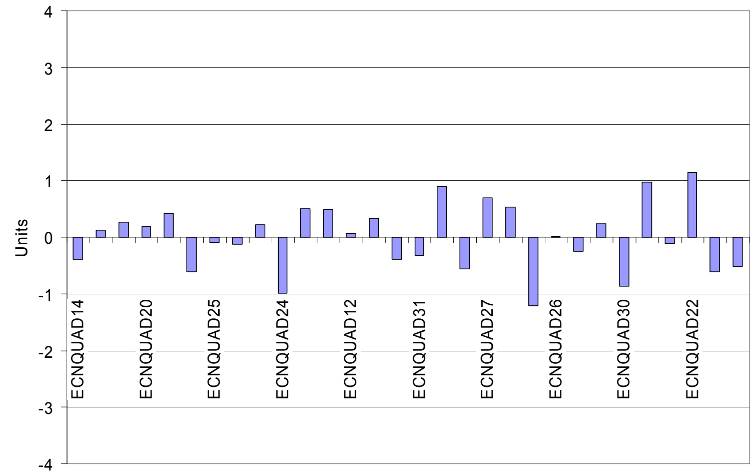
Reference Quadrupole:

Improvements of radius calibration:

Repeatability of radius measuremens:

- 10 different quadrupole long shaft sectors, 3 repetitions each

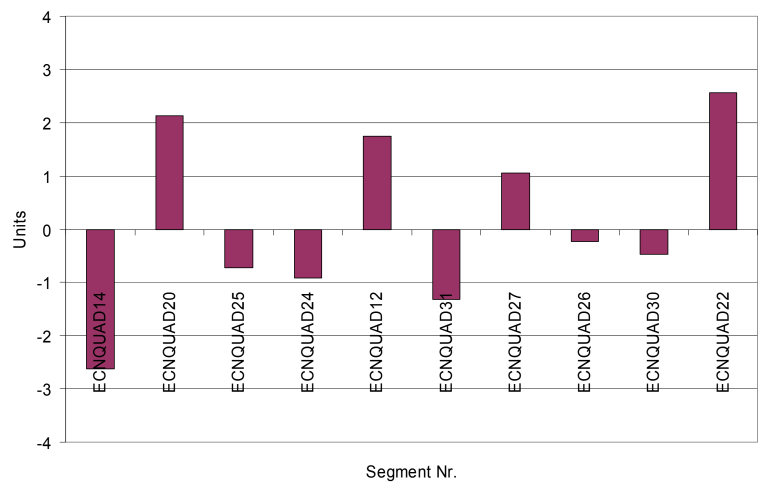
→ Uncertainty: < 2 units (peak to peak)



Reproducibility of radius measurements:

- Variation w/r to average measured on 10 different quadrupole long shaft sectors

→ Overall uncertainty: < 5 units (peak to peak)



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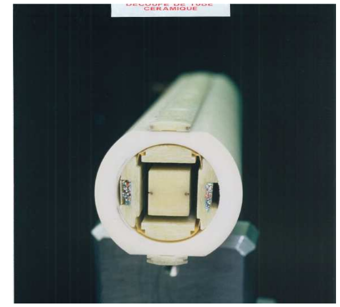
Reference Quadrupole:

Cross calibration between SSW (Single Streched Wire) and SSS Long Shaft segment (rotating coils)



Long Shaft Segment

Measurement of integral field gradient:

- SSW: integral measurement by def.→ well reproducible reference
- SSS Long Shaft → « assembled » integral from 4 local measurements

  Some difficulties:

  - longitudinal positioning needs to be controlled within 0.1mm
    (we used a Leica Laser Tracker)
  - control of roll angle of coil during the longitudinal displacement

3. Result:

System/Method	SSW	Long Shaft Segment
Gdl [T]	14.2299	14.2323
Difference [Units]	0	-1.7

Single Streched Wire System

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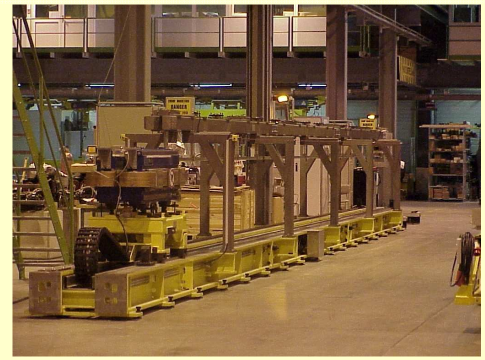
Long Shaft Calibration Bench (on magnet test site)



- Magnet Aperture:
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- Calibration Field:
  0.51Tesla @ 200 A (max: 250 A)
- Bench Stroke: 17.25m

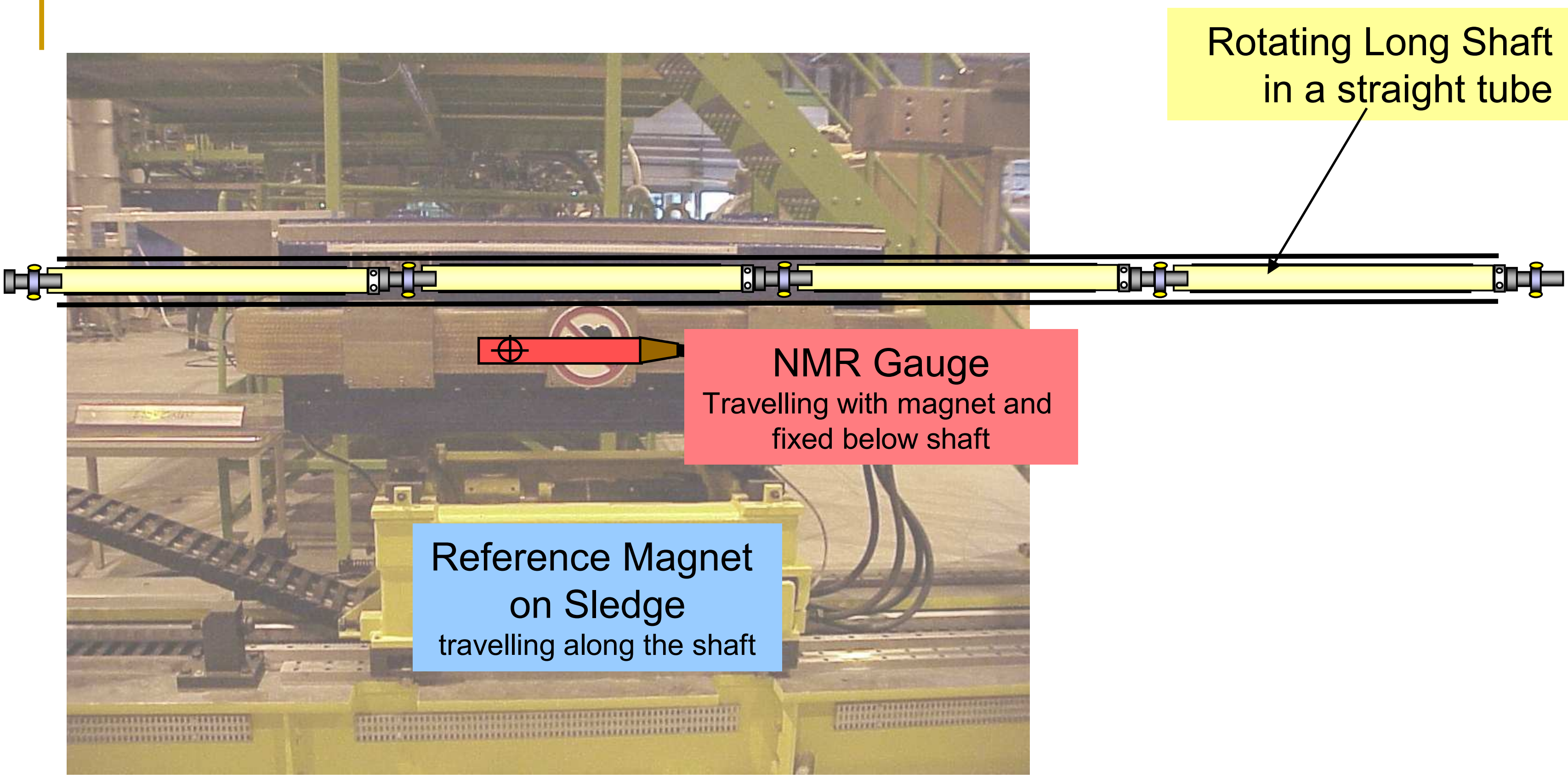
Used for:

- **Coil area, rel. coil angle and electrical integrity check on long shafts before / after magnetic measurement**

- Calibration of 1 coil / run

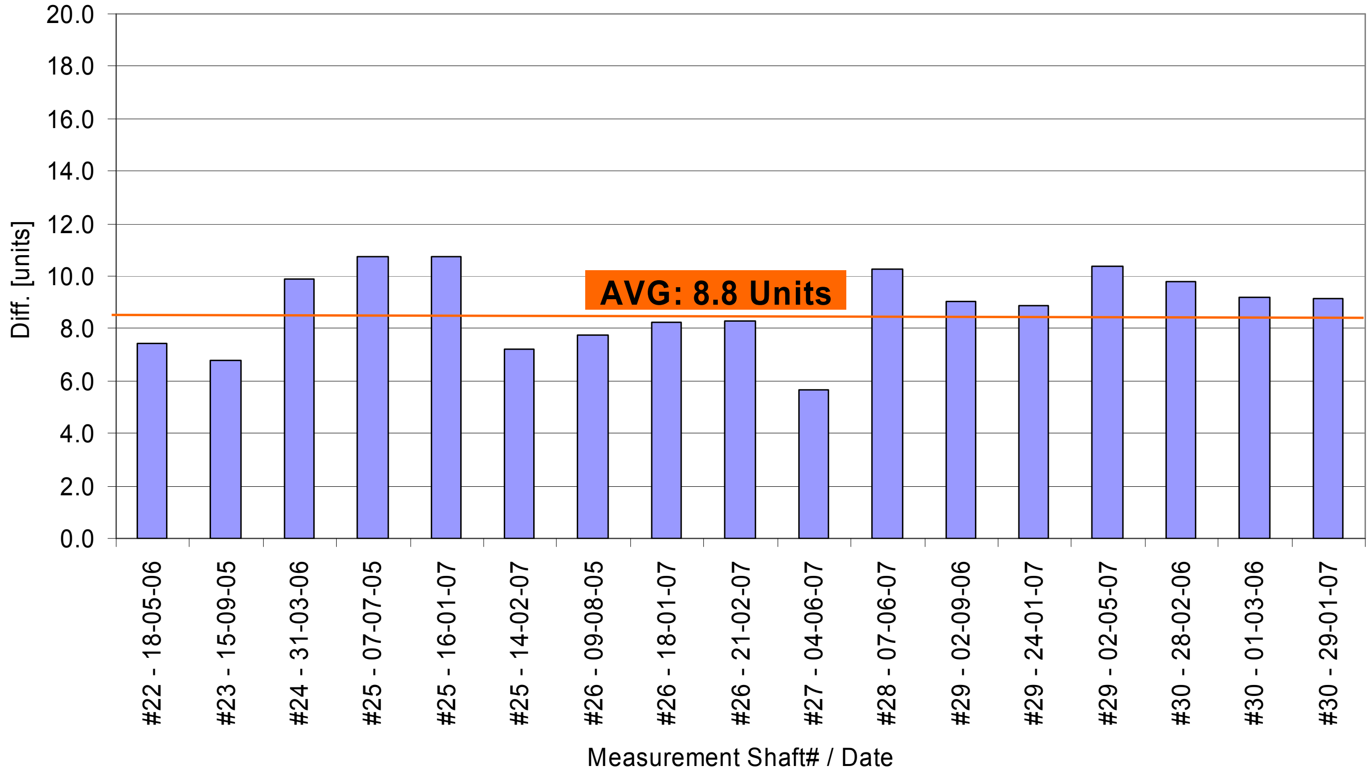
Method of Calibration in Calibration Bench for Long Shafts:

360º Rotation of the shaft → Magnet travels along the shaft → Another 360º rotation of the shaft…etc



Calibration Bench for Long Shafts

Problem:
Coil Areas calibrated in Calibration Bench for Long Shafts on the magnet test site were systematically smaller by nearly 10 units than those calibrated in Reference Dipole in the calibration lab: **Why?**



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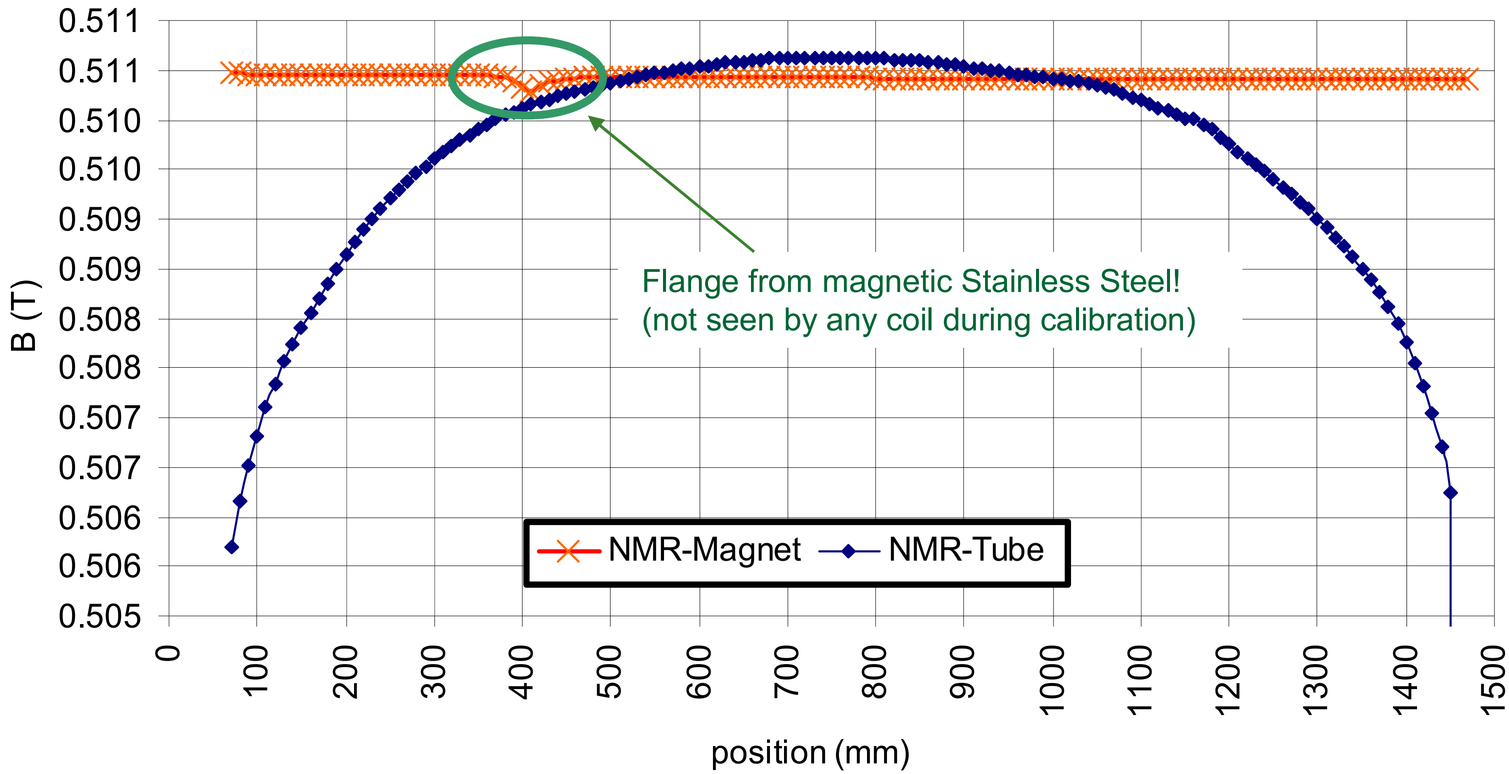
Calibration Bench for Long Shafts

- Field map of reference dipole
- 2 NMR gauges: 1 travelling with magnet and fixed below Shaft
  1 fixed in shaft tube (magnet travels along)



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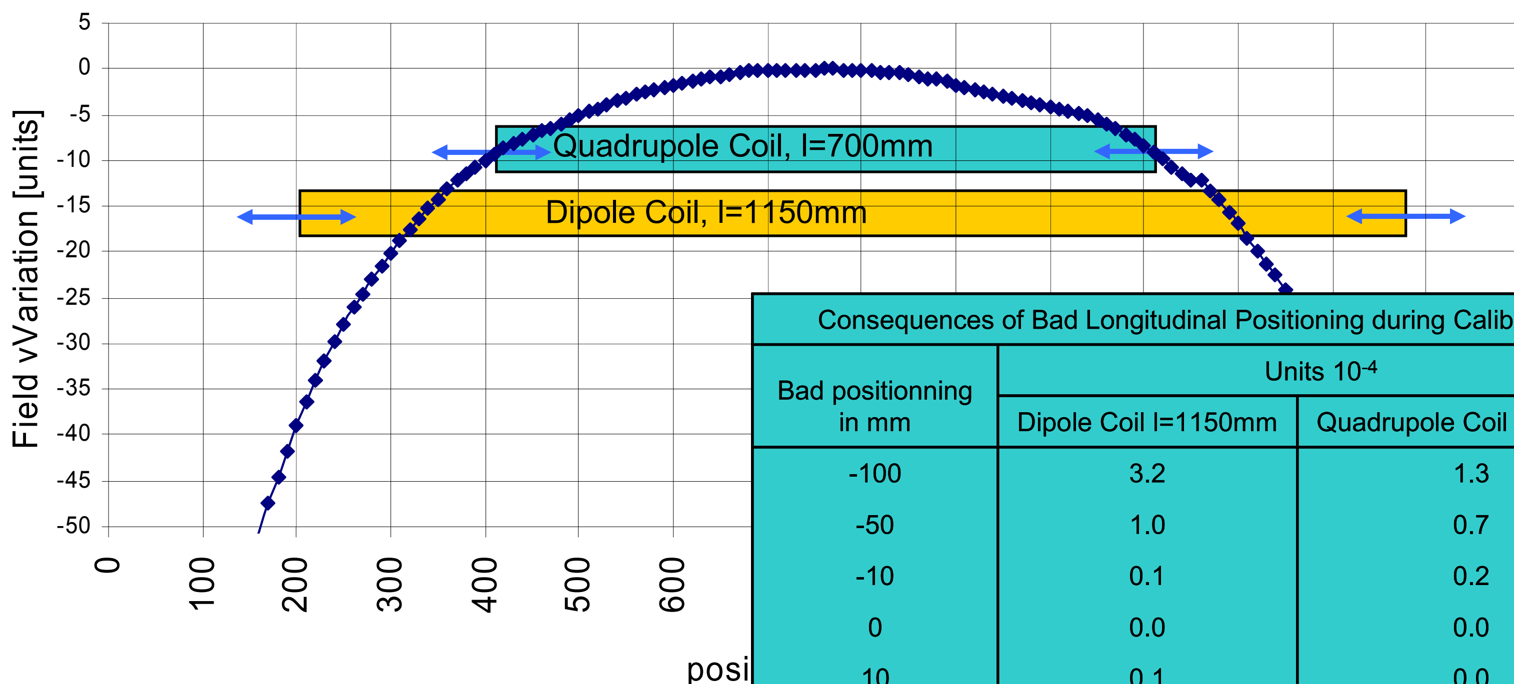
Calibration Bench for Long Shafts

- Only small part of the coil in maximum field, major part of the coil in lower field
- Importance of longitudinal coil positioning
  (accurate stop of traveling magnet at each segment of the long shaft)



Consequences of Bad Longitudinal Positioning during Calibration		
Bad positionning in mm	Units 10^{-4}	
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-100	3.2	1.3
-50	1.0	0.7
-10	0.1	0.2
0	0.0	0.0
10	0.1	0.0
50	0.1	0.0
100	1.4	0.7

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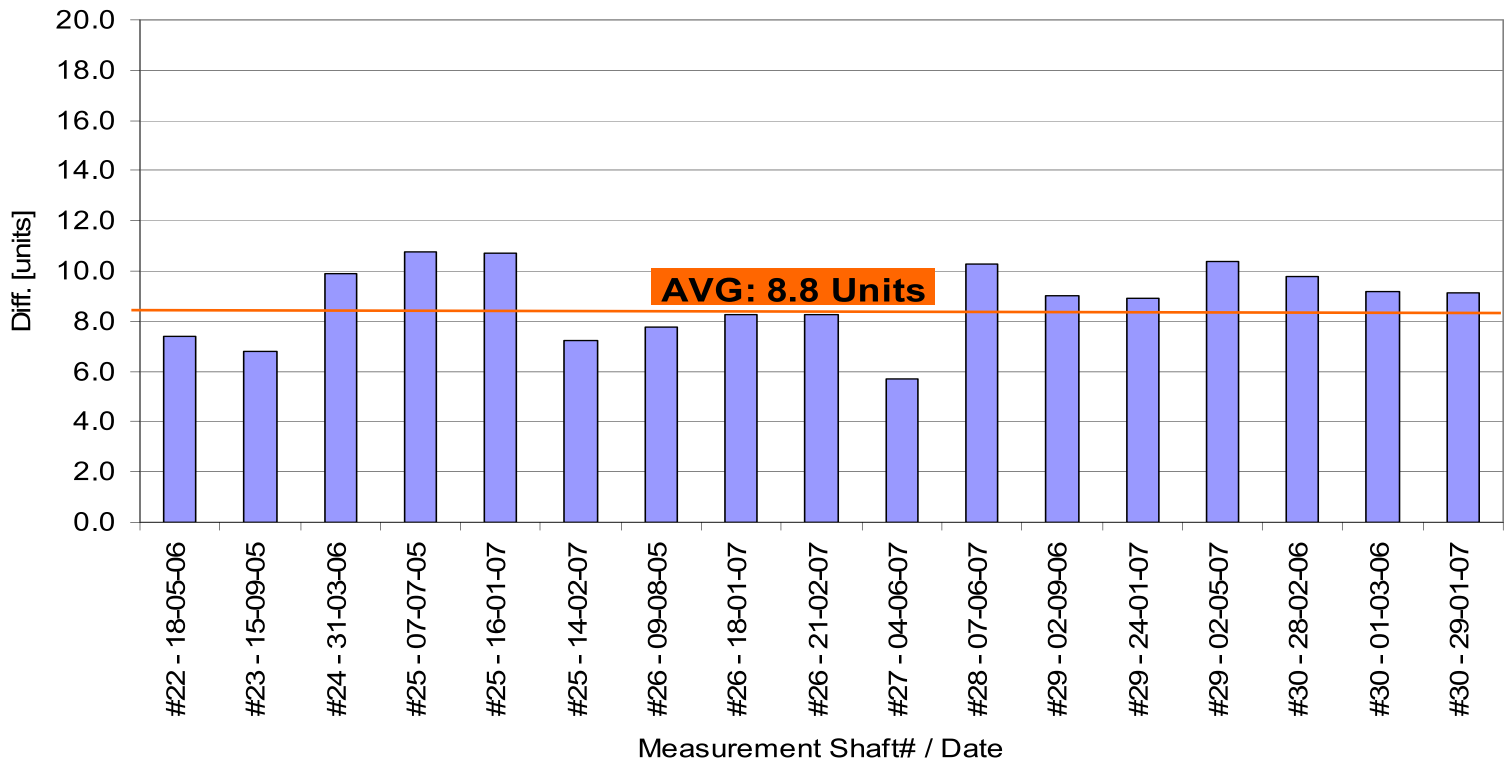
Calibration Bench for Long Shafts

Reason:
- Non uniform field profile of ref. magnet not taken into account for coil area measurement

Solution:
- Need to apply a correction factor after calibration



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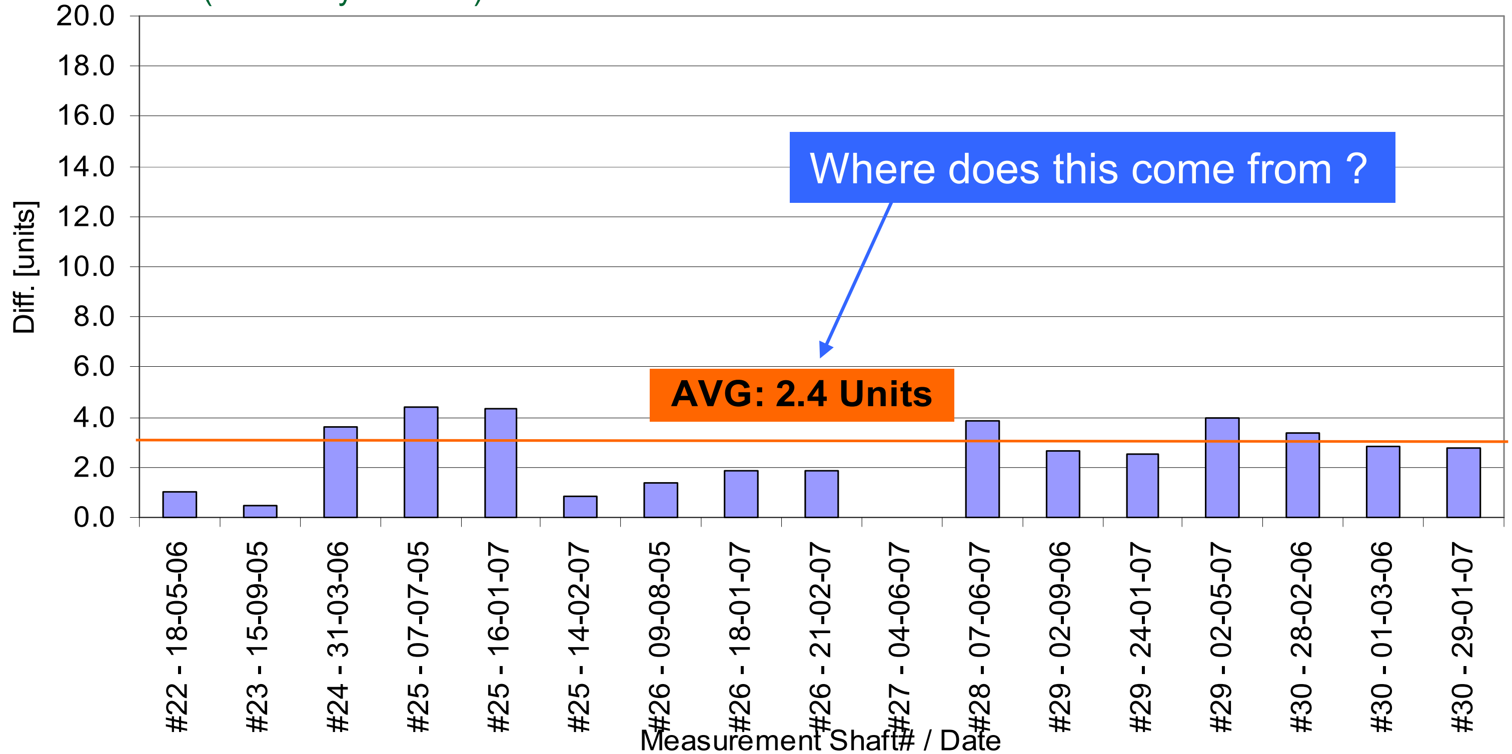
Calibration Bench for Long Shafts

Result:
After application of correction factor:
→ Average difference between both calibrations: **~ 2.5 Units**
(but still systematic)



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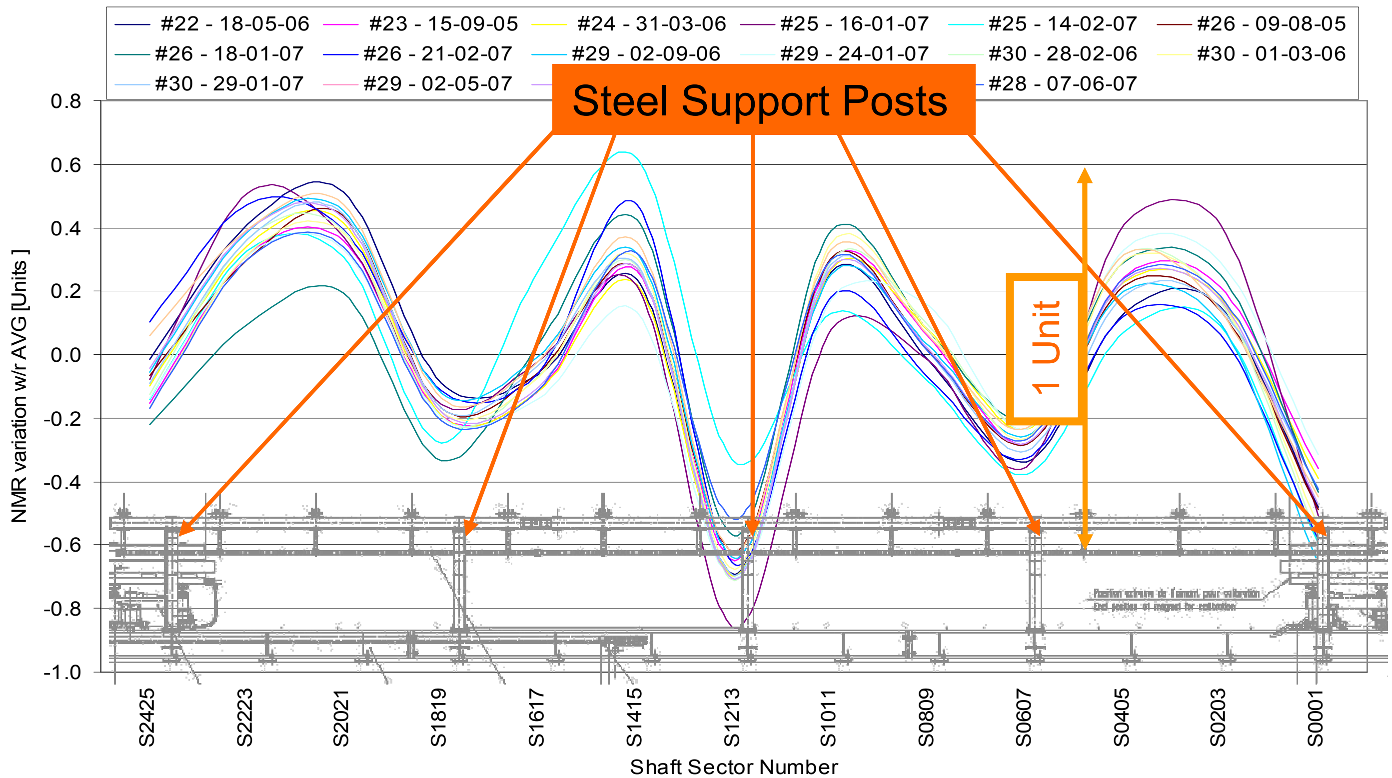
Calibration Bench for Long Shafts

- Systematic NMR variations during a measurement on long bench (~ 1 Unit Peak to Peak)
- Same NMR behavior for numerous measurements



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Outlook

Some ideas for improvements:

…angle measurements on bench for long shafts (absolut, relative)

…more cross checks between other instruments

…maintain and trace stability for future calibrations

…adapt present system to new coil shafts i.e FAME, Linac4, etc.

…find solutions for bigger diameters than LHC

…etc.