Joint Universities Accelerator School

JUAS 2014

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Normal-conducting accelerator magnets

Thomas Zickler,

CERN

Lecture 5: QA, tests and measurements

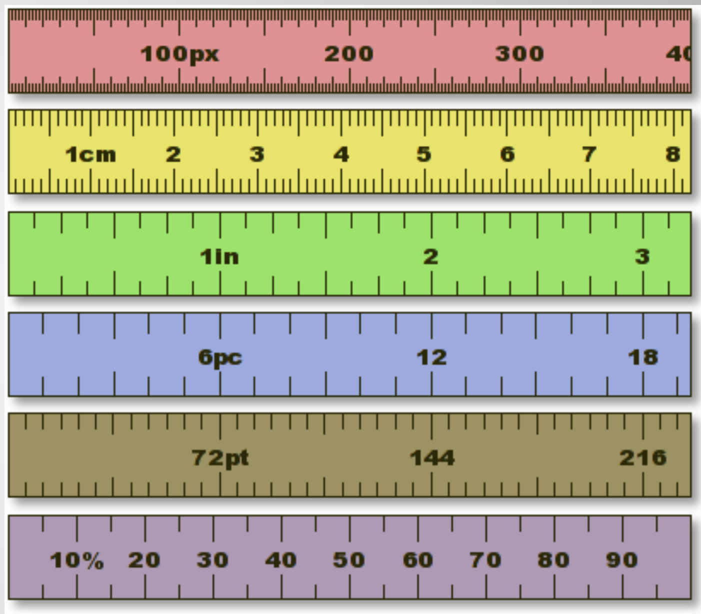
QA & Acceptance tests

Sample testing

Mechanical and electrical measurements

Recurrent issues

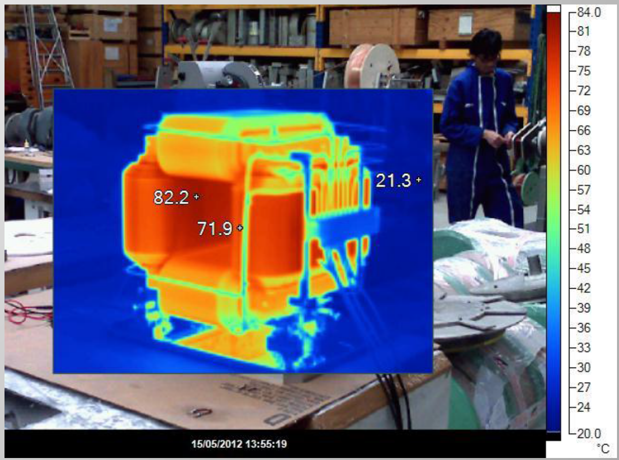
Magnetic measurements



QA & Acceptance tests

QA is important at each production stage

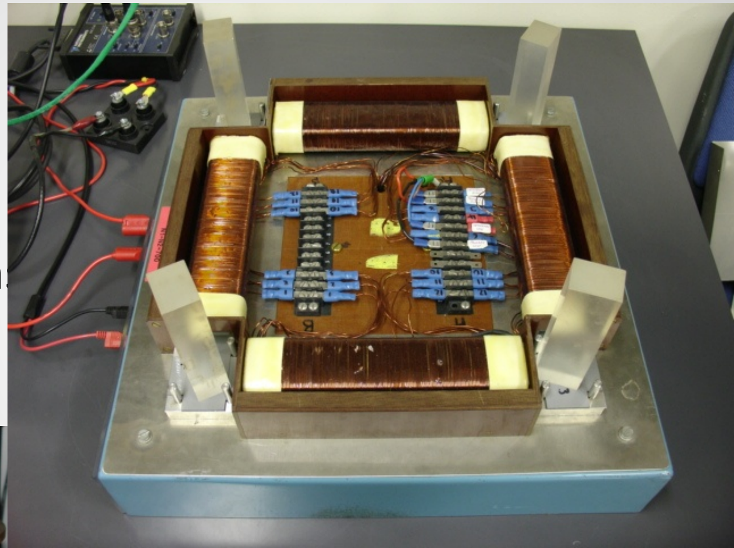
- Constant monitoring of critical items from the raw material, to semi-finished parts, to sub-components to the final product
- Sample testing (destructive or non-destructive) to qualify materials, manufacturing techniques and processes
- Acceptance test can include electrical, hydraulic, mechanical, thermal, and magnetic measurements
- Tests/measurements can be systematically (entire series) or on specific/random samples
- Complete recording and documentation indispensible (back-tracing in case of doubts or failures)

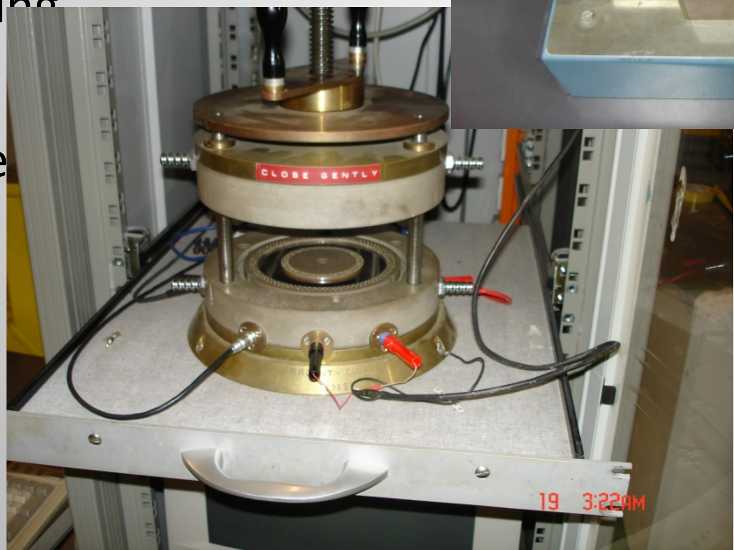


Sample testing

Typically the following samples are tested to validate material performance and production processes:

- Magnetic steel
- Laminations
- Bond strenght (lamination
- Brazing
- Welding
- Bond
- Impre





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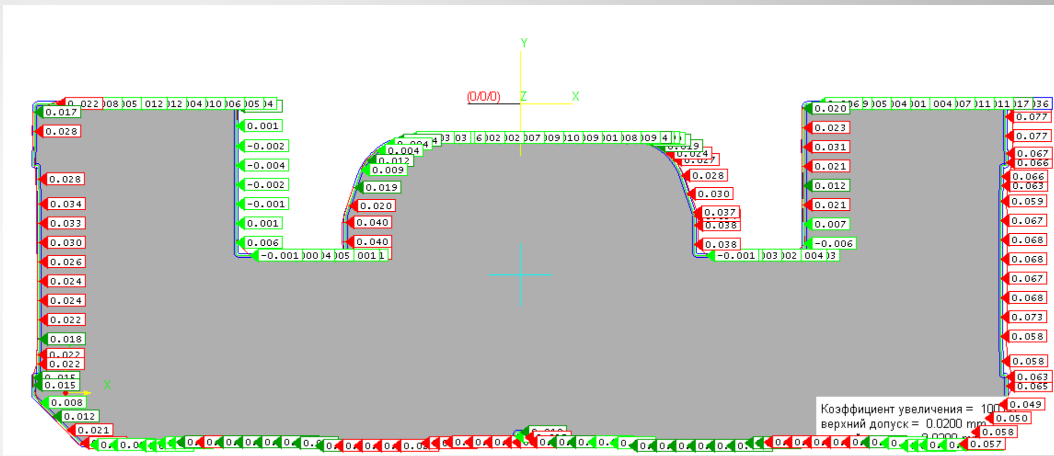

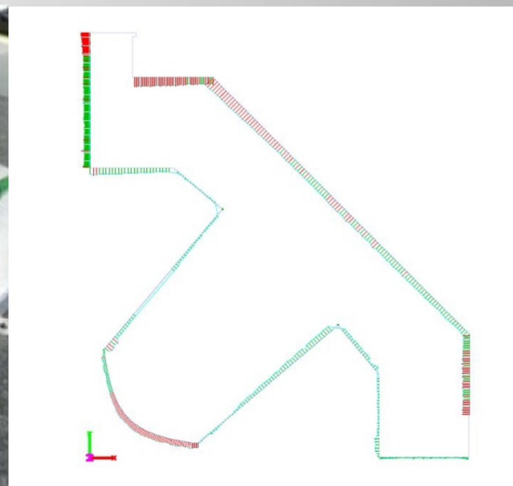

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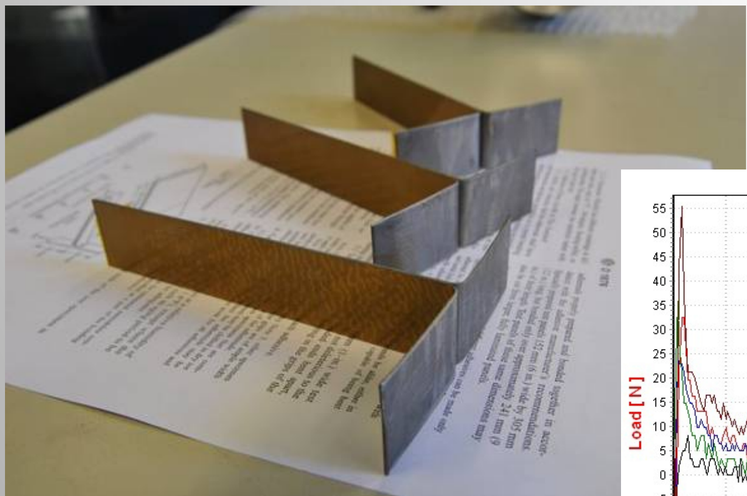

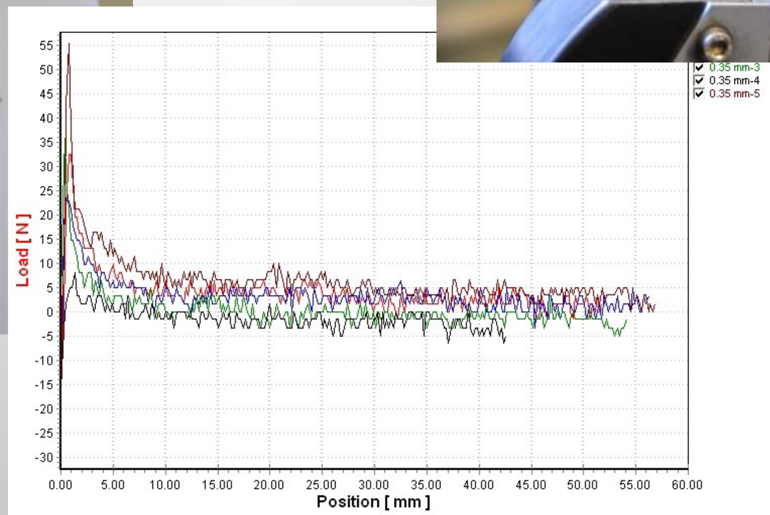

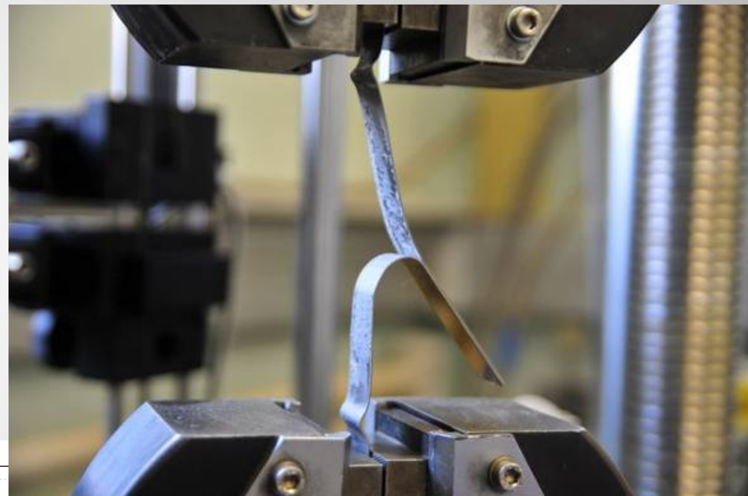

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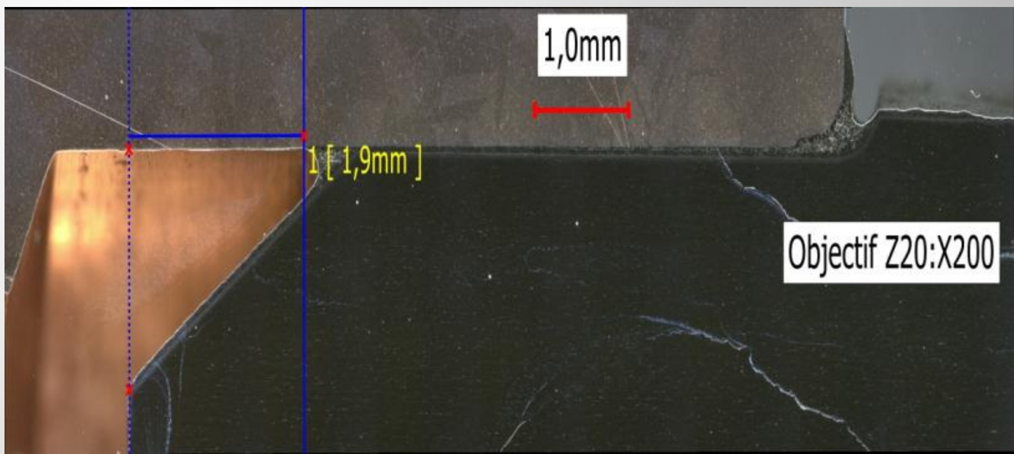

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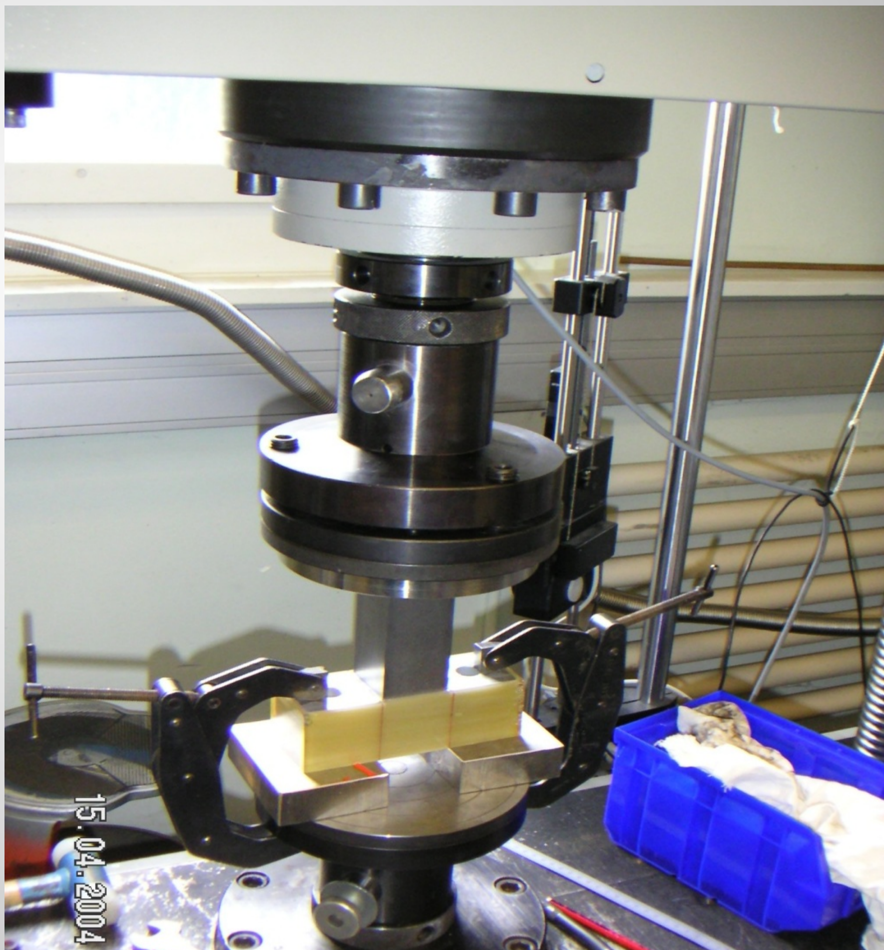

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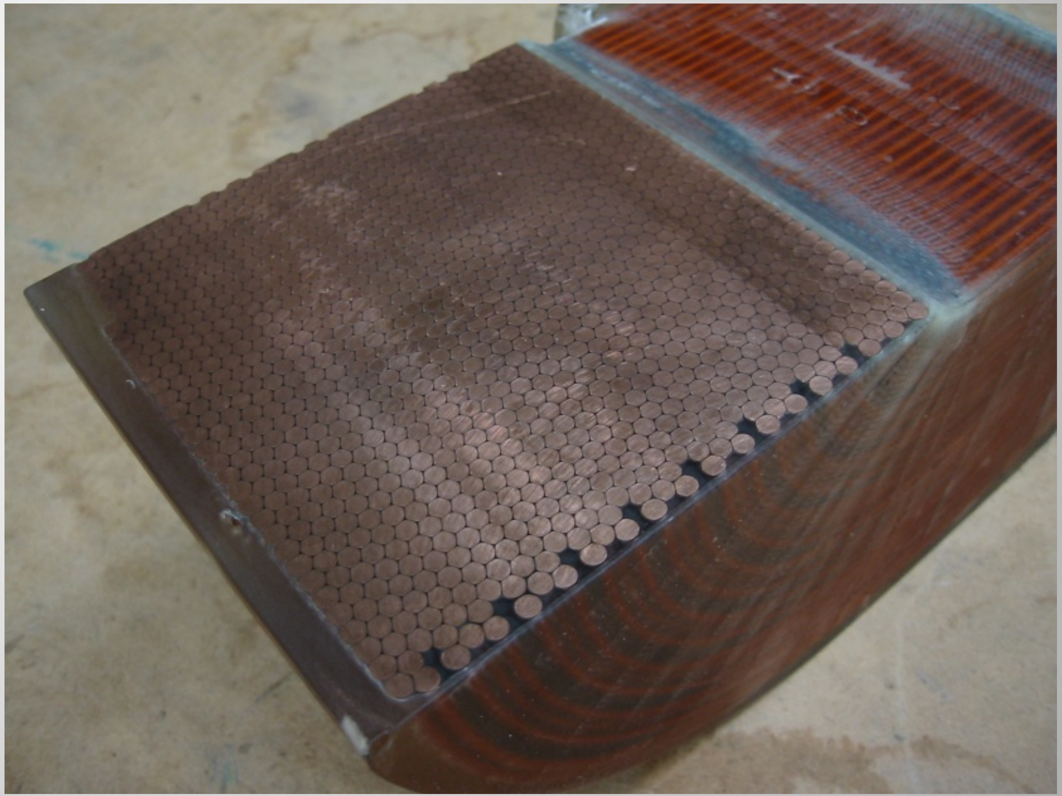


Mechanical measurements

Yoke shape and dimensional accuracy is essential for magnetic field quality in iron-dominated magnets

Mechanical errors can significantly influence the magnetic performance

We distinguish between:

Systematic errors

- lamination contour (punching)
- lamination thickness
- effect can be relativley easy determined and corrected

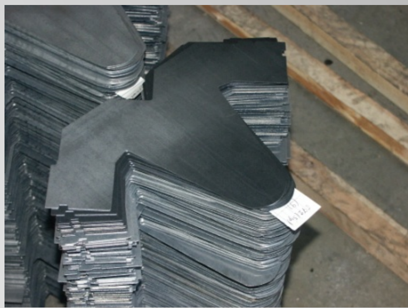
Random errors

- stacking
- machining
- assembly
- difficult to predicted
- in general known only after series production
- can be partly minimized by imposing low mechanical tolerances (expensive), enlarged design margins (expensive, too), strict quality assurance and close follow-up of production processes

Mechanical measurements

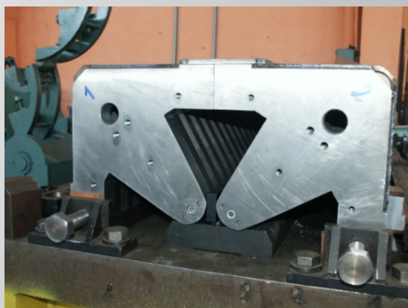
Mechanical measurements are required after each manufacturing step:

- Lamination punching
  - flatness
  - contouring accuracy
  - burr height



- Yoke pieces (half-yoke, quadrants) manufacture
  - lenght
  - straightness
  - flatness (planarity)
  - perpendicularity of end faces
  - shape accuracy
  - after and before welding

- Yoke assembly
  - lenght
  - straightness
  - gap height and parallelism (dipole)
  - aperture radius (quadrupole, sextupole)



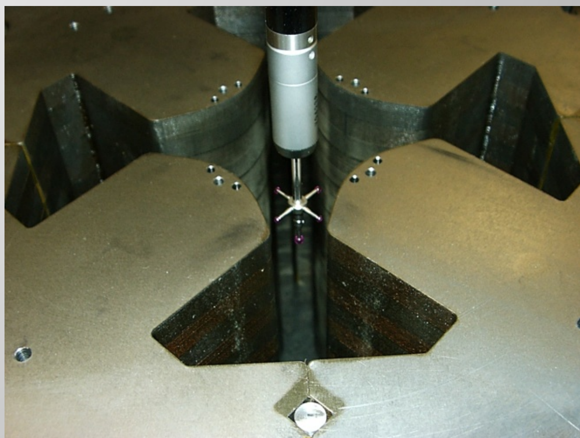
- Reproducability: after disassembling and re-assembling (dowel pins)
- Stability: no deformation due to handling, lifting, transport (lifting test)

Mechanical measurements

Various optical and mechanical techniques with different accuracy, precision and resolution are available for mechanical measurements





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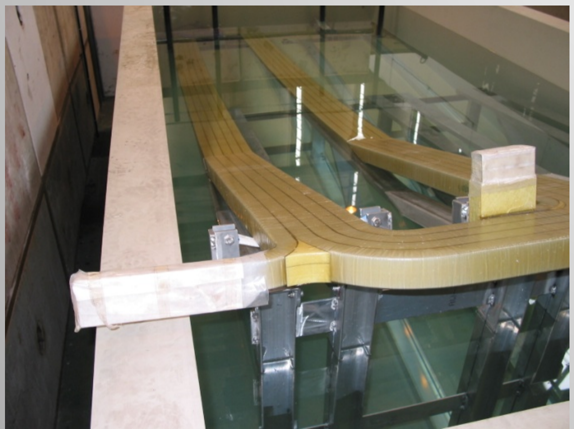
Electrical testing

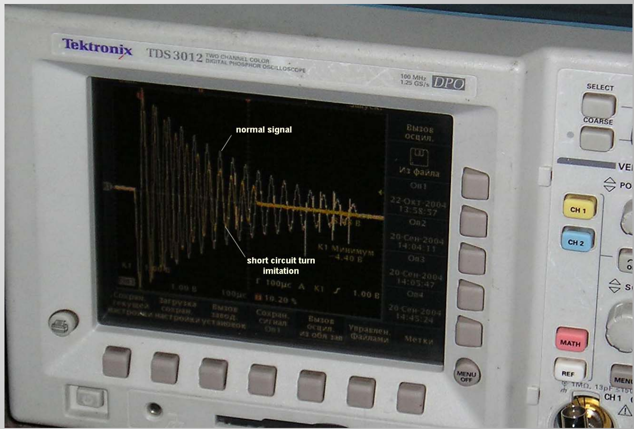
- Insulation tests are an integral part of the electrical testing in addition to the measurements of the electrical coil resistance and inductance
- An electrical insulation shall be tested to ensure its ability to provide the required insulation levels for specified operation and faulty conditions and during a specified time → tests shall reveal manufacturing deficiencies
- In most cases, this means specifying test levels much beyond the real operational conditions
- The following properties can be measured to give evidence whether an insulation has been correctly designed (with the appropriate materials, technologies and geometries) and correctly manufactured:
  - Resistivity (step voltage or leakage current vs voltage)
  - Dielectric constant and loss factor over a range of frequencies
  - Partial discharge
  - Breakdown voltage

Insulation testing

For acceptance testing we typically perform two types of tests:

- High voltage test of a conductor to ground
  - coil completely immersed in tap water (ground)
  - application of test HV (several kV)
  - measurment of leakage current (→ insulation resistance)
- Capacitor discharge test for inter-turn insulation
  - discharging a capacitor (C) into a coil (L) and record the ringing signal
  - frequency and damping gives information about the interturn short circuits
  - comperative methode: good sample vs. specimen
  - alternative: transformer method

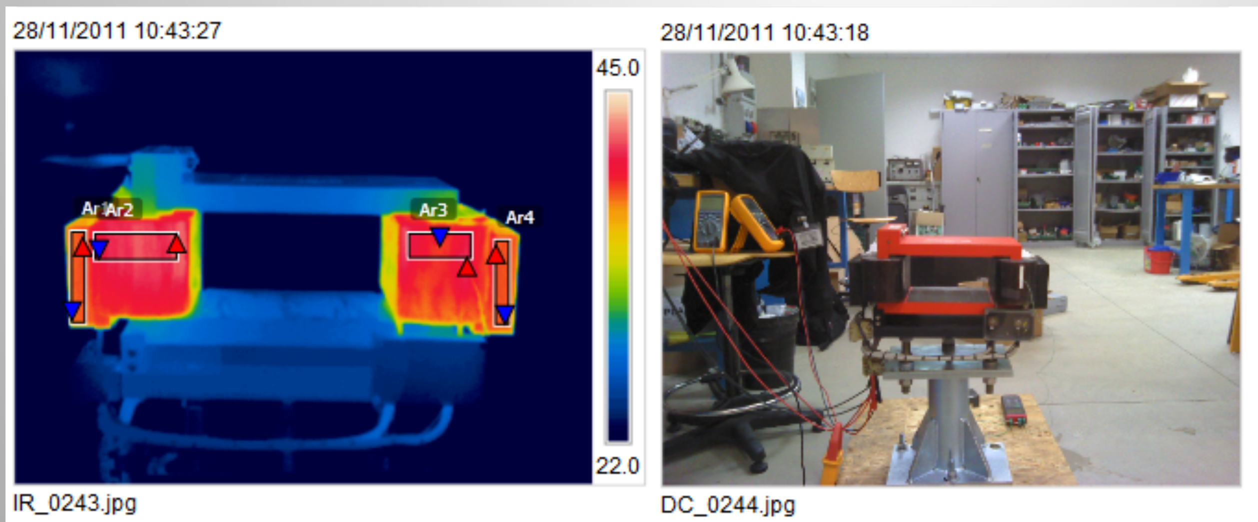


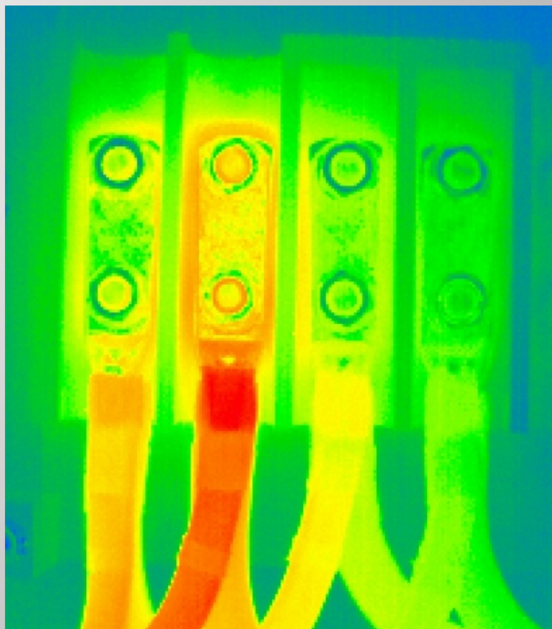


Power and heating tests

Power test are performed to verify:

- correct interlock functioning
- no accidental over-heating
- correct cooling performance
- absence of poor electrical contacts
- absence of moving or loose parts (pulse test)





Recurrent quality issues

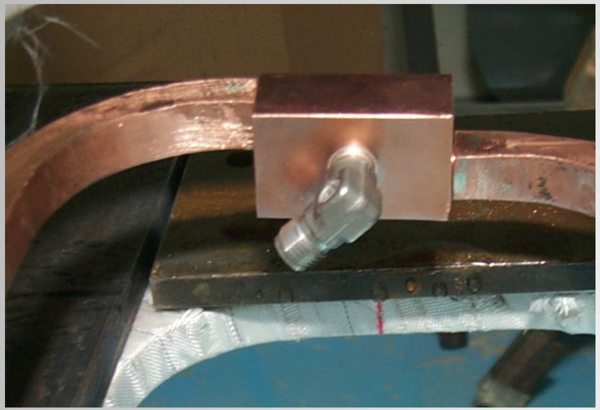
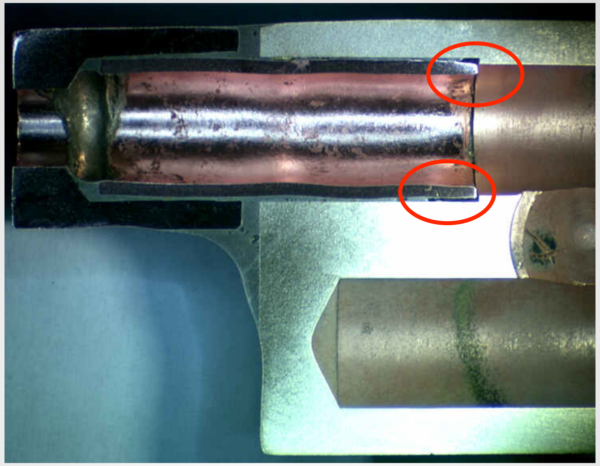
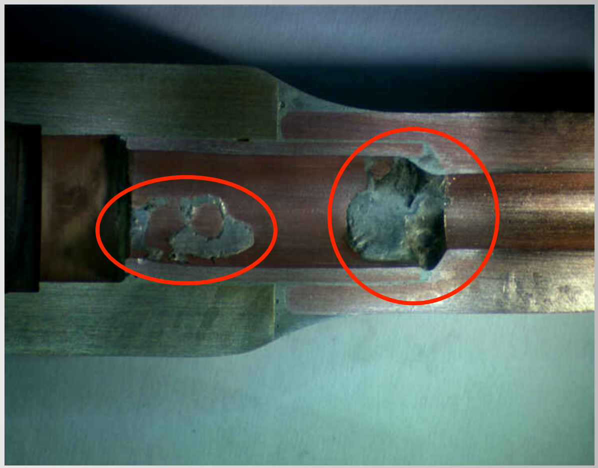
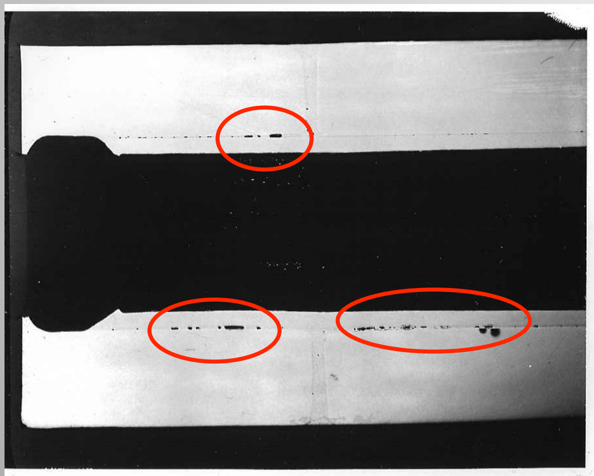
Despite a severe quality control by the manufacturer, we often find quality deficiencies during the acceptance tests and certification at CERN

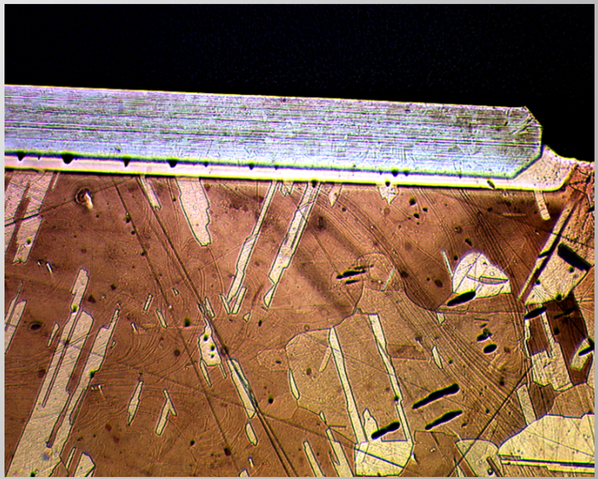
Amongst several other recurrent issues, the following are the most frequent and most serious ones:

- Poor brazing quality
- Poor bonding stength
- Poor coil insulation/impregantion
- Insufficient rust protection
- Loose or moving parts
- Covers not respecting IP2X
- Insufficient cable cross-section
- Obstructed cooling circuits
- Transport damages due to inadequate packaging

Recurrent quality issues

Lack/excess of brazing filler



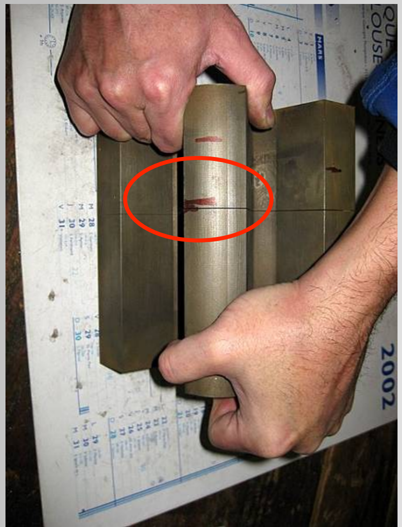
Recurrent quality issues

Lack of resin: bubbles, voids, fissures, cracks, poor penetration, poor wetting

Excess of resin: volumes of pure resin

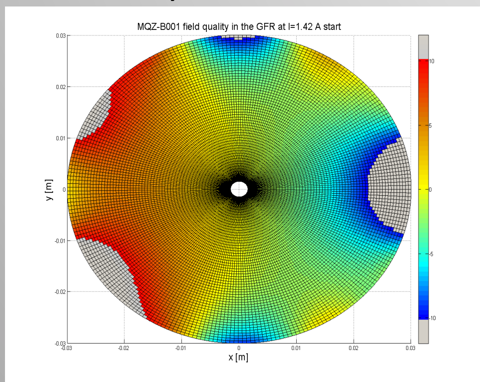
Recurrent quality issues

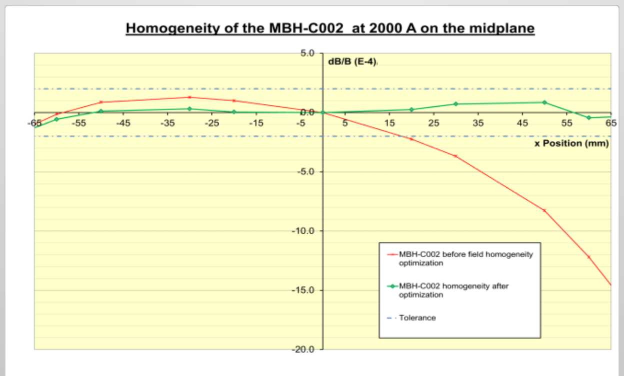
Poor lamination bonding stength

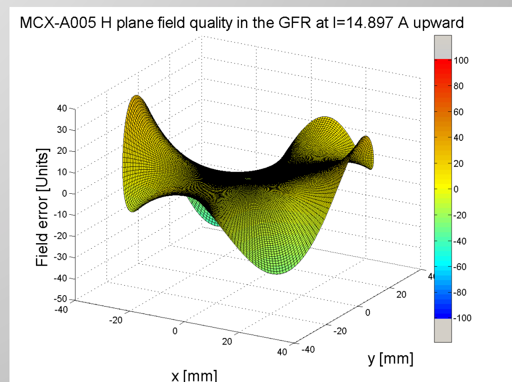


Magnetic measurements

- Magnetic measurements as final proof if design and manufacturing is correct are an essential part of the magnet qualification process
- Magnetic measurements are complementary to computer simulation and beam based measurements
- No single instrument or method can cover all requirements
  – Multiple instruments are complementary
  – Overlaps provide estimation of absolute uncertainty and error correction
- Commercial availability is very limited → requires R&D, time and experience
  – Precise mechanics, stable materials, heavy benches are the foundation of good instruments
- Different strategies for error correction:
  – random errors are reduced by repetition
  – systematic errors are reduced by cross-checks and by the use of symmetries







Instrument selection

Criteria for instrument selection (in order of priority):

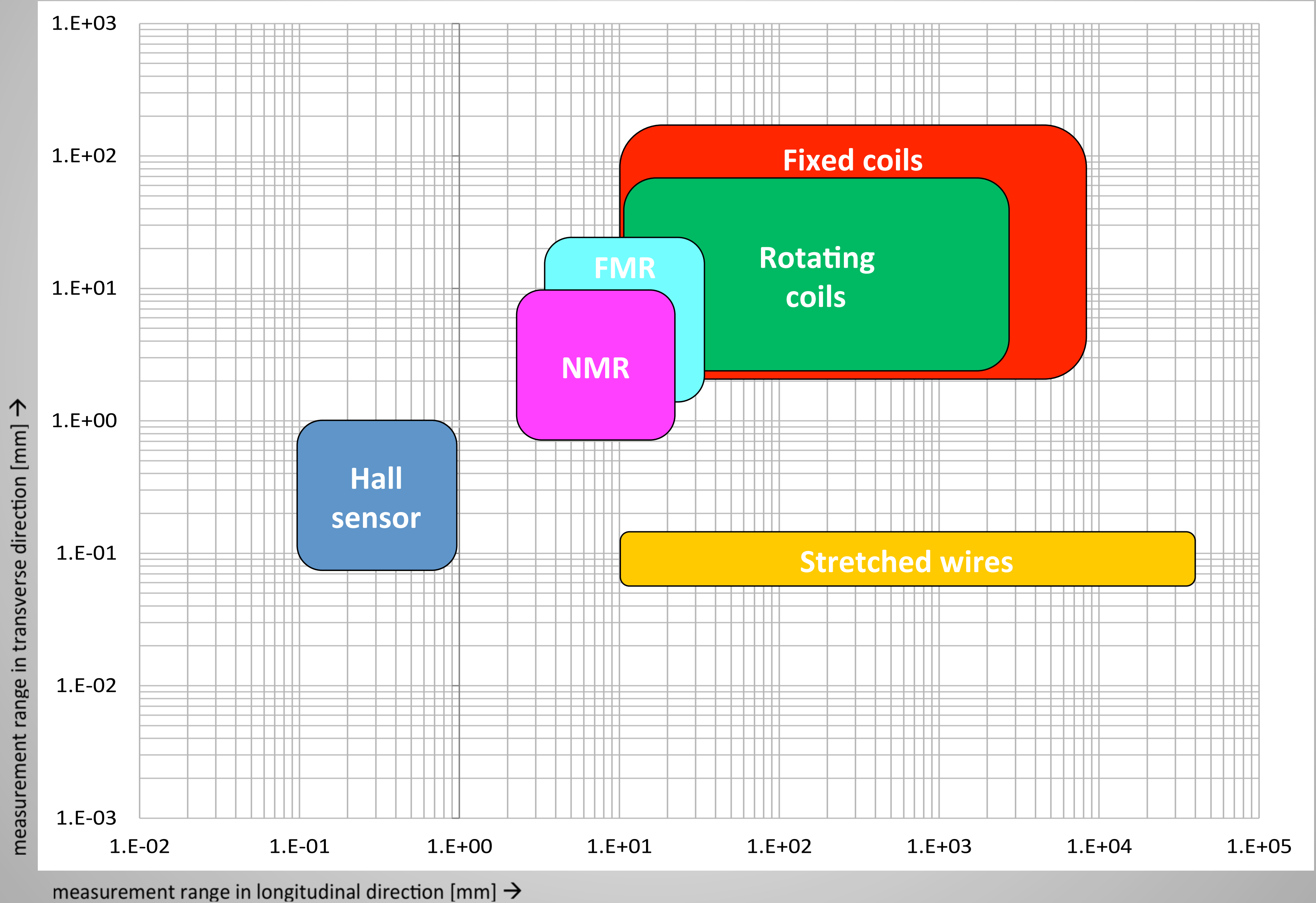
- Compatibility with field level/gradients
- Transverse size
  - instrument must fit and should reach as wide as possible
  - accuracy of harmonics degrades with decreasing transversal size
  - extrapolation can be applied under certain conditions
- Bandwidth
  - signal must be detectable
  - sufficient SNR
  - sensitivity decays at the bounds
- Longitudinal size (integral or profile?)
  - integral can be computed by scanning longitudinally (time-consuming)
- Accuracy
  - uncertainty can be reduced by repetition, changing orientation, cross-checks …
- Result format: harmonics vs. uniformity
  - can be converter into each other (with limitations)
- Practical considerations:
  - costs
  - measurement time
  - availability of equipment and trained personnel …

Overview of measurement techniques

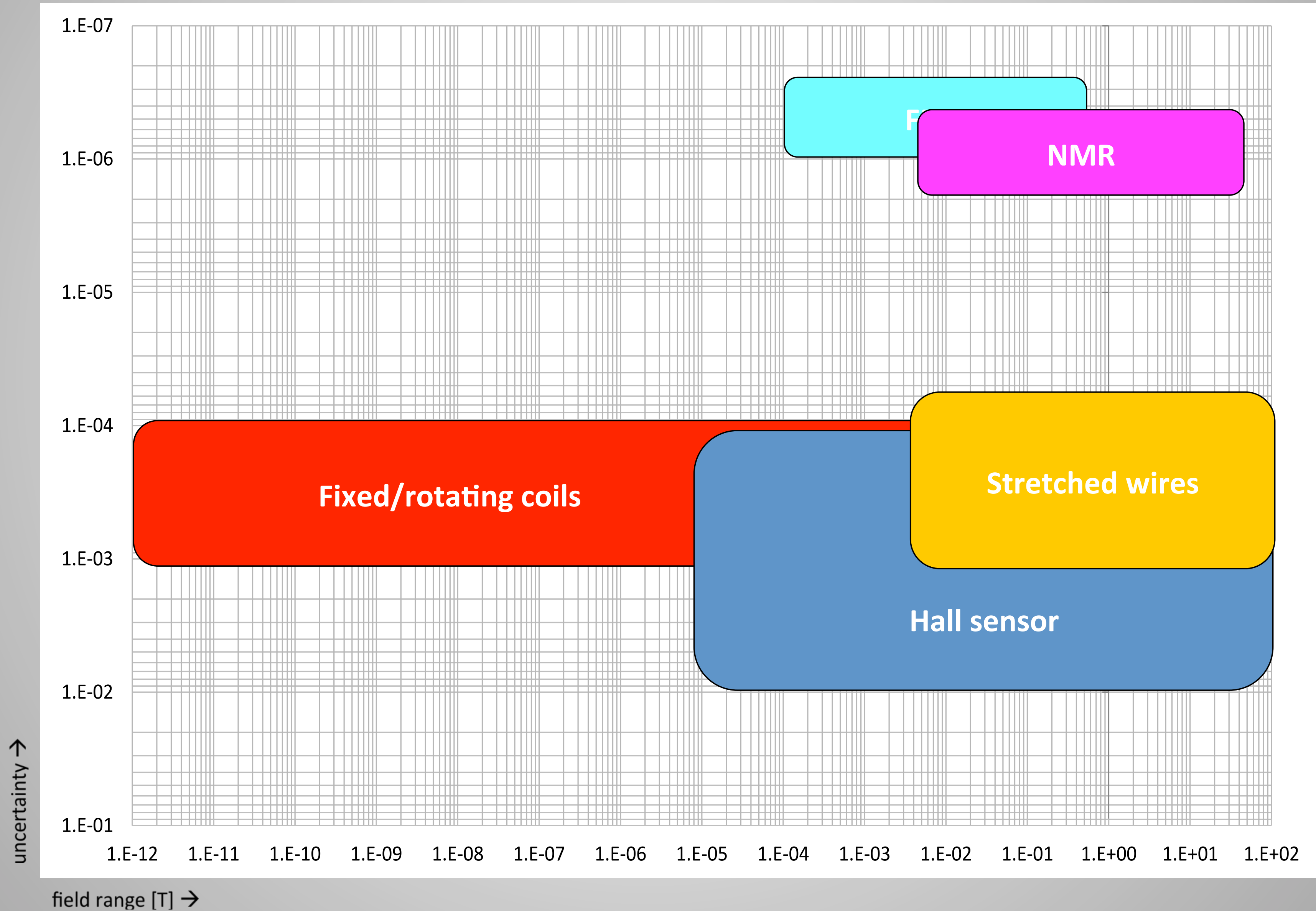
Method	Type[1]	Range [T]	u[2] [-]	BW[3] [Hz]	Cost[4] [€]	Size[5] [mm]	Length[6] [mm]	Notes
SQUID	V	10^{-14}~10^{-4}	10^{-5}	DC~10^{0}	10^{3}	< 1	< 1	Highest sensitivity, needs cryogenics
Fluxgate	V	10^{-7}~10^{-2}	10^{-2}	DC~10^{3}	10^{2}	3	10	Main application: geomagnetic fields
Fiber optic	V	10^{-12}~10^{-3}	10^{-6}	DC~10^{2}	10^{4}	30	100	Magnetostrictive sample deformation detected by Mach-Zender interferometer
M-optical	V	>10^{-4}	10^{-2}	DC~10^{9}	10^{3}	>100	>100	Faraday effect (rotation of polarization). Extreme BW, compatible with extremely high fields
M-induction	V	10^{-6}~10^{-3}	10^{-2}	DC~10^{3}	10^{0}	5	5	Used for low-power compass devices in GPS, smartphones … Digital out, T-insensitive
M-resistance	V	10^{-9}~10^{-3}	10^{-2}	DC~10^{9}	10^{1}	< 1	< 1	GMR sensor vital for magnetic recording industry; non-linear
M-diode	V	10^{-5}~10^{1}	10^{-1}	DC~10^{4}	10^{1}	< 1	< 1	High sensitivity = 10x Hall, non-linear
M-transistor	V	10^{-6}~10^{0}	10^{-1}	DC~10^{4}	10^{1}	< 1	< 1	Very high sensitivity = 100x Hall, non-linear
Hall effect	V	10^{-5}~10^{2}	10^{-3}	DC~10^{4}	10^{3}	<1	<1	Higher low-prec BWsimple, cheap, commercially available accuracy requires laborious calibration
Fixed coil	V	>10^{-12}	10^{-4}	10^{-2}~10^{6}	10^{4}	5~500	1 mm ~ 10 m	Linear, sensitivity increases wth BW
Rotating coil	V	>10^{-12}	10^{-4}	DC~10^{1}	10^{4}	∅8-400	1 mm ~ 2 m	Best all-round performer for accelerator magnets
Translating wire	V	>10^{-3}	10^{-4}	DC	10^{4}	∅0.1	< 20 m	Classical system
Oscillating wire	V	>10^{-3}	10^{-3}	DC	10^{4}	∅0.1	< 20 m	Ongoing R&D
NMR	S	10^{-5}~10^{2}	10^{-6}	DC~10^{0}	10^{4}	10	10	Low field range only with custom flowing/water method
FMR/EPR	S	10^{-8}~10^{-1}	10^{-4}	DC~10^{3}	10^{4}	40	40	Experimental
Optical pump	S	10^{-5}~10^{-4}	10^{-6}	DC~10^{1}	10^{4}	100	1 m	Based on Zeeman effect in Rb, Ce Best resolution: 10 pT

(1) V=vector, S=scalar (2) u=typical uncertainty (3) bandwidth (4) system cost (5) transversal sensor size (6) sensor size along the beam direction

Instrument size



Field range and uncertainty



Summary

- Tight QA is the key for success and important at each production stage
- Sample testing to qualify materials, manufacturing techniques and processes
- Acceptance tests to verify the correct performance of the final product
- The yoke shape and dimensional accuracy is essential for magnetic field quality in iron-dominated magnets
- Magnetic measurements are an essential part of the magnet qualification process and complementary to computer simulations and beam measurements
- Different complementary measurement techniques and instruments can help to reduce the absolute uncertainty
- Complete recording and documentation indispensible

Literature

- Fifth General Accelerator Physics Course, CAS proceedings, University of Jyväskylä, Finland, September 1992, CERN Yellow Report 94-01
- International Conference on Magnet Technology, Conference proceedings
- Iron Dominated Electromagnets, J. T. Tanabe, World Scientific Publishing, 2005
- Magnetic Field for Transporting Charged Beams, G. Parzen, BNL publication, 1976
- Magnete, G Schnell, Thiemig Verlag, 1973 (German)
- Field Computation for Accelerator Magnets: Analytical and Numerical Methods for Electromagnetic Design and Optimization, S. Russenschuck, Wiley-VCH, 2010
- CAS proceedings, Magnetic measurements and alignment, Montreux, Switzerland, March 1992, CERN Yellow Report 92-05
- CAS proceedings, Measurement and alignment of accelerator and detector magnets, Anacapri, Italy, April 1997, CERN Yellow Report 98-05
- Physik der Teilchenbeschleuniger und Synchrotronstrahlungsquellen, K. Wille, Teubner Verlag, 1996
- CAS proceedings, Magnets, Bruges, Belgium, June 2009, CERN Yellow Report 2010-004

Thanks for your attention…

… and many thanks to all my colleagues who contributed to this lecture, in particular L.Bottura, M.Buzio, B. Langenbeck, N.Marks, S.Russenschuck, D.Schoerling, C.Siedler, S.Sgobba, D.Tommasini, A.Vorozhtsov