Measurement and control of low magnetic fields at CERN

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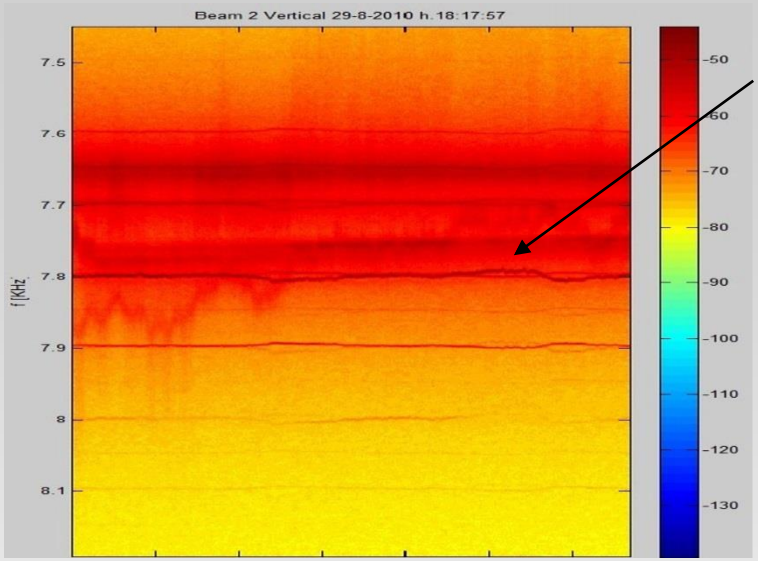
1) Examples of low field measurements
2) Commercial instrumentation
3) Available facilities

Examples of low field measurements

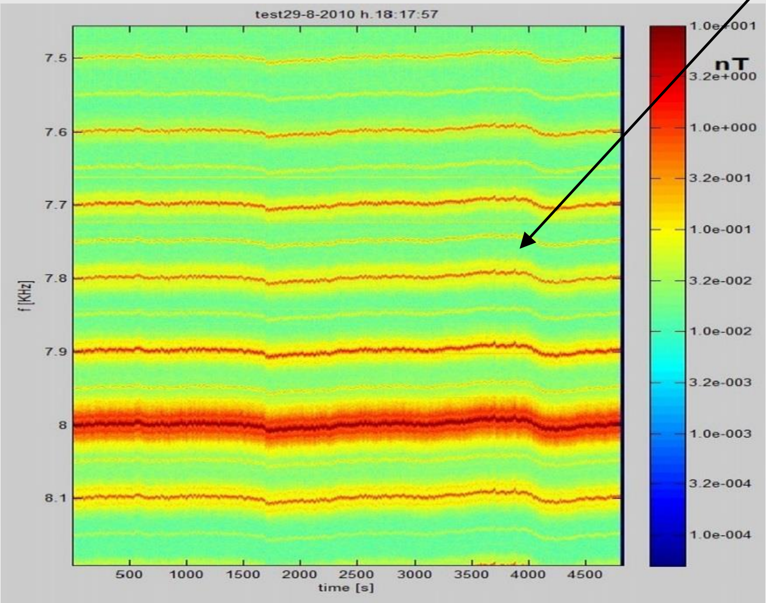
LHC hump hunt (1/2)

- “the hump”: weak excitation bands observed in the LHC transverse spectra at ~8 kHz (& multiples) from 2009 to 2011
- peculiar quasi-periodic frequency drift over a timescale of ~20 min
- localized investigation campaigns carried out with induction coils while equipment categories (pumps, UPS etc …) were switched on and off
- 7 remotely acquired coils left in place in 2011
- some correlations were found but the underlying cause was never clarified
- “spontaneously” disappeared during 2011 YETS

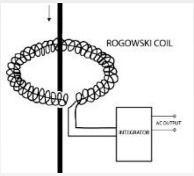
Example: UPS-caused event seen by:



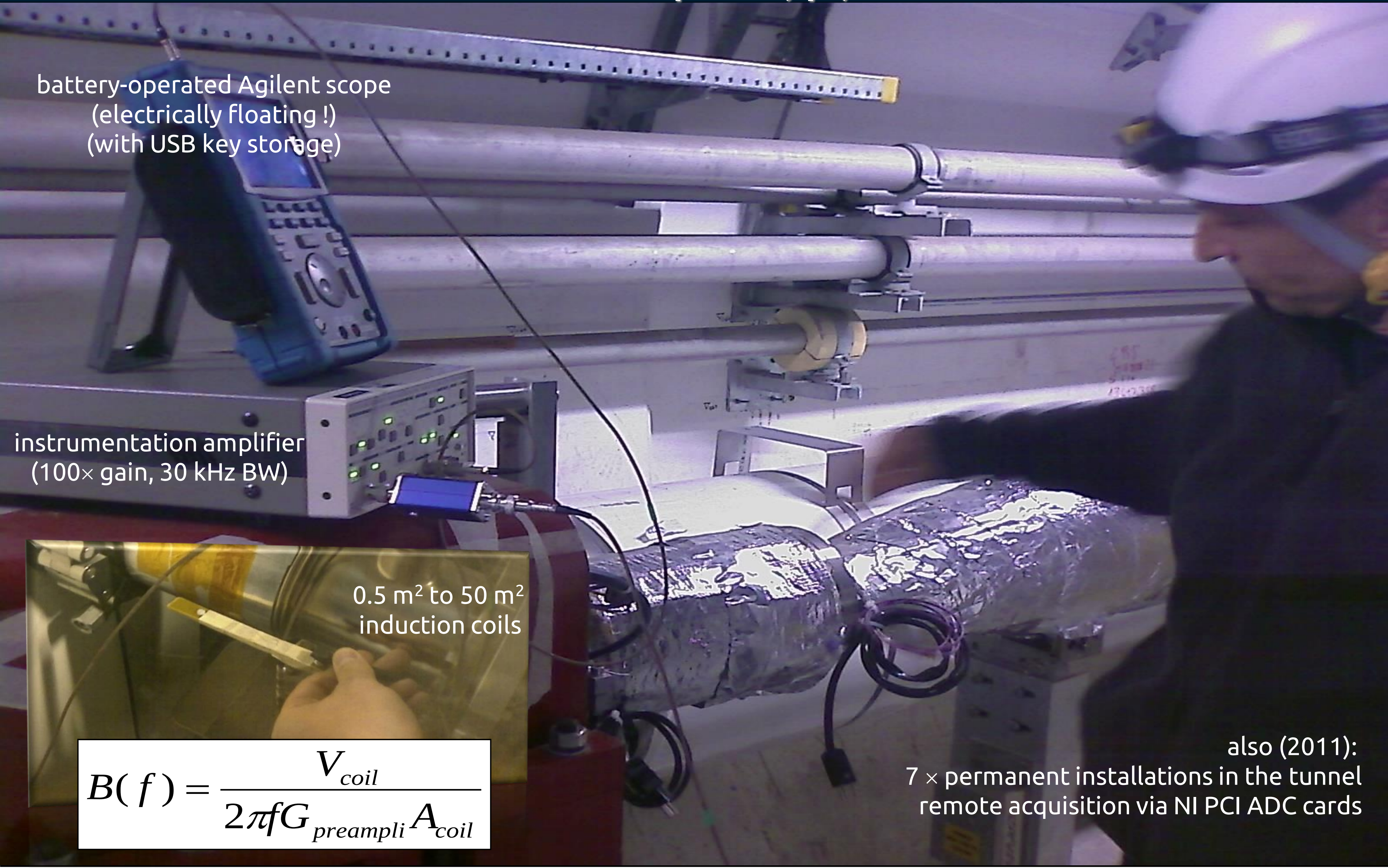
BBQ (tune meas.) on Beam 2



“Rogowski” measurement on a 3-phase UPS



LHC hump hunt (2/2)



battery-operated Agilent scope
(electrically floating !)
(with USB key storage)

instrumentation amplifier
(100× gain, 30 kHz BW)

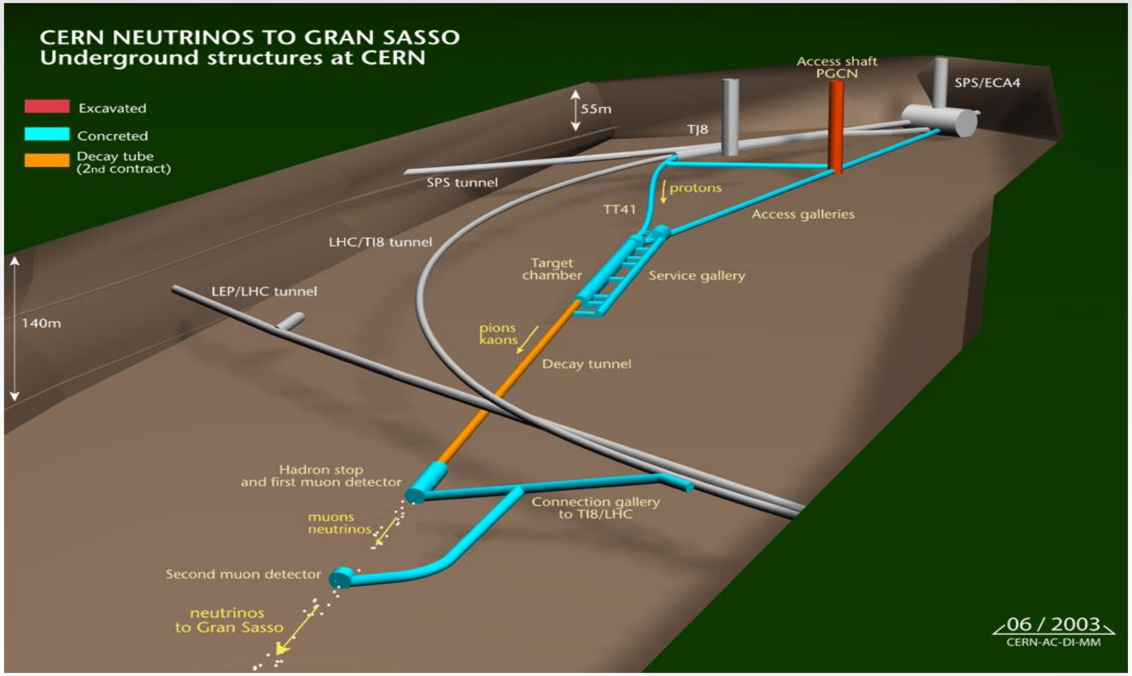
0.5 m^2 to 50 m^2
induction coils

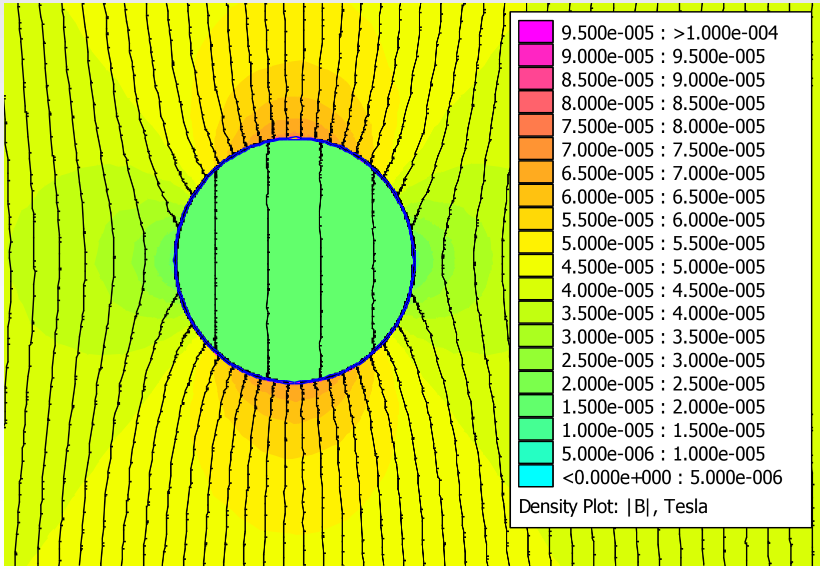
$$B(f)=\frac{V_{coil}}{2\pi f G_{preampli} A_{coil}}$$

also (2011):
7 × permanent installations in the tunnel
remote acquisition via NI PCI ADC cards

CERN Neutrino to Gran Sasso

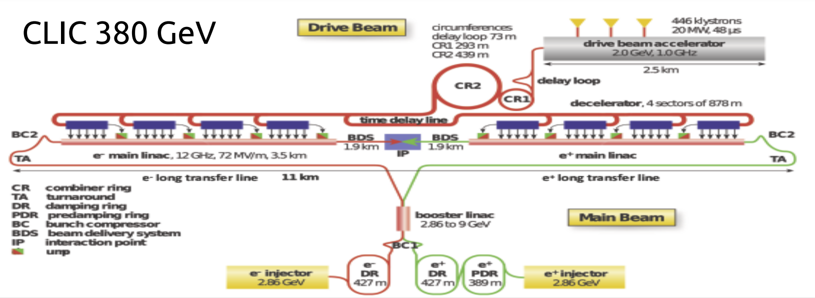
- pions/kaons were made to decay to neutrinos in the 998 m long CNGS tunnel
- ~200 mm position errors observed at the target over 700 km away, attributed to integrated background field in the tunnel
- measurements within 20-50 μT confirmed simulation
- prediction of earth field attenuation difficult due to uncertainty on material properties

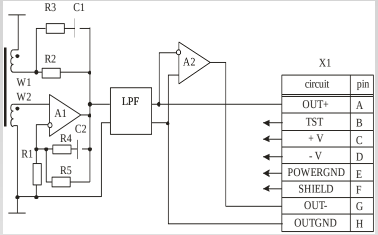




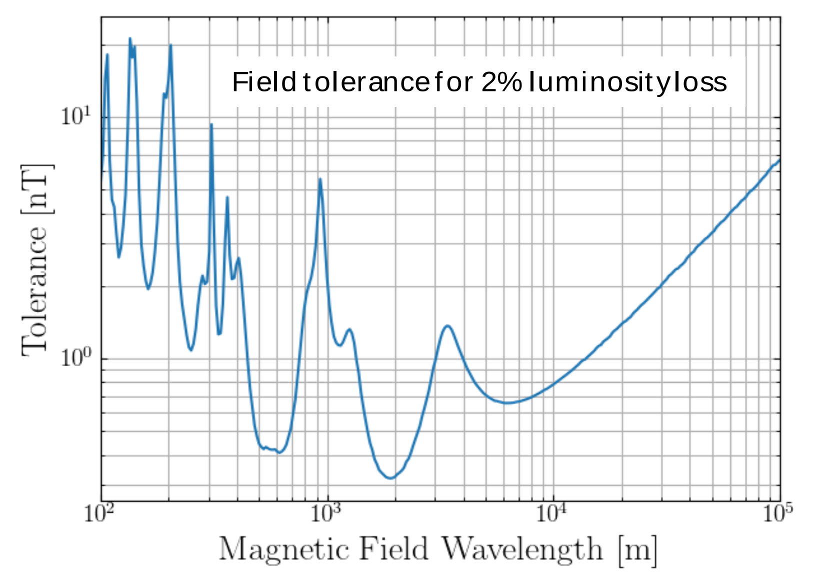
Compact Linear Collider (CLIC) studies

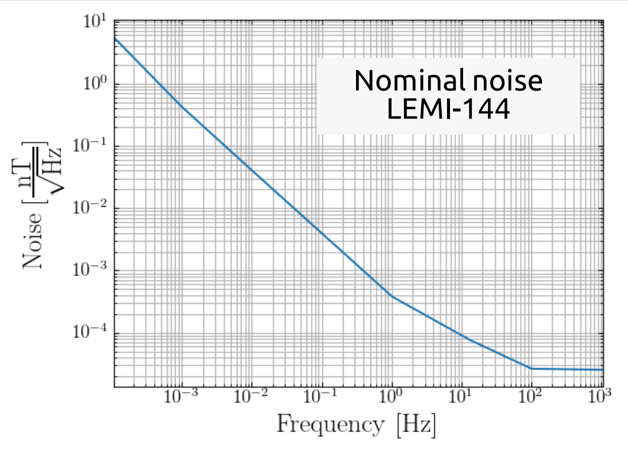
- CLIC is a 50 km long, 3 TeV e^-e^+ collider with nm-sized beams
- Very tight tolerances: residual stray field ≤ 20 nT in general, ≤ 0.3 nT over λ=3 km
- Stray field characterization of CERN beam lines with LEMI and Bartington magnetometers, Geomagnetic characterization of Jura region under way

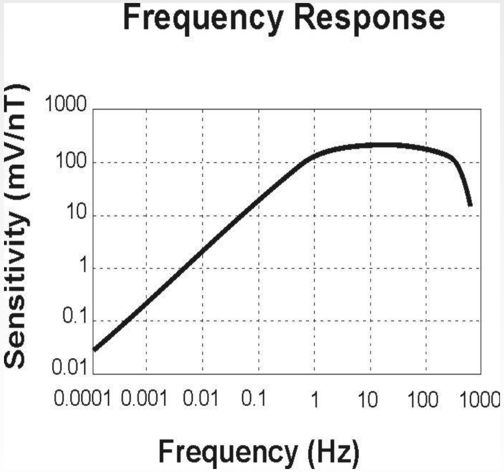




LEMI-144 (Laboratory of Electromagnetic Innovations, Ukraine)
1-axis induction-coil magnetometer with feedback stabilization of frequency response at f > 1 Hz
Rugged construction for outdoors operation
Field range up to 250 nT, bandwidth 0.001 to 300 Hz
Nominal noise 0.6 pT/√Hz @ 1 Hz







Courtesy Chetan Gohil, BE/ABP

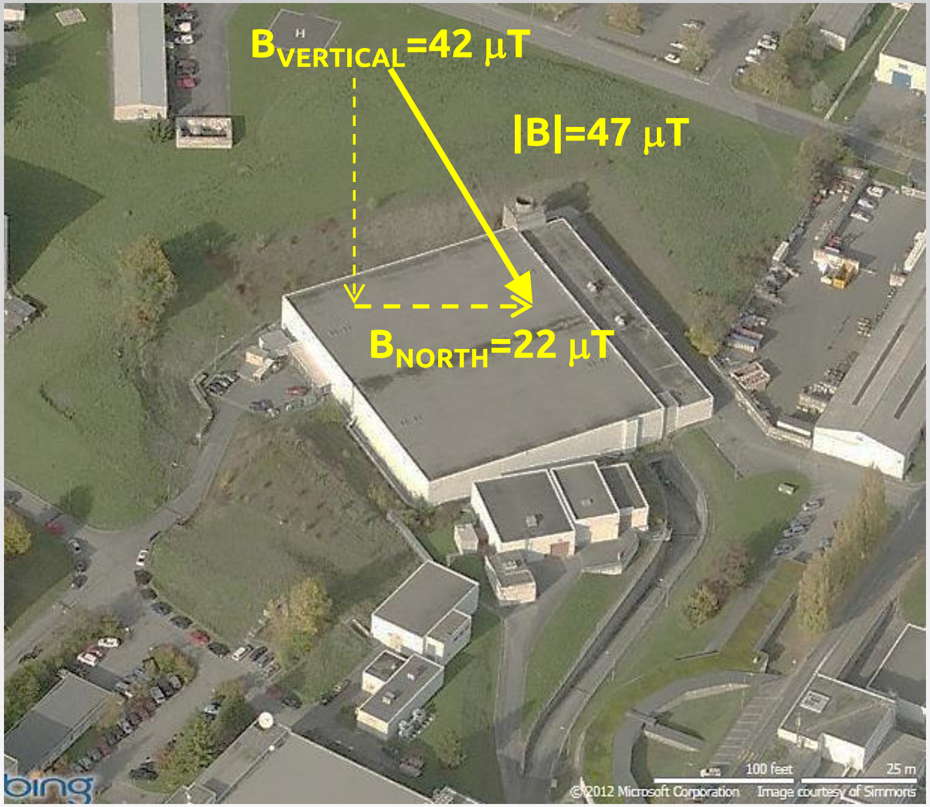
AD/ELENA investigations (1/3)

Geomagnetic field in Geneva

Daily and yearly change < 1%

General field level in the hall: $B_{VERTICAL} \sim 35\ \mu T$

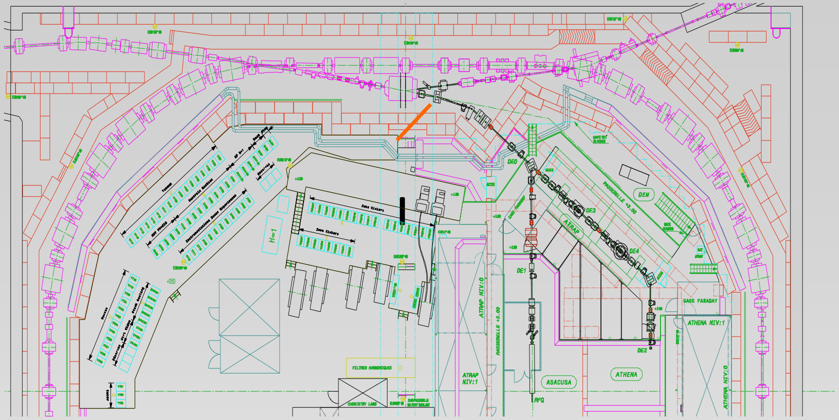
$B_{HORIZONTAL} \sim 30\ \mu T$



Scaffolding structure behind kicker spools:
150 μT (70 μT @ 0.2 m)

Field at AD ring concrete shielding blocks:
|B|~ 10 μT (~stable)

AD/ELENA investigations (2/3)



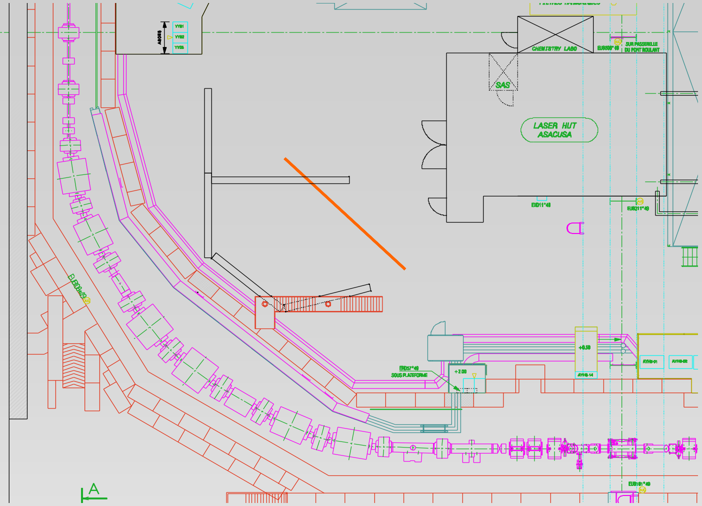
300 μT at the door frame

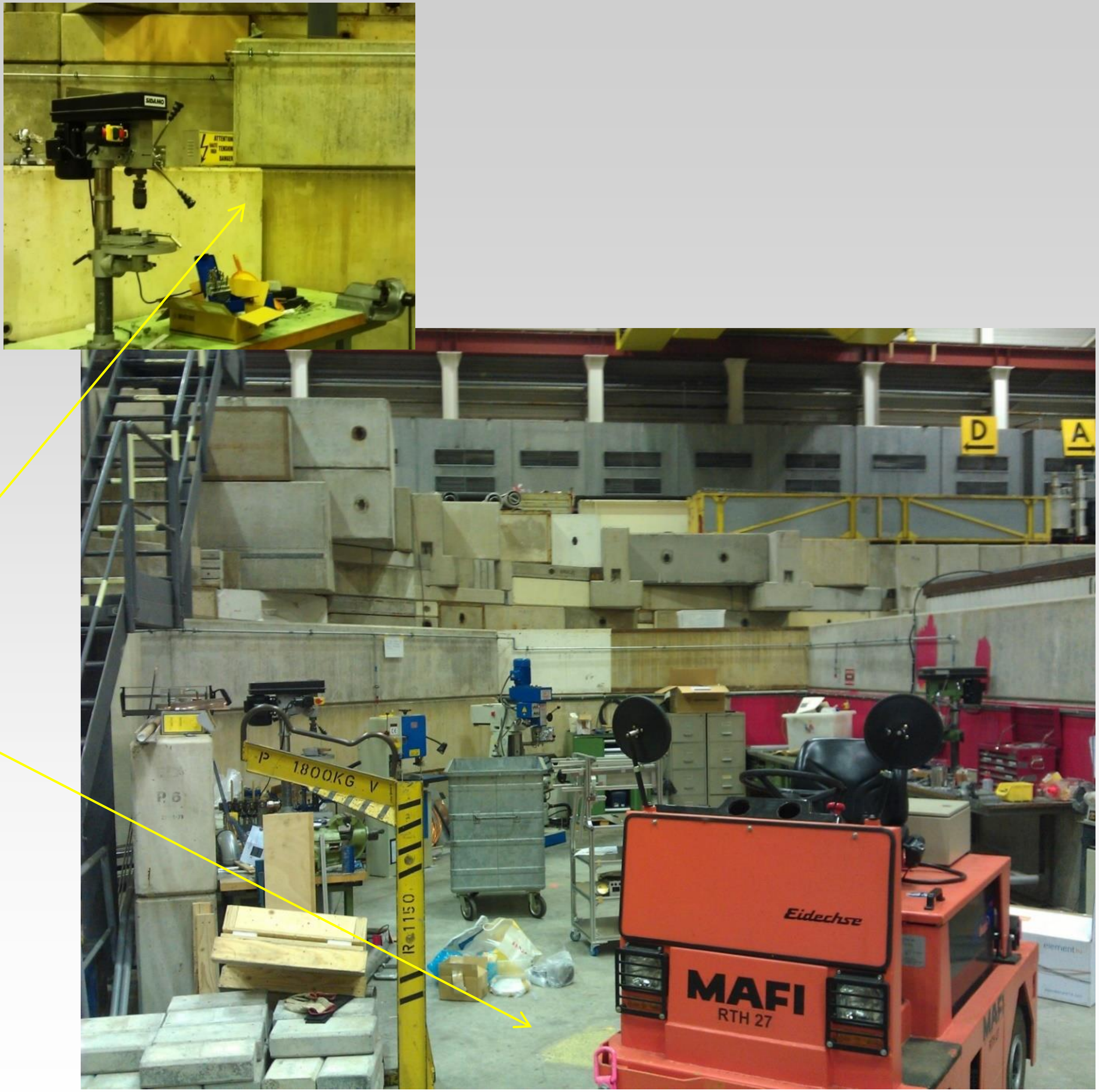
6500 μT at the Ar bottle

1000 μT at 1 m from the bottle

10 μT baseline in the area

AD/ELENA investigations (3/3)





1500 µT along the corner of the concrete block

50 µT at 1 m

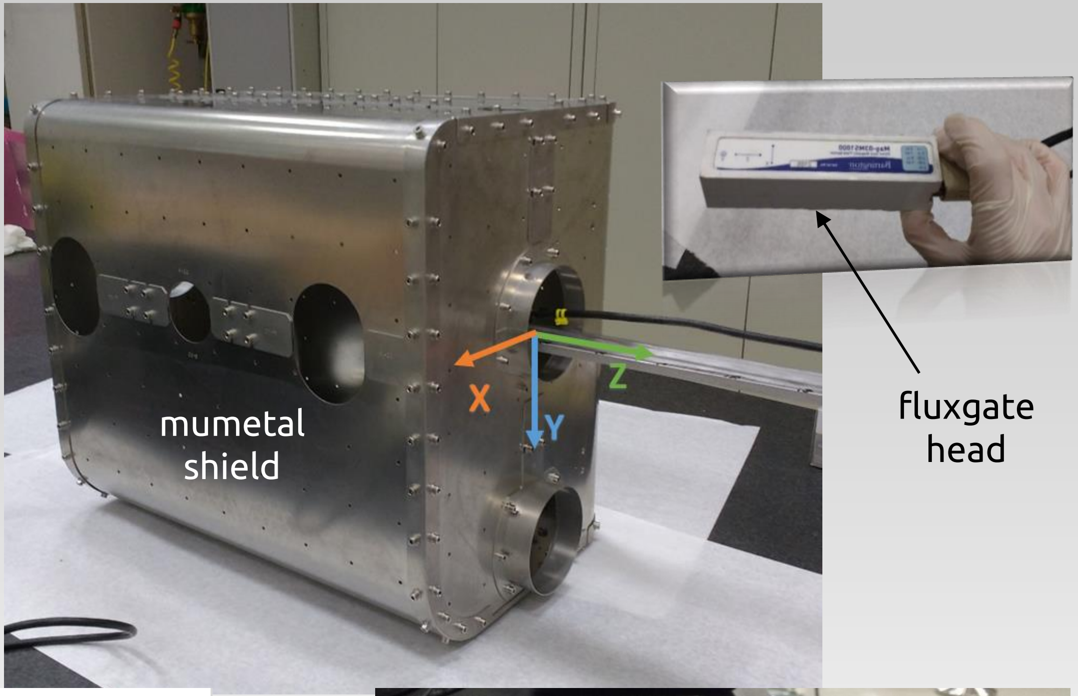
baseline (center of workshop area):

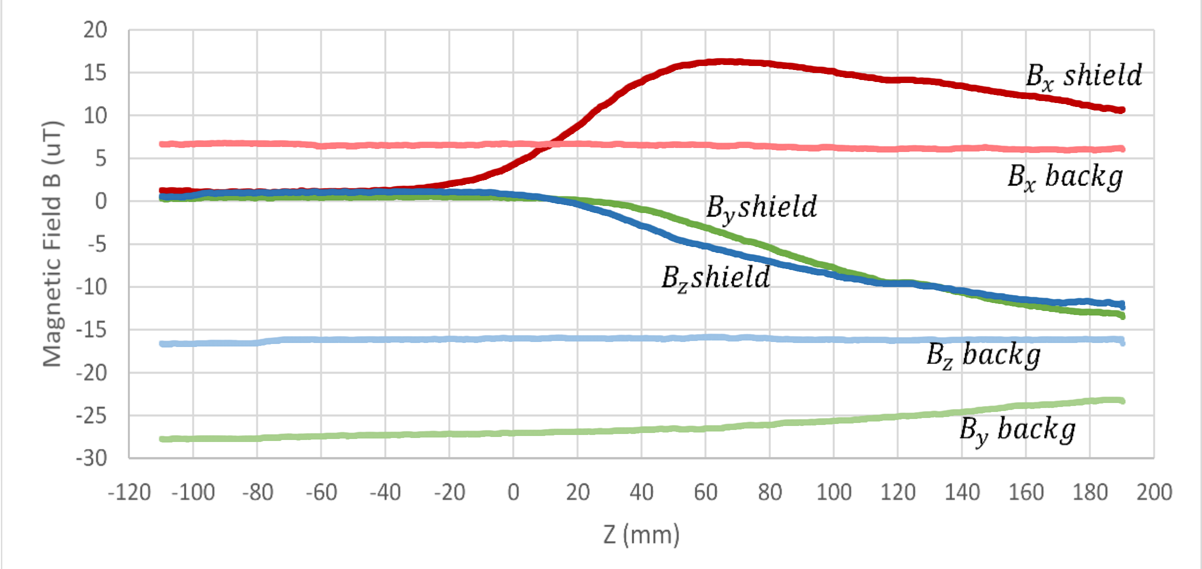
$B_{VERTICAL}$ = **25 µT**

$B_{HORIZONTAL}$ = **25 µT**

Measurement of LHC Crab Cavity shield effectiveness

- New RF crab cavities have a design field tolerance of ~100 nT → passive shielding necessary
- Magnetic performance of mumetal depends critically upon the thermal and mechanical history of material (20~30% fluctuations between units) → predictive calculation is not possible
- Accurate measurement of shielding factor in the 10^2 range requires sub-μT instrument precision (new head recently acquired)





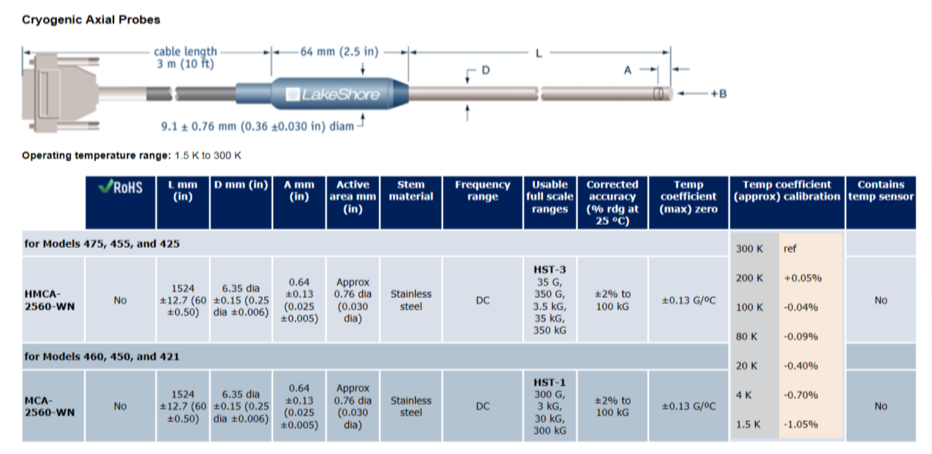
Bartington fluxgate with battery-operated 3-axis display unit (various models, lowest range is 70 nm to 70 μm, up to few kHz analog out)

Commercial instrumentation

Hall probes

- Widespread off-the-shelf solution: small, (relatively cheap), easy to use
- Many models marketed for sub-μT resolution; few working at cryogenic temperatures
- **Main problem at low field: fluctuating offset**, typical range **1-50 mT**
  caused by sensor asymmetry: geometry, doping, T gradients, mechanical stress …

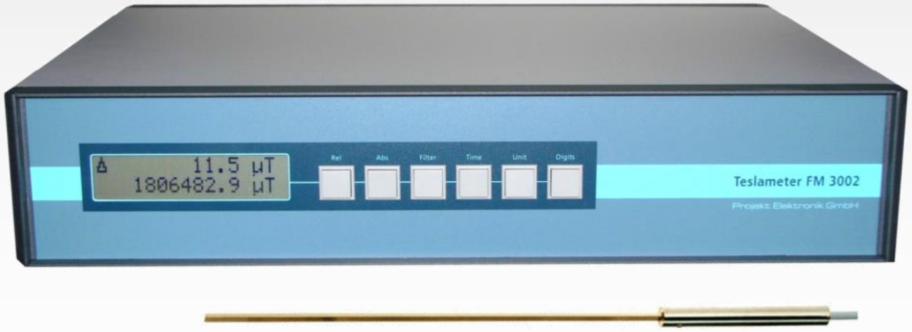
Lakeshore model 475 DPS Gaussmeter + Cryo Probe HST-3 (35 G)
300 nT resolution, DC Hz



Cryogenic Axial Probes

Operating temperature range: 1.5 K to 300 K

	✓RoHS	L mm (in)	D mm (in)	A mm (in)	Active area mm (in)	Stem material	Frequency range	Usable full scale ranges	Corrected accuracy (% rdg at 25 °C)	Temp coefficient (max) zero	Temp coefficient (approx) calibration	Contains temp sensor
for Models 475, 455, and 425											300 K ref 200 K +0.05% 100 K -0.04% 80 K -0.09% 20 K -0.40% 4 K -0.70% 1.5 K -1.05%	
HMCA-2560-WN	No	1524 ±12.7 (60 ±0.50)	6.35 dia ±0.15 (0.25 dia ±0.006)	0.64 ±0.13 (0.025 ±0.005)	Approx 0.76 dia (0.030 dia)	Stainless steel	DC	**HST-3** 35 G, 350 G, 3.5 kG, 35 kG, 350 kG	±2% to 100 kG	±0.13 G/ºC		No
for Models 460, 450, and 421												
MCA-2560-WN	No	1524 ±12.7 (60 ±0.50)	6.35 dia ±0.15 (0.25 dia ±0.006)	0.64 ±0.13 (0.025 ±0.005)	Approx 0.76 dia (0.030 dia)	Stainless steel	DC	**HST-1** 300 G, 3 kG, 30 kG, 300 kG	±2% to 100 kG	±0.13 G/ºC		No



Project Elektronik GmbH + RT transverse probe (2T)
150 nT resolution, DC-1 Hz

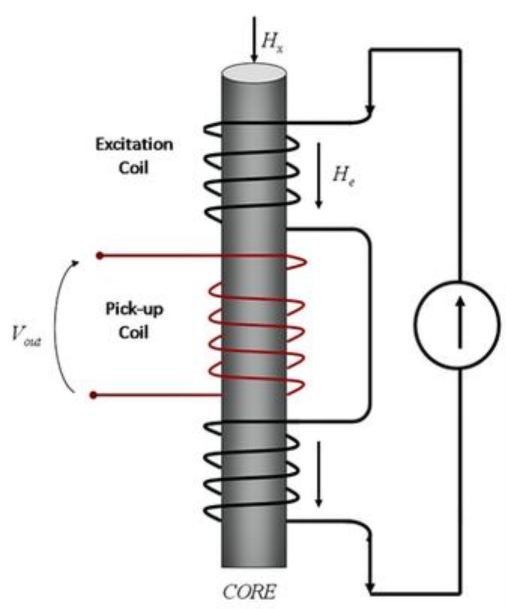
AREPOC 3-axial sensor (1.5 to 350 K, 5 G)
sensitivity **70 nV/μT**, offset < 200,000 nV

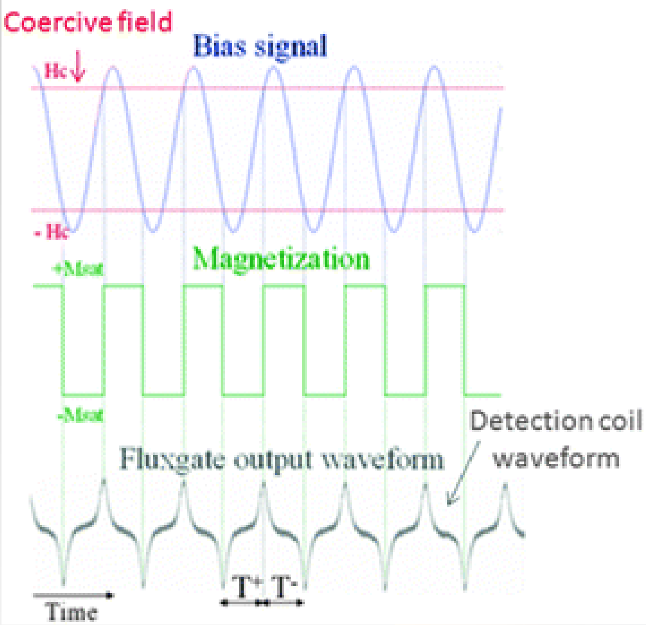
Fluxgate magnetometers

- Developed for wartime submarine detection, commonly used for geomagnetic applications
- **Mainstream choice for low fields at RT**: precise, stable, relatively inexpensive
- Major drawbacks: **bulky** sensor, **perturbs the field being measured**

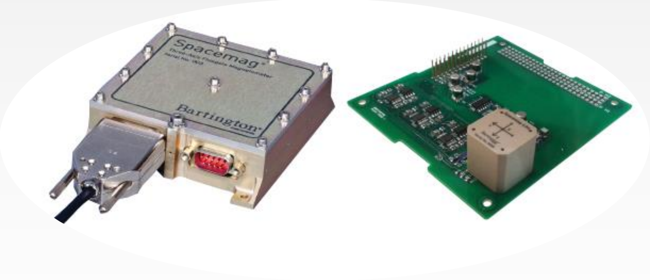
One or more high-μ cores (per measured component) are magnetized into saturation by a bias current in the 10-100 kHz range

A pick-up coil provides a signal proportional to the derivative of the core magnetization





Any external field H_x shifts the B(H) loop, causing a temporal asymmetry in the output peaks that is linearly correlated to H_x and can be measured very precisely

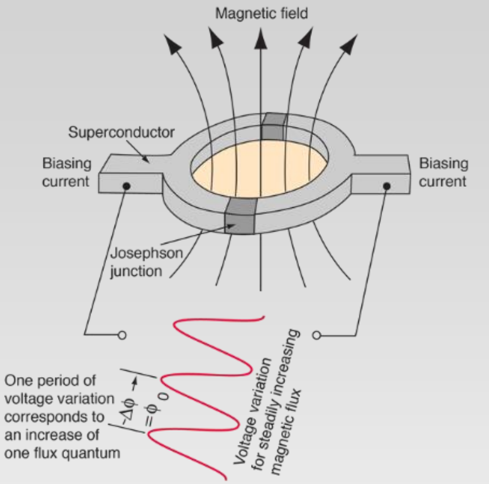


Bartington's Spacemag, MIL Temperature range -55-125°C
vacuum- and rad-compatible, 20 pT/VHz

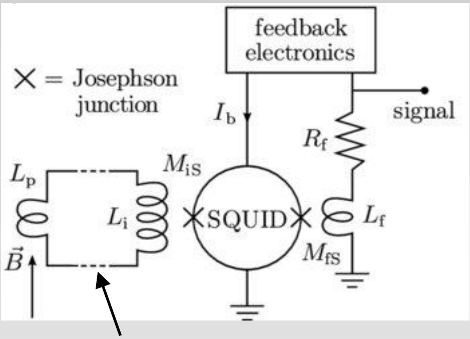
Applied Physics Systems Model 520 and 520A - 3-Axis Fluxgate Magnetometers
(with custom cryogenic probe option) 30 pT/√Hz, 1 G DC rejection

SQUIDs

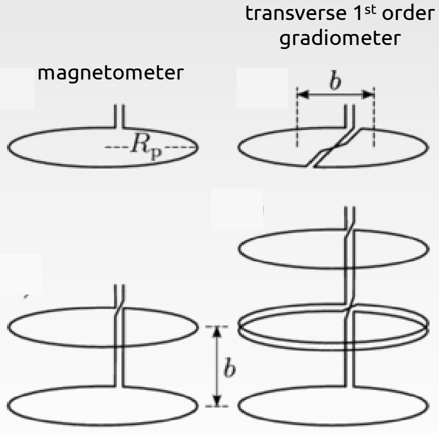
- Unique **flux-to-voltage sensor** class with **sensitivity close to quantum limits**
- **DC type** (2× Josephson junctions + feedback bias current) preferred for sensor applications
- Wide commercial availability (but expensive …)



Field measurement
=
incremental count



External SC flux transformer to link remote field



magnetometer

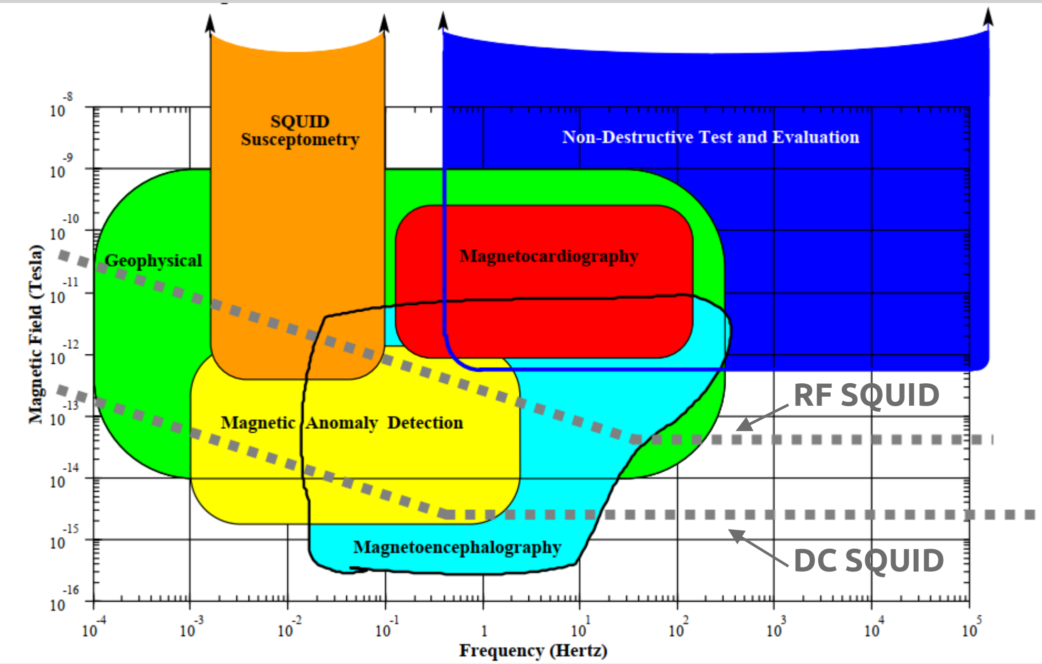
transverse 1st order gradiometer

axial 1st order gradiometer

axial 2nd order gradiometer

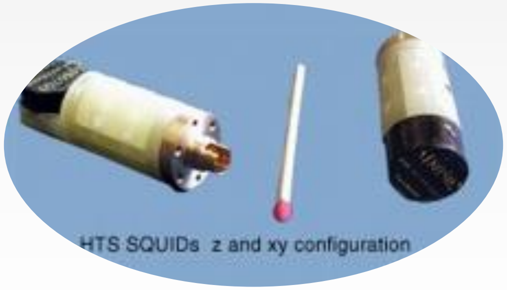
gradiometer configurations of the external pick-up coil for robustness w.r.t. background field

Typical magnetometer accuracy vs. bandwidth



supracon
SQUID AND MICROFABRICATION TECHNOLOGIES

Example: integrated 3-axis magnetometer



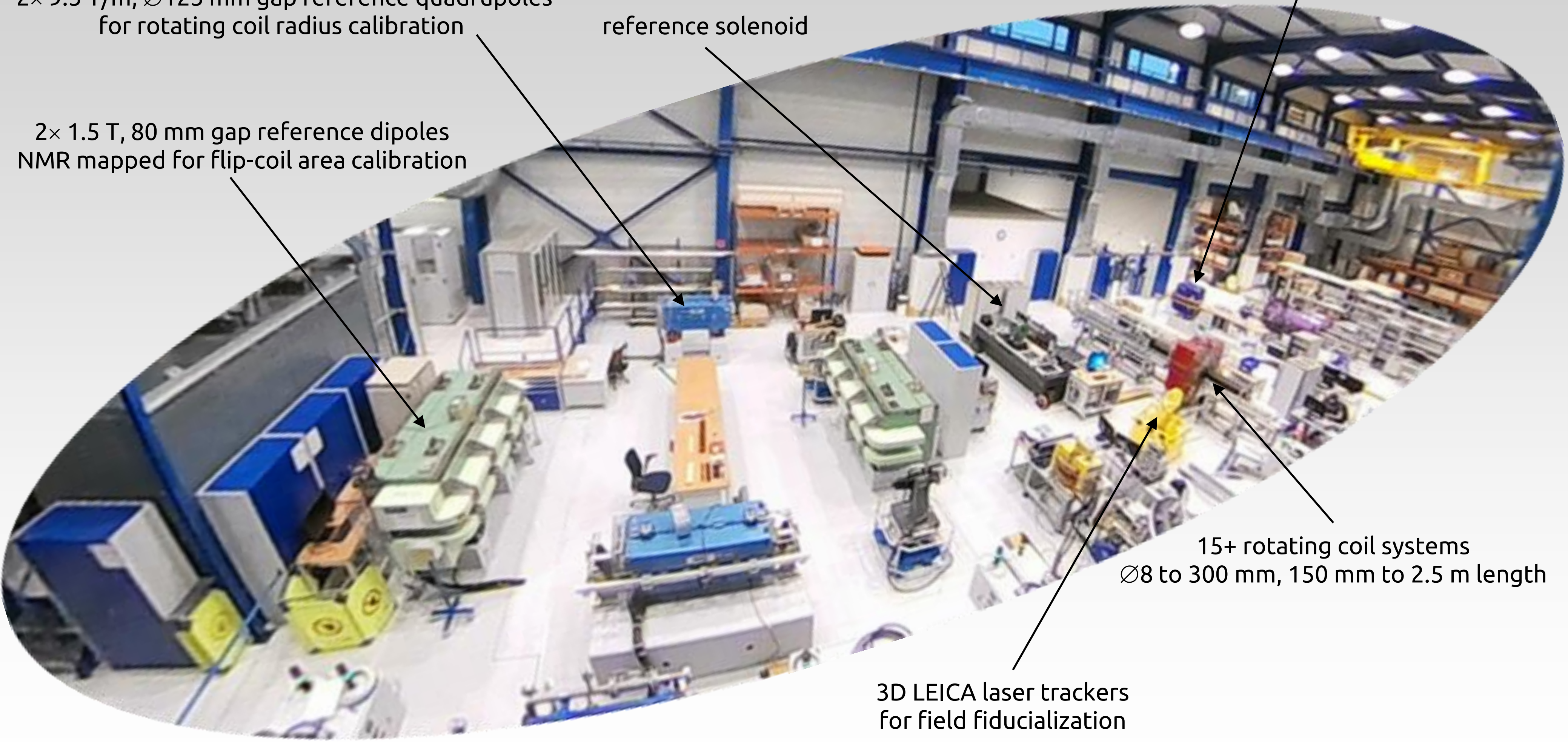
Example: HTS magnetometers by TRISTANTECH

See: RL Fagaly, SQUID instruments and applications, Review of Scientific Instruments, 2004

Manufacturing, test and calibration facilities

Bldg. 311 – Main test hall

- 25+ individually powered test benches for water-cooled magnets up to 40 tons, 1.5 kA
- Operated by 30+ technical/scientific staff, students and associates



1D/3D Hall-probe and fluxmeter field mappers

2× 9.5 T/m, ∅125 mm gap reference quadrupoles for rotating coil radius calibration

reference solenoid

2× 1.5 T, 80 mm gap reference dipoles NMR mapped for flip-coil area calibration

15+ rotating coil systems ∅8 to 300 mm, 150 mm to 2.5 m length

3D LEICA laser trackers for field fiducialization

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Bldg. 311 – Reference test hall

- Separated high-accuracy test hall with high mechanical/thermal stability (21±0.2 °C)
- Optimized AC airflow for resonant vibrating wire systems
- 5 T crane

Helmholtz coil system

Low-resonant frequency granite benches

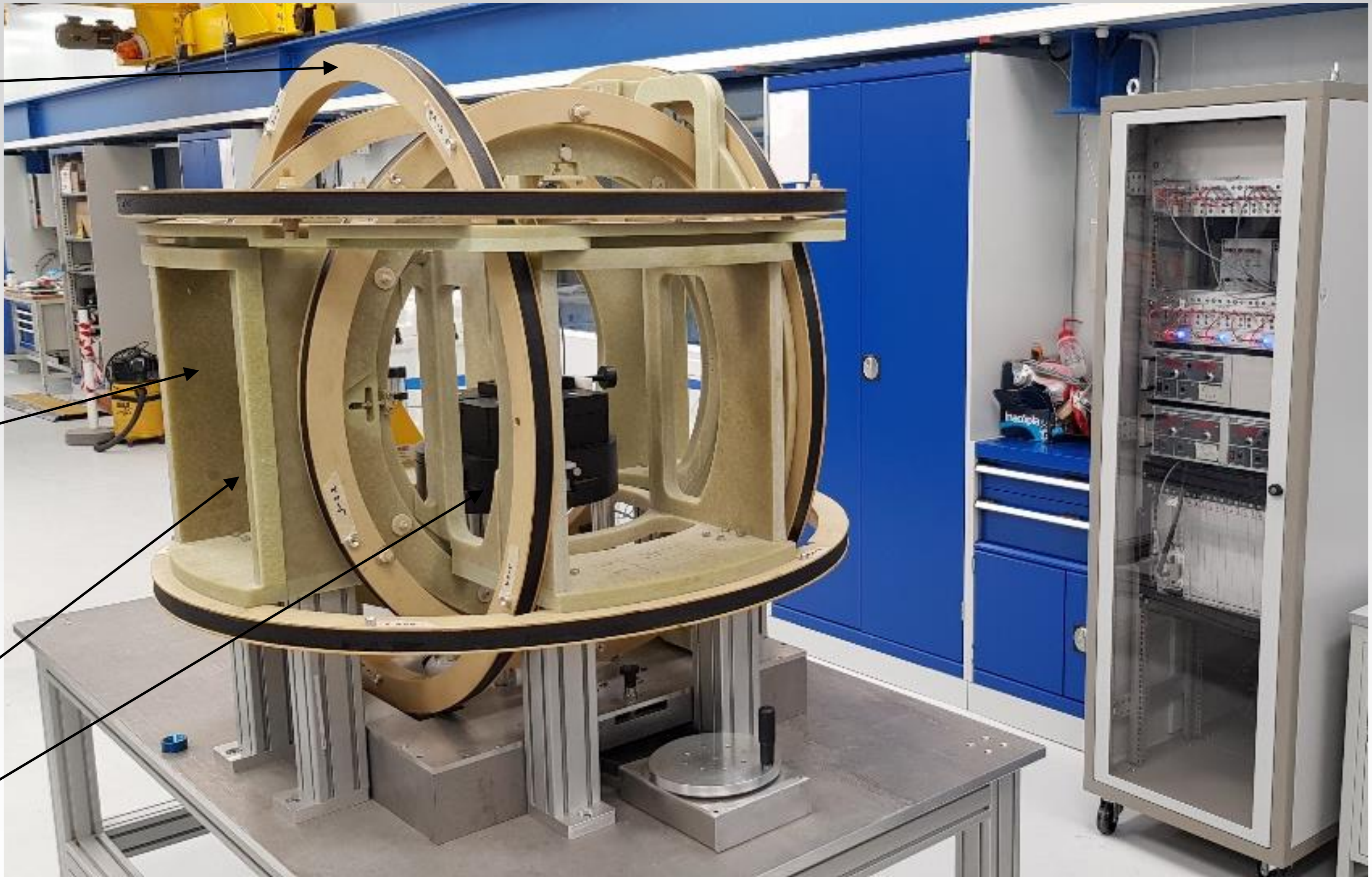
Vibrating/translating stretched wire systems (reference for integral field strength and axis)

NMR/Hall-probe teslameters

3D Helmholtz coil

- Designed in-house to measure the vector moment of PM blocks
- 3 × DC field source: ±800 μT @ ±200 mA
- First results: 0.6% uniformity over 50 × 50 × 50 mm^3
- Active field cancellation at the center < 0.2 μT (Bartington-03MS70)

A commercial unit bought earlier



2 × 2002, 2227, 2575 – turn coils
d = r = 873, 995, 1126 mm
R = 478, 620, 793 Ω
L =8.3, 12.3 ,17.8 H

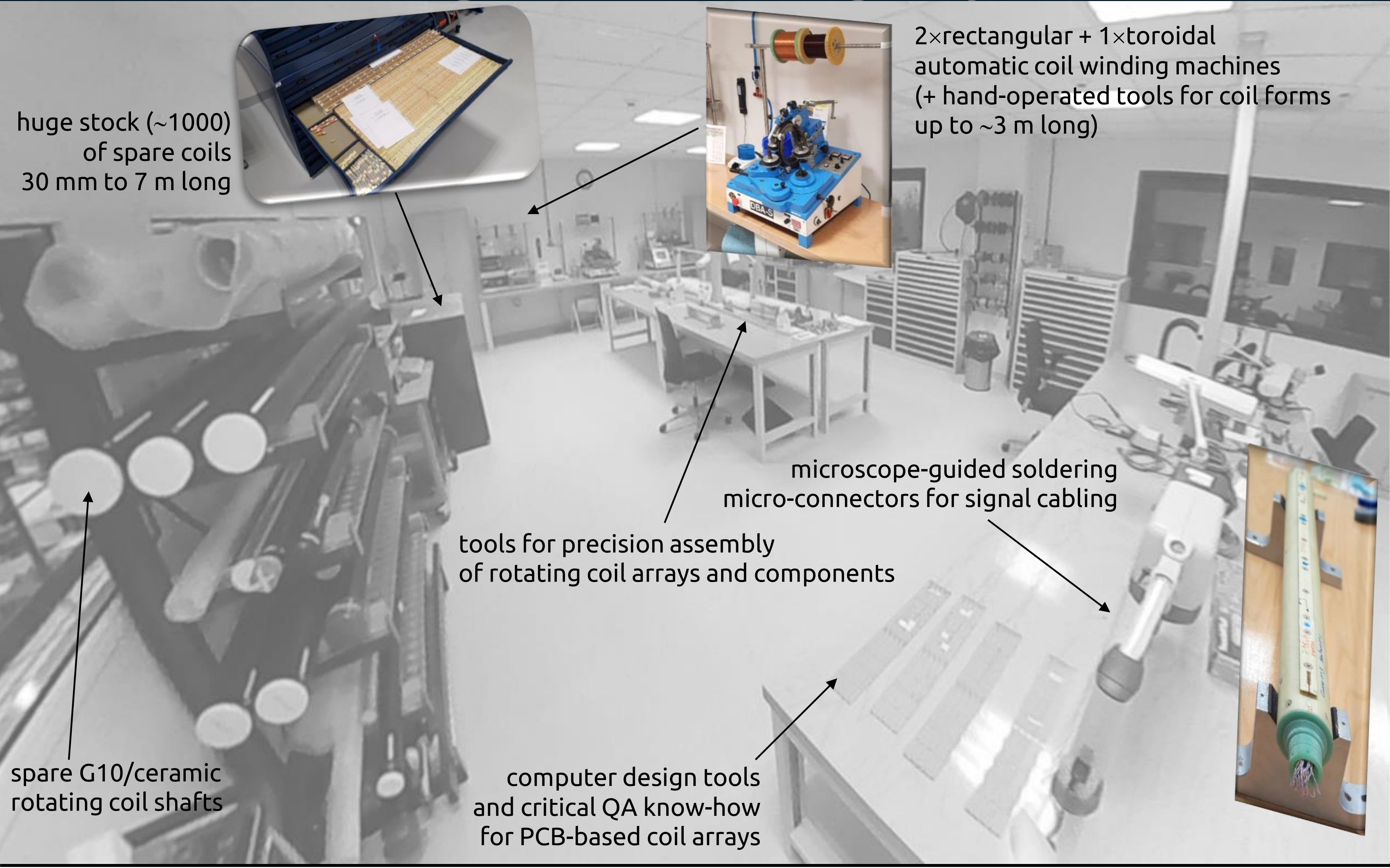
Coil misalignment
can be compensated vectorially

Usable volume
300 × 300 × 300 mm^3

Adjustable aluminum
support

See also: https://indico.cern.ch/event/666496/contributions/2724568/attachments/1536010/2406245/MW-StrayFields_Helmholtz_Zickler.pdf

Bldg. 311 – Coil manufacturing facility



2×rectangular + 1×toroidal automatic coil winding machines (+ hand-operated tools for coil forms up to ~3 m long)

huge stock (~1000) of spare coils 30 mm to 7 m long

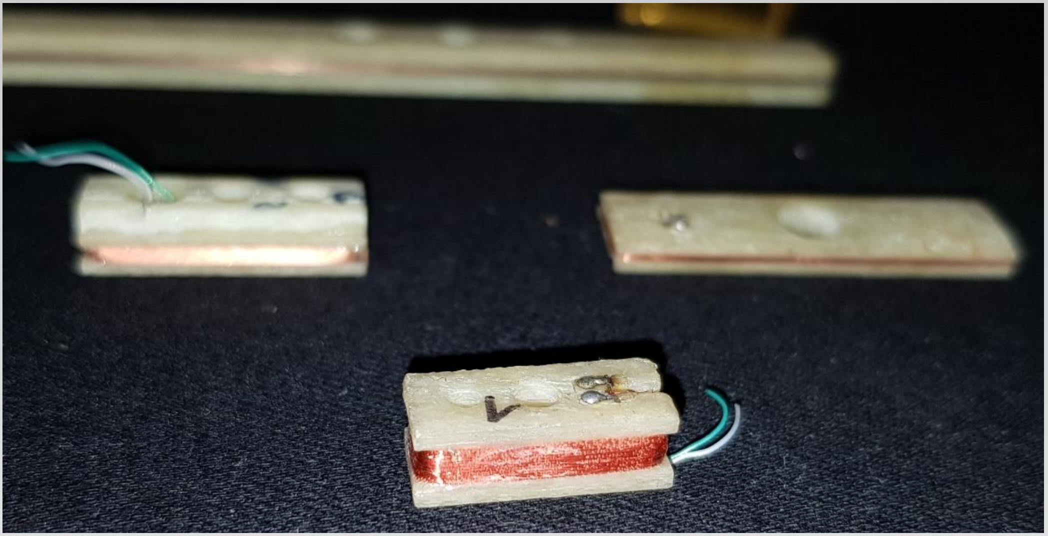
microscope-guided soldering micro-connectors for signal cabling

tools for precision assembly of rotating coil arrays and components

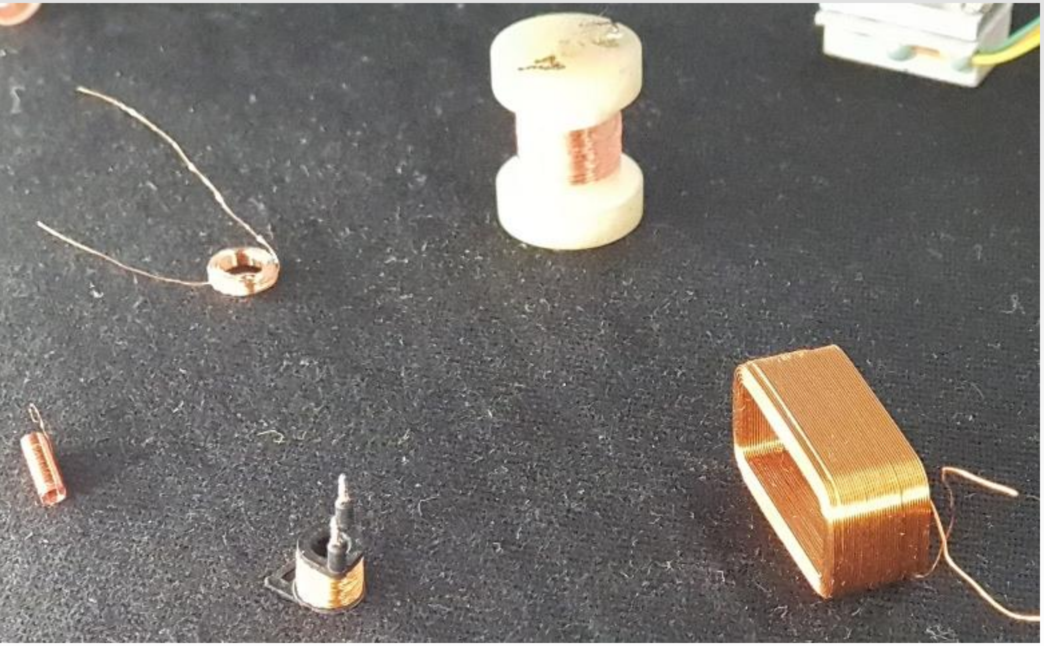
spare G10/ceramic rotating coil shafts

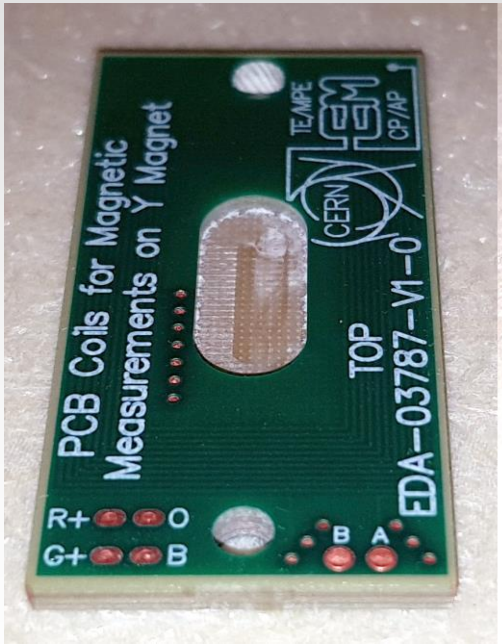
computer design tools and critical QA know-how for PCB-based coil arrays

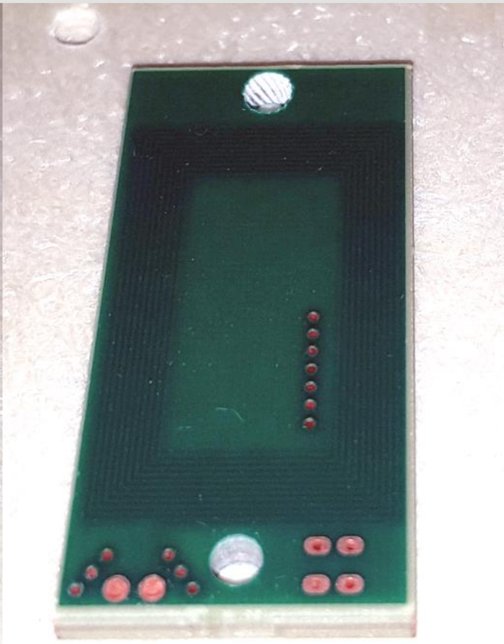
Small induction coils



- Multi-layer PCB design or machine-wound from single or multi-conductor flat wire (for best cross-section geometry)
- Example: $\varnothing_w = 30\ \mu m$, $10 \times 10\ mm^2$ coil area, $5 \times 5\ mm^2$ cross-section $\Rightarrow$ 30k turns
  dB/dt = **1 nT/ms** $\Rightarrow$ $\mathbf{V_{out} \approx 3\ \mu V}$
- Cheapest option for array deployment !

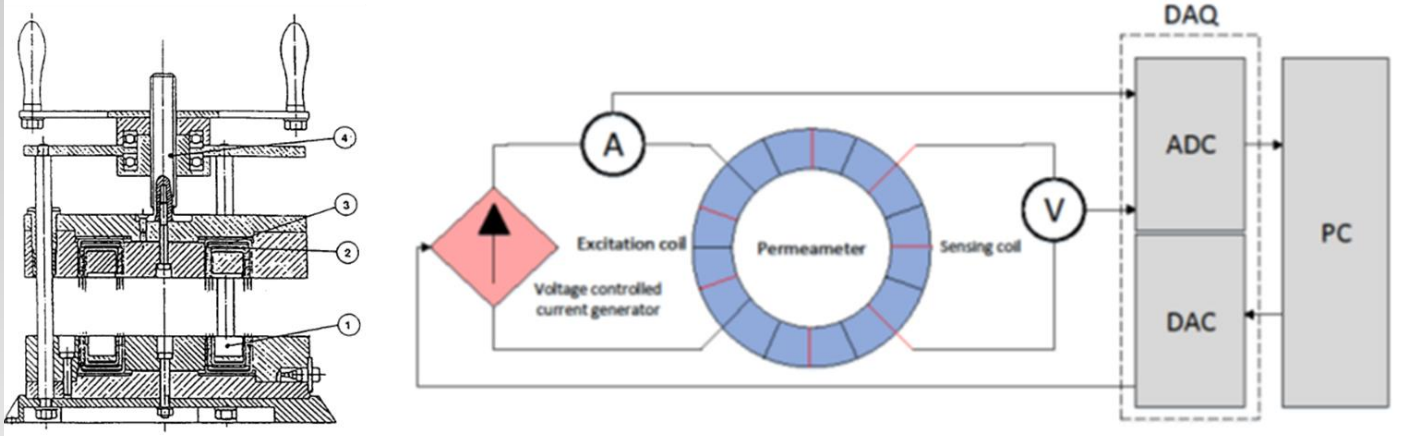


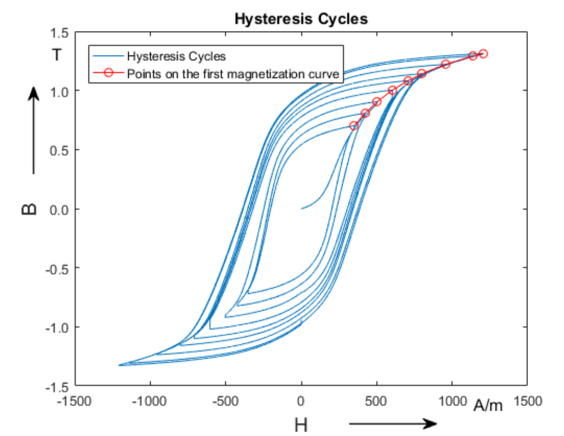




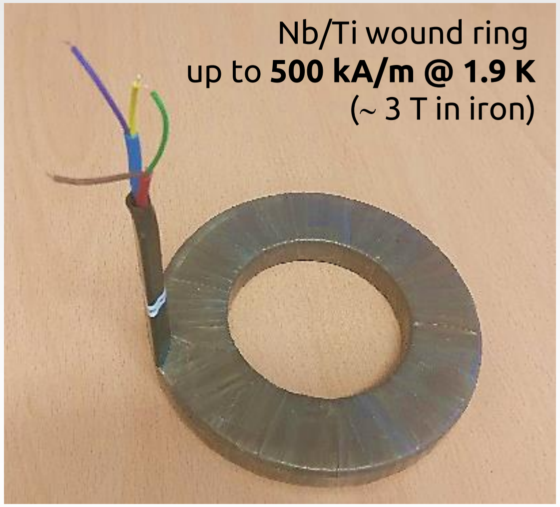
Magnetic material characterization (1/2)

- Measurement of the full hysteresis cycle (coercivity, remanence, permeability) of standard ring and laminated (Epstein frame) samples **up to 24 kA/m at RT** according to IEC 60404

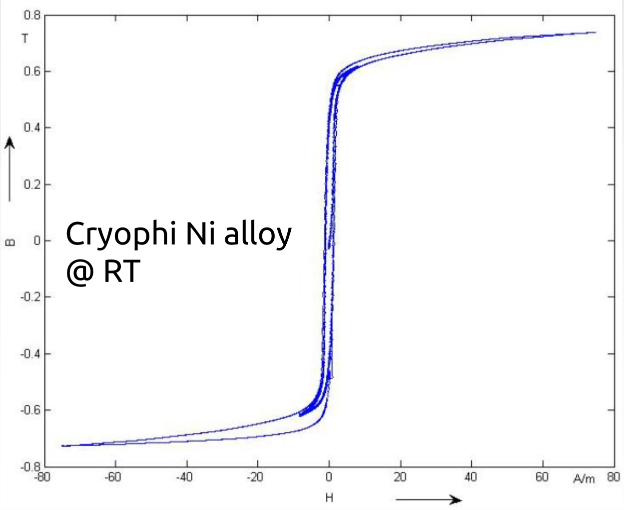




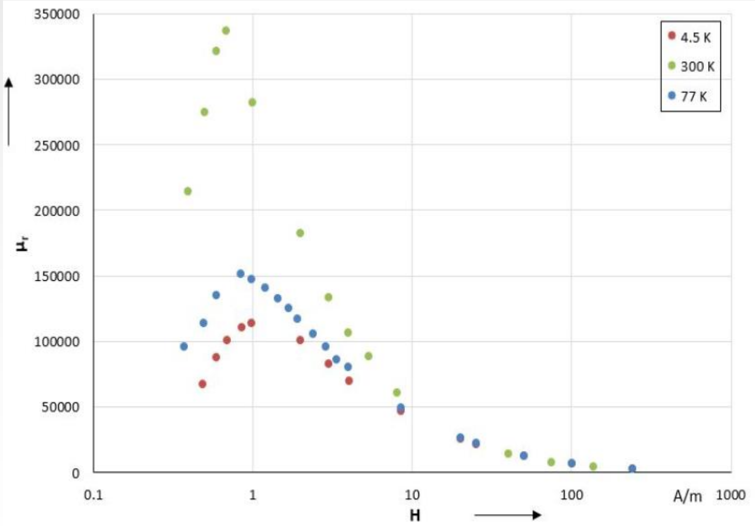
- Custom setups for cryogenic tests / magnetic shield alloys with $\mu_r > 10^5$



Nb/Ti wound ring
up to **500 kA/m @ 1.9 K**
(~ 3 T in iron)



Cryophi Ni alloy
@ RT



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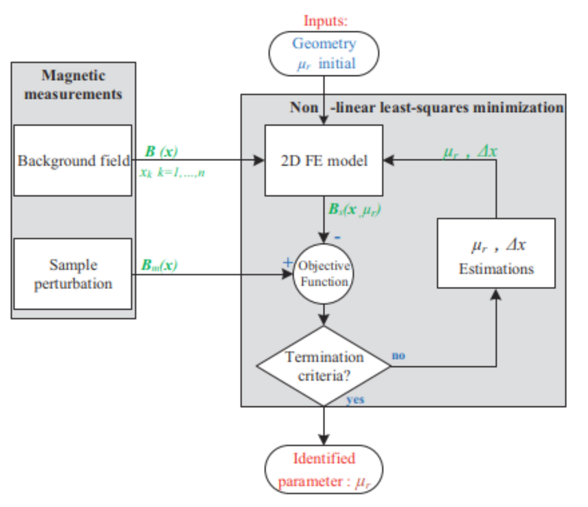
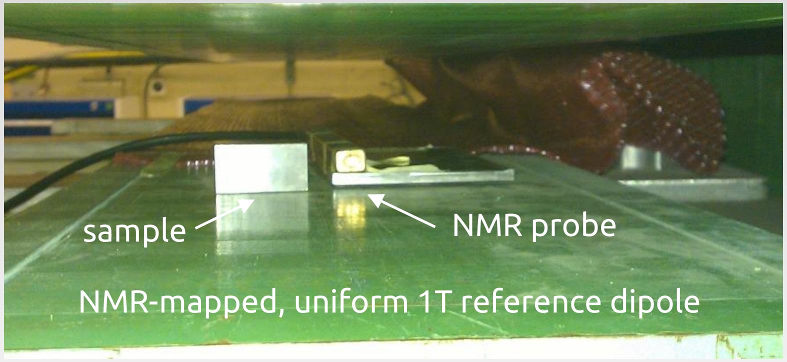
Magnetic material characterization (2/2)

- Inverse technique developed for accurate measurement of the permeability of non magnetic-materials of arbitrary shape (e.g. austenitic steel, W alloys)
- Parametric FE simulation of the field perturbation is compared to measurements and iterated
- Uncertainty **~10^{-4}** reached on calibrated cylinders with μ_r=1.004

(NB tests of thick parts possible with commercial instruments e.g. Foerster Magnetoscop 1.069)



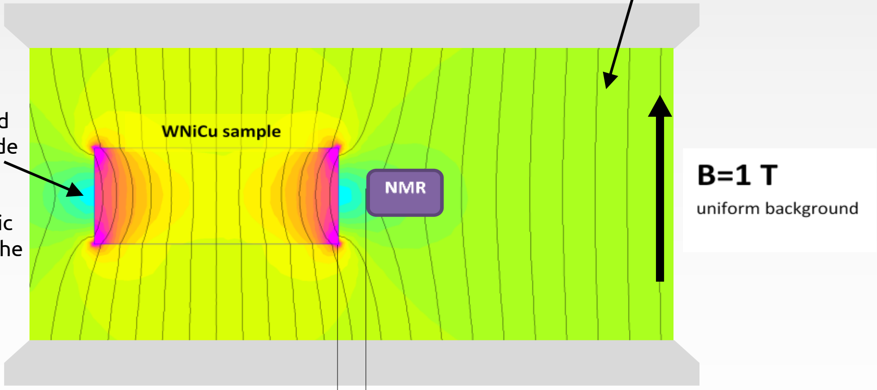
The perturbation is matched to a uniform μ_r in the sample



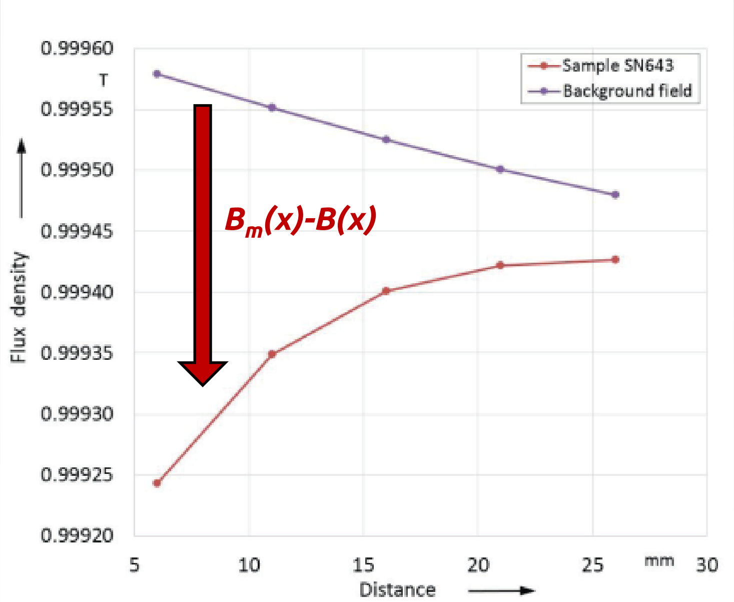
- 2D FE simulation adequate for very long or axisymmetric samples
- 3D model necessary for arbitrary shapes

Even $\chi\approx0$ will cause the flux to be concentrated in the sample and the field to drop measurably outside

(assumption: the total reluctance of the magnetic circuit is not changed by the sample)



Δx (NMR probe moved with a linear translation stage)



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