Magnetic measurement challenges for compact & low-consumption magnets

M Buzio on behalf of the Magnetic Measurement Section

(CERN, Technology Department, Magnet, Cryostats and Superconductors Group)

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Review of major measurement techniques:
Hall probes, fixed/rotating coils, stretched wires

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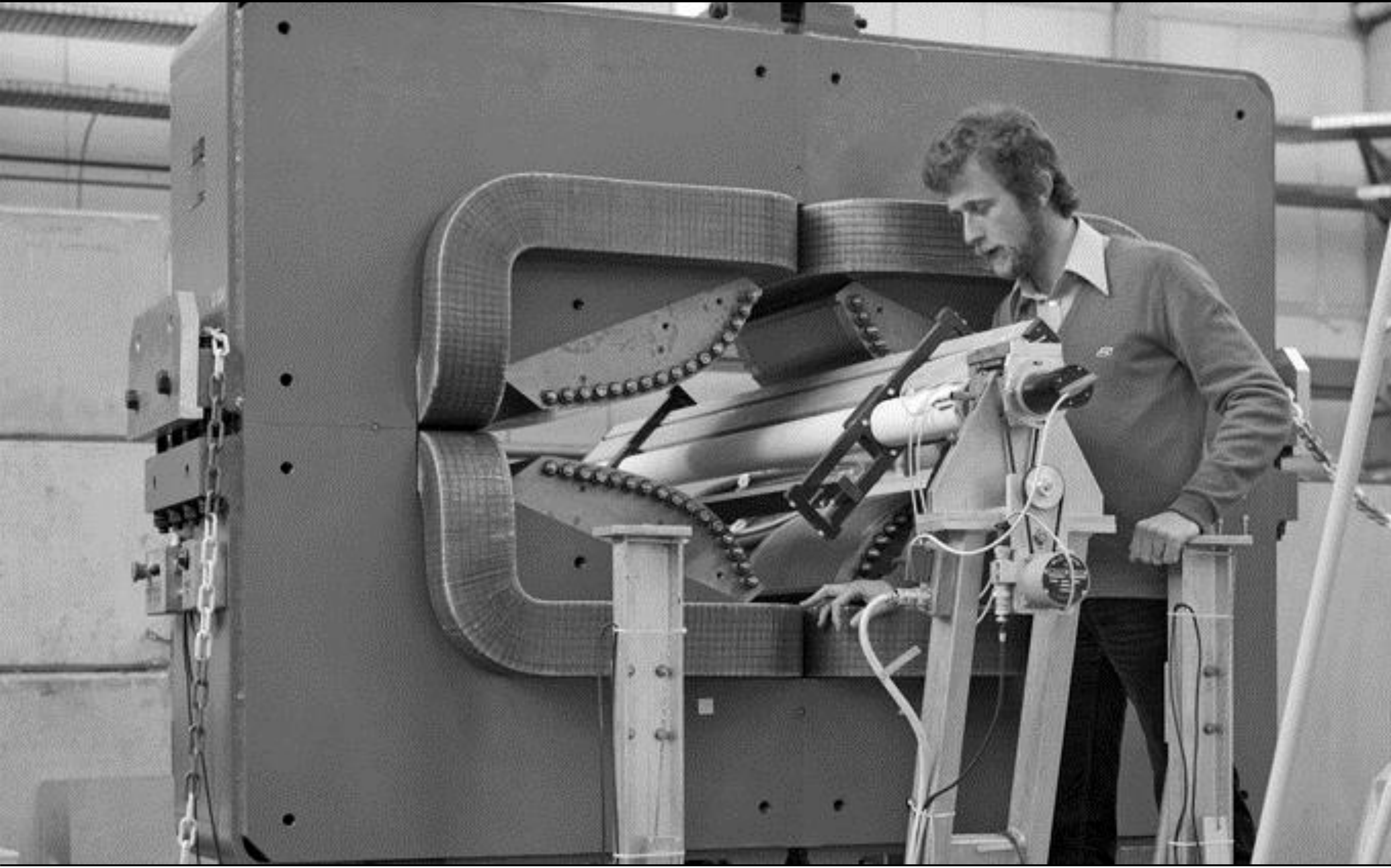
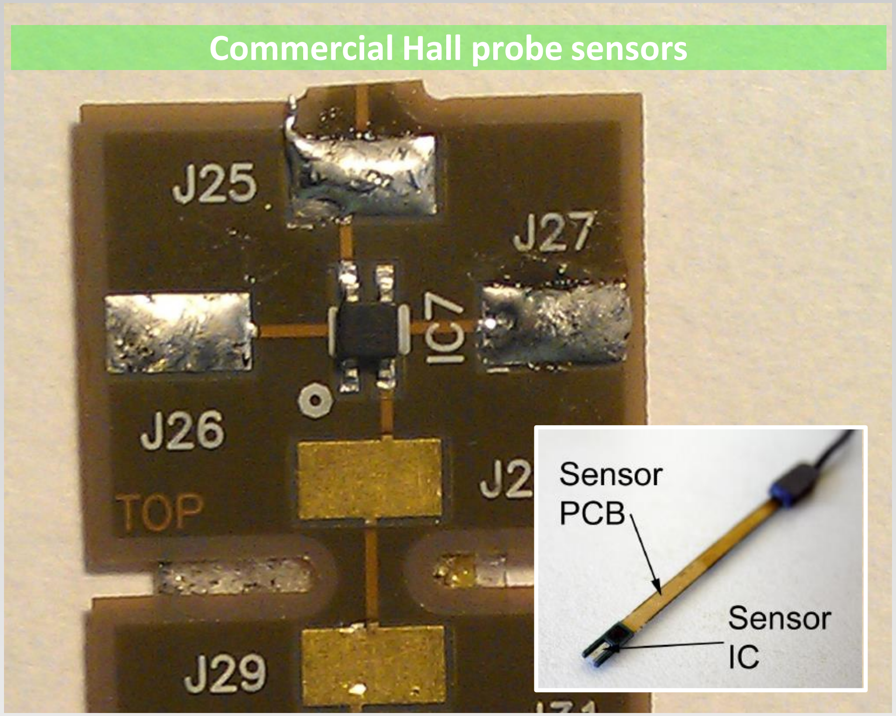
Compact magnets at CERN …

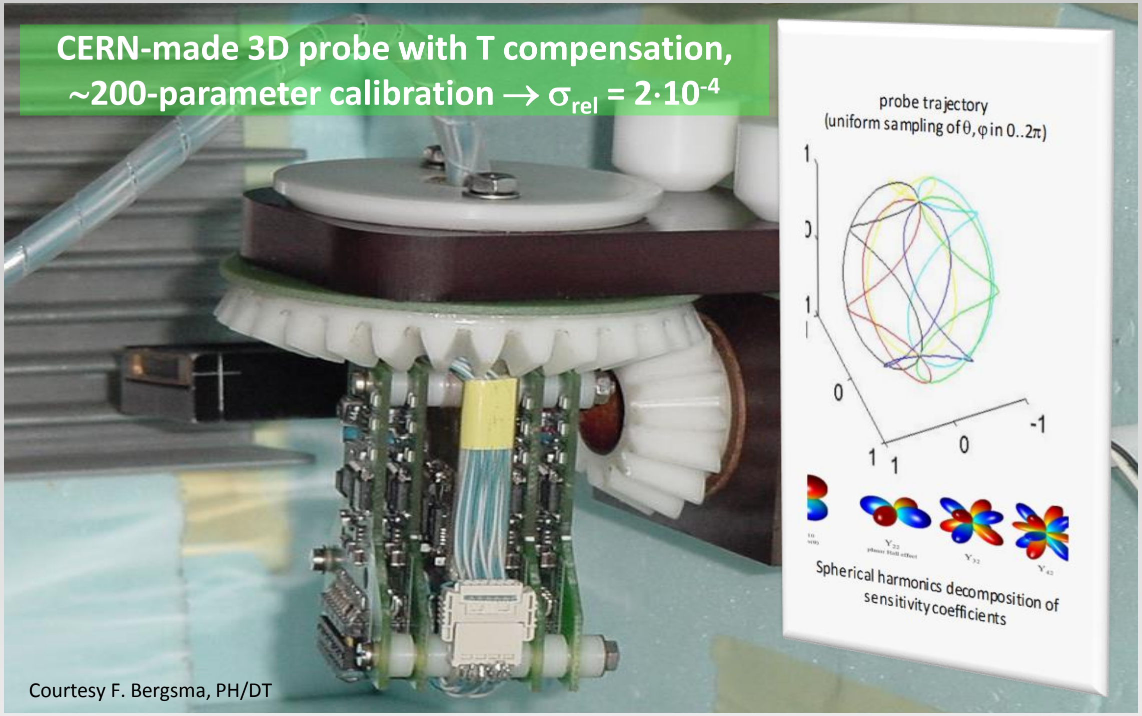


Measurement methods

Hall probes



Commercial Hall probe sensors



CERN-made 3D probe with T compensation, ~200-parameter calibration → $\sigma_{rel} = 2{\cdot}10^{-4}$

Courtesy F. Bergsma, PH/DT

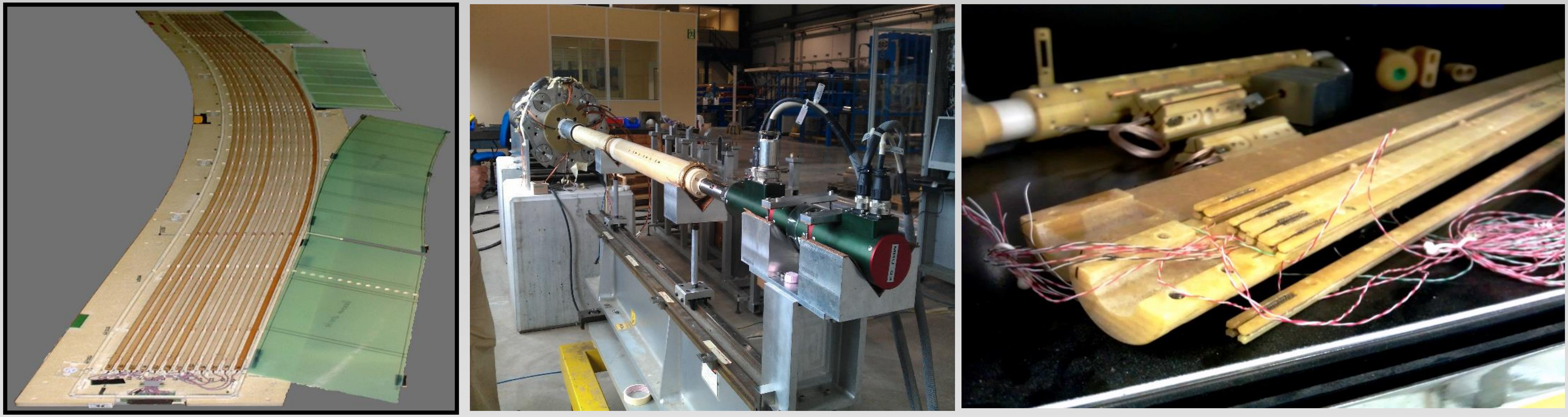
Advantages

- easy to use, readily available on the market (typical accuracy 1%)
- ~1 mm^2 sensor area → best suited to detailed maps (e.g. fringe fields)

Drawbacks

- uncertainty better than a few ~10^{-3} require complex and frequent calibration + temperature control or compensation
- small probe sensitive to local effects → precise integrals require *many* points
- precise positioning in translation and angle requires expensive mechanics
- errors in multipolar/fast ramping fields

Fixed and rotating measurement coils



Advantages

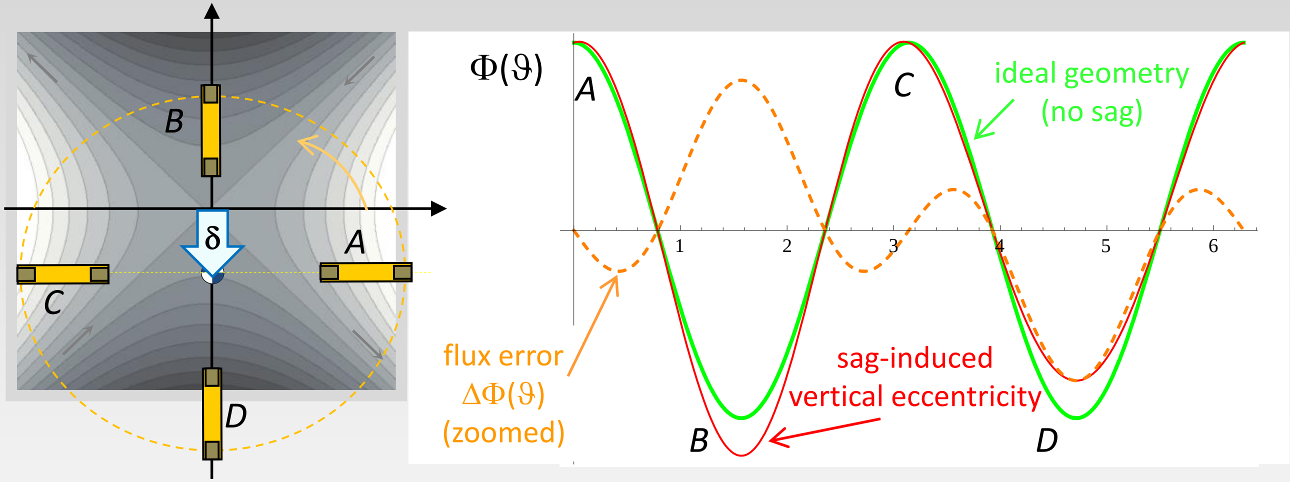
- natural choice for time-varying/integral fields (S/N improves with increasing size, B, dB/dt)
- DC rotating coil: one turn (0.1~1 s) → full characterization of the field integral within the spanned volume: **field strength, harmonics, direction and axis**
- typical uncertainty: absolute $\mathbf{10^{-4}}$ (straight or PCB coils), harmonics $\mathbf{10^{-5}}$, resolution $\mathbf{10^{-6}}$

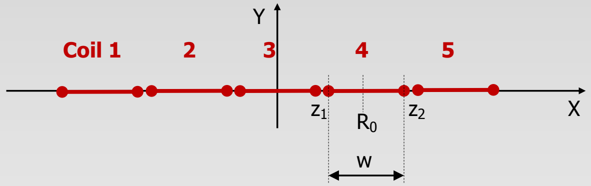
Drawbacks

- not commercially available, specialized in-house winding (or PCB design) required
- special techniques required for strongly curved, or large aspect-ratio gap magnets
- expensive mechanics (non-magnetic, non-conducting shaft, motor) and top-quality electronics (digital integrators, programmable amplifiers, angular encoders) necessary to get good results

Coil bucking

- The accuracy of higher harmonics measured by individual coils may be affected by geometry errors
- Solution = **coil bucking** (or compensation): suitable linear combinations of coil signals cancel out the sensitivity to the main (and lower) harmonics → robustness to mechanical imperfections
- Example: in a perfect quadrupole, average gravity-induced sag δ on a radial coil → flux error including mainly B_1 and B_3 components. A four-coil series/anti-series combination cancels out B_2 sensitivity → error-free harmonic measurement

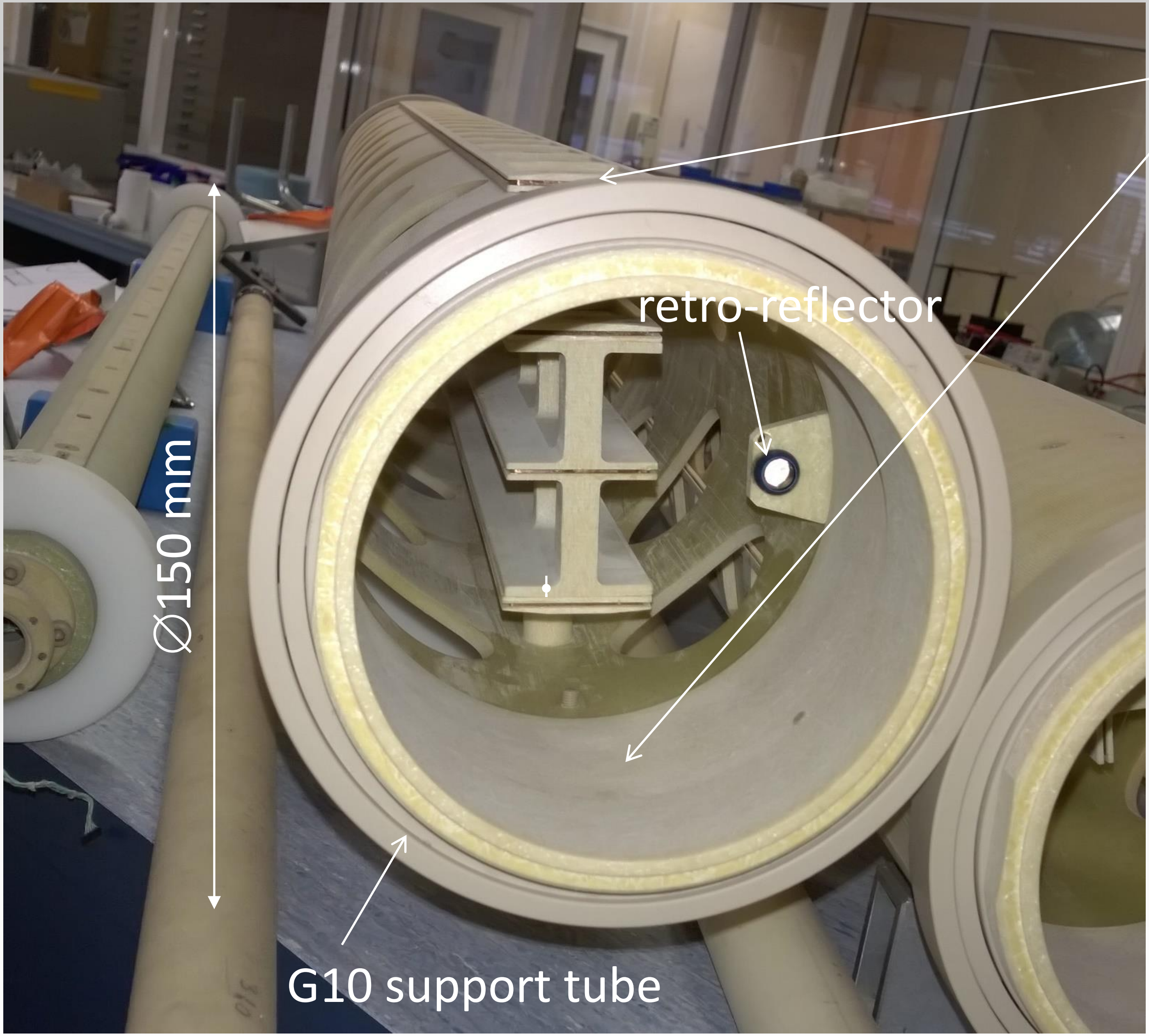




Sensitivity coefficient	Coil 1	Coil 2	Coil 3	Coil 4	Coil 5 (spare)	Bucked coil: Linear combination 1-2-3+4
κ_1	A	A	A	A	A	0
κ_2	-2Aw	-Aw	0	Aw	2Aw	0
κ_3	$\frac{49}{12}Aw^2$	$\frac{13}{12}Aw^2$	$\frac{1}{12}Aw^2$	$\frac{13}{12}Aw^2$	$\frac{49}{12}Aw^2$	$4Aw^2$

- Arbitrary *static* coil imperfections: no major concern (effective geometry can be calibrated)
- Position- or time-dependent **transversal imperfections** → **errors ∝ harmonic n=main order**
- Position- or time-dependent **torsional imperfections** → **errors ∝ harmonic n=main order -1**
- Coil design objective: $\kappa_{main}=\kappa_{main-1}=0$, maximize $|\kappa_n|$ with n>main order
- Additional benefit: **common mode rejection, improved S/N** (requires separate amplification)

Example: quadrupole-compensated rotating coil array

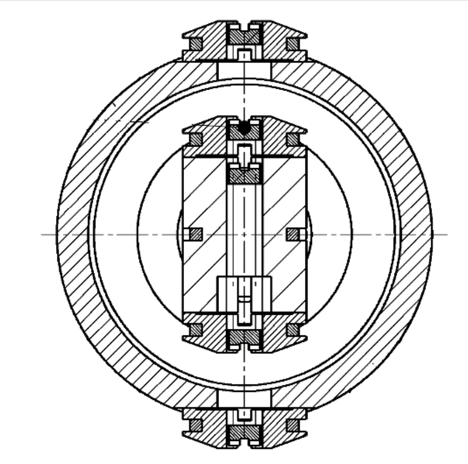


5× tangential coils

retro-reflector

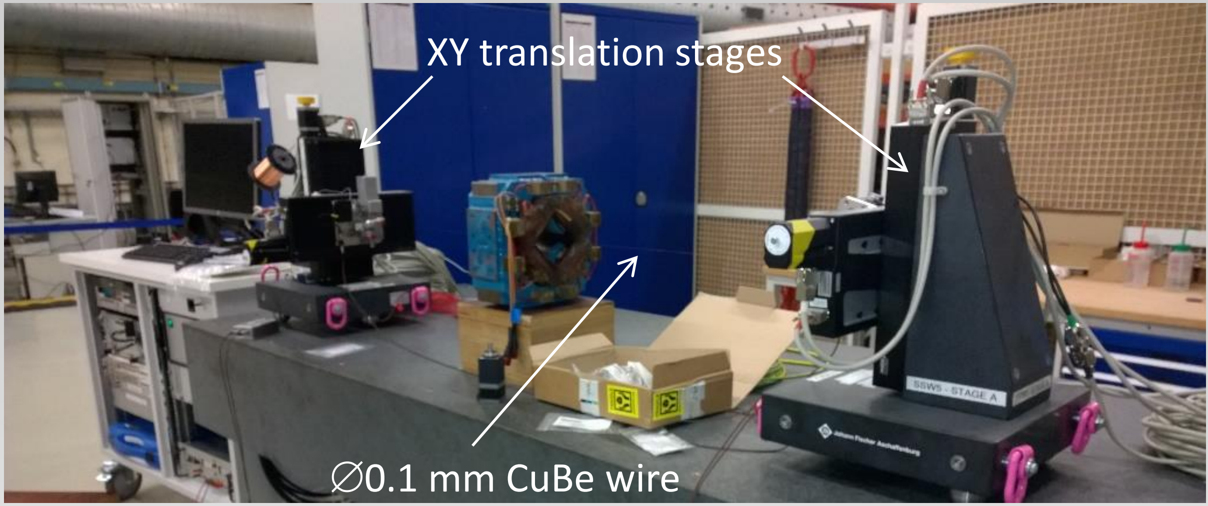
Ø150 mm

G10 support tube

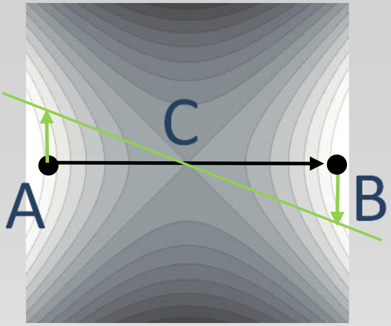


- large number of coils made to pick well-matched equivalent surfaces
- coil parallelism measured inside a large dipole
- rotation radius measured inside a large quadrupole

Single Stretched Wire



3× multi-mode systems at CERN (based on FNAL's units used as a reference for LHC cryomagnets)



classic measurement in a quadrupole: if $\int_A^B B_y dx = 0$, then C=magnetic center

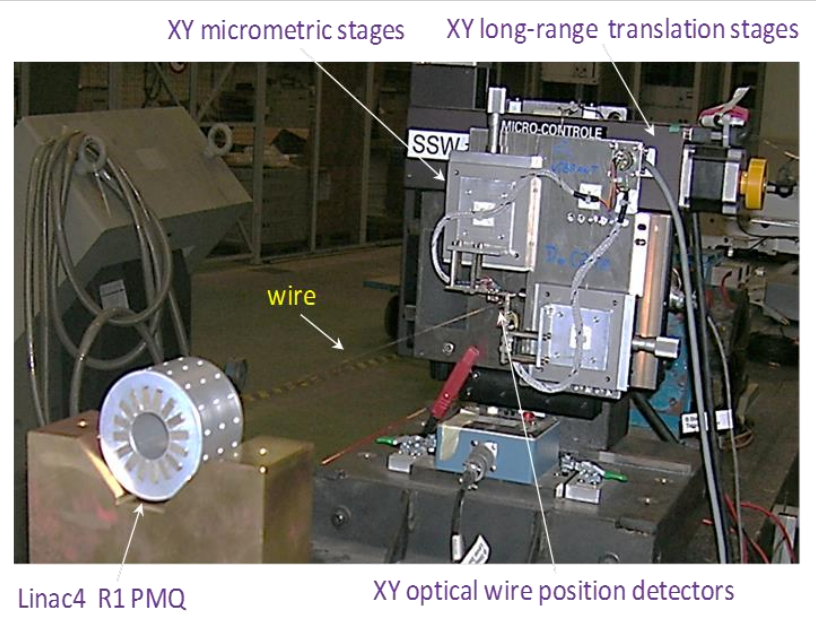
Advantages

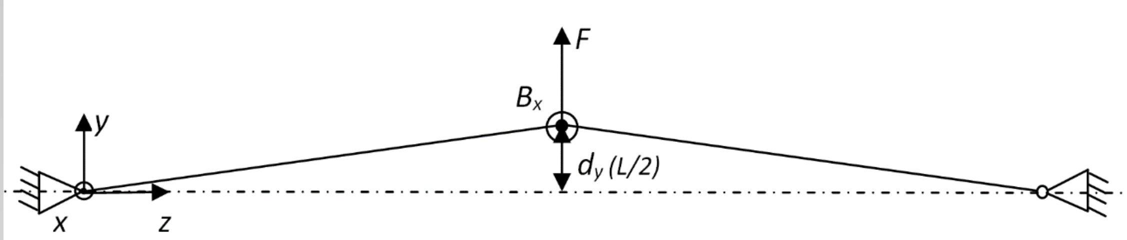
- unique flexibility: the same sensor adapts to any size, shape and length of magnet gap (limited by the range of the translation stages)
- unique capability to measure longitudinal center + pitch and yaw axis angles in lenses and solenoids (counter-directional wire movements)
- unique sub-micron sensitivity for axis localization in vibrating mode at resonance
- metrological reference for integrated field strength, axis and direction in high-field magnets
- Very promising ongoing R&D:
  - integrated harmonics in vibrating mode
  - longitudinal field profiles from measurements in vibrating mode at multiple frequencies

Drawbacks

- Equivalent to 1 turn-coil only → low sensitivity of field integrals in short/weak magnets

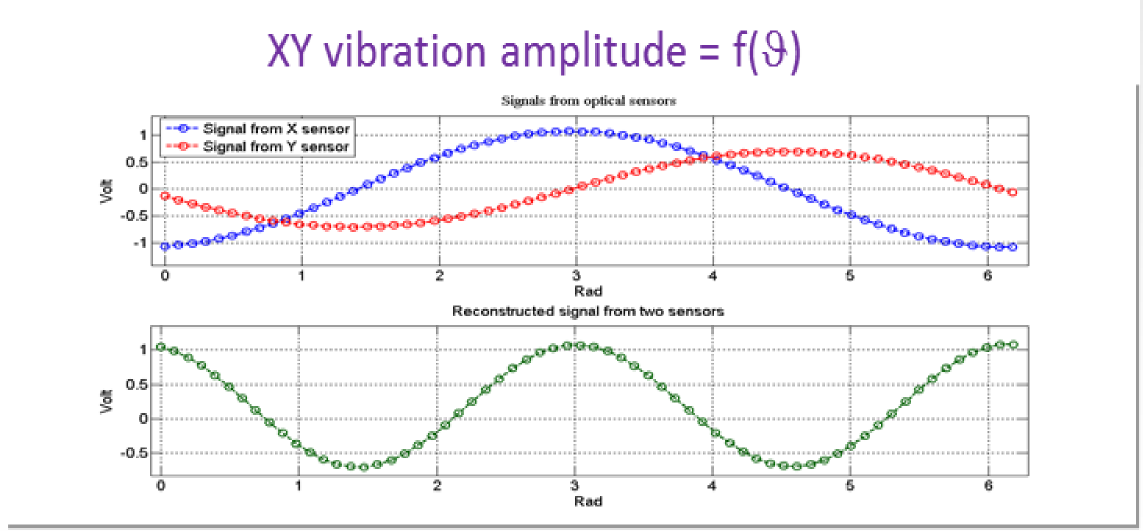
Recent development: oscillating stretched wire

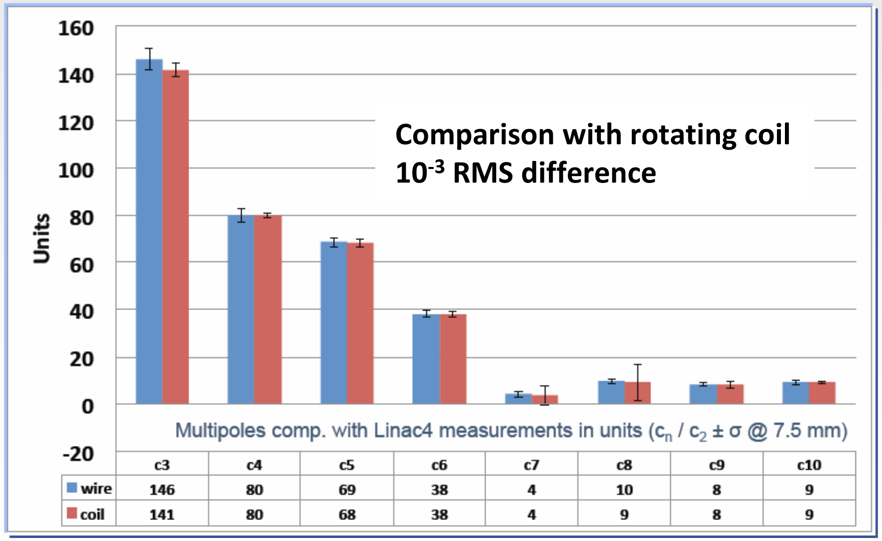




- Stretched-wire system with AC current passed through the wire → Lorentz force → oscillation ∝ BdL
- zero amplitude = wire on magnetic axis
- ideal method for very small aperture magnets (CLIC)
- integrated harmonics by stepwise scan around a circle (quasi-static regime → insensitive to frequency fluctuations)

XY vibration amplitude = f(ϑ)





Comparison with rotating coil
10^{-3} RMS difference

Multipoles comp. with Linac4 measurements in units (c_n / c_2 ± σ @ 7.5 mm)

	c3	c4	c5	c6	c7	c8	c9	c10
🟦 wire	146	80	69	38	4	10	8	9
🟥 coil	141	80	68	38	4	9	8	9

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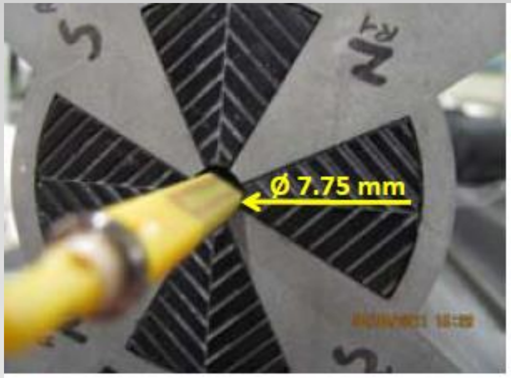
Challenges

Impact of low-consumption techniques on magnetic measurements

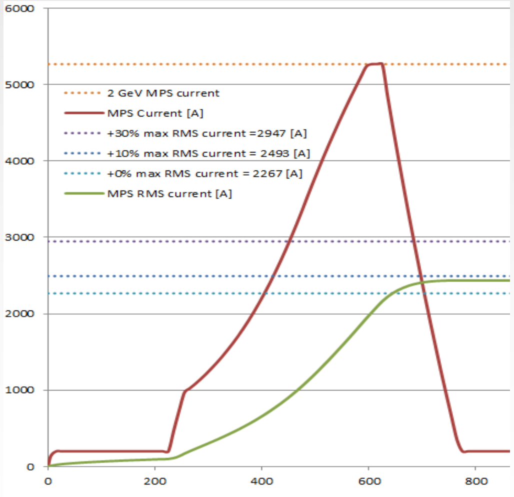
Excitation source (Cu, PM or SC), current density and power consumption: not important *per se* (assuming of course that temperature effects are controlled !)

Small gaps



- Hall probes (very) difficult
- Critical mechanical tolerances
- Reduced n. of turns, weak signals

Low RMS



proposed CERN PS Booster upgrade cycle

fast ramps

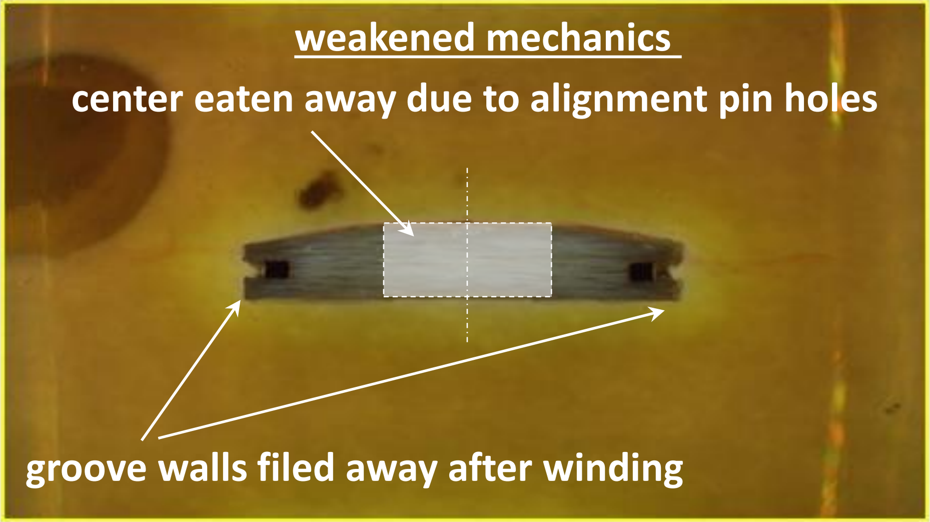
low flat-bottom

- Hall probes hardly possible at all (bandwidth, dynamic range)
- Good coil signals, but RC complicated (remanent lost)
- Extrapolation from low field measurements
- current/magnet cycle reproducibility issues

Small gaps

∅38 mm QIMM (Quadrupole Industrial Magnetic Measurement)

∅38 mm coil array approaches the limit of traditional fabrication techniques

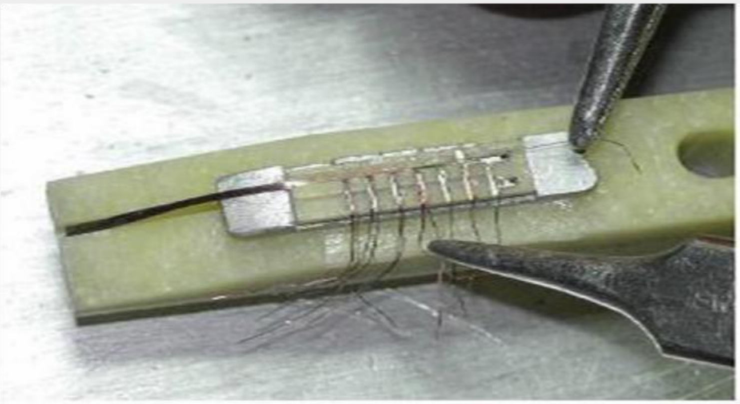


weakened mechanics

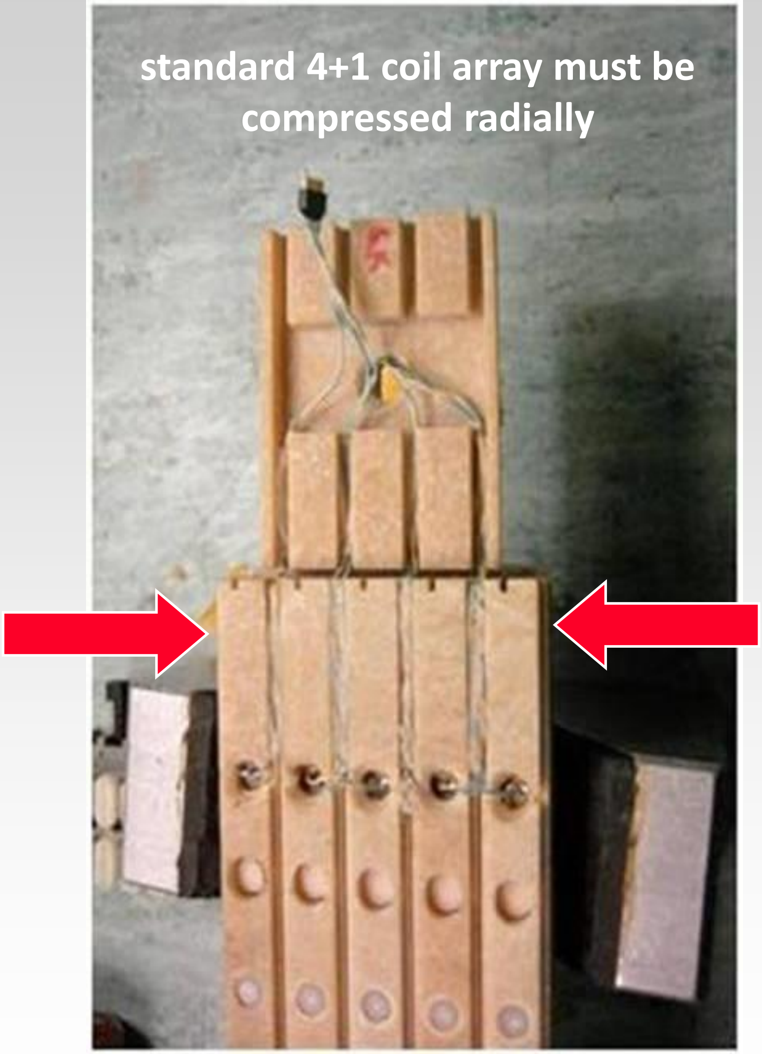
center eaten away due to alignment pin holes

groove walls filed away after winding

up to 4/5 waste (also due to fragile 20-wire cable) !



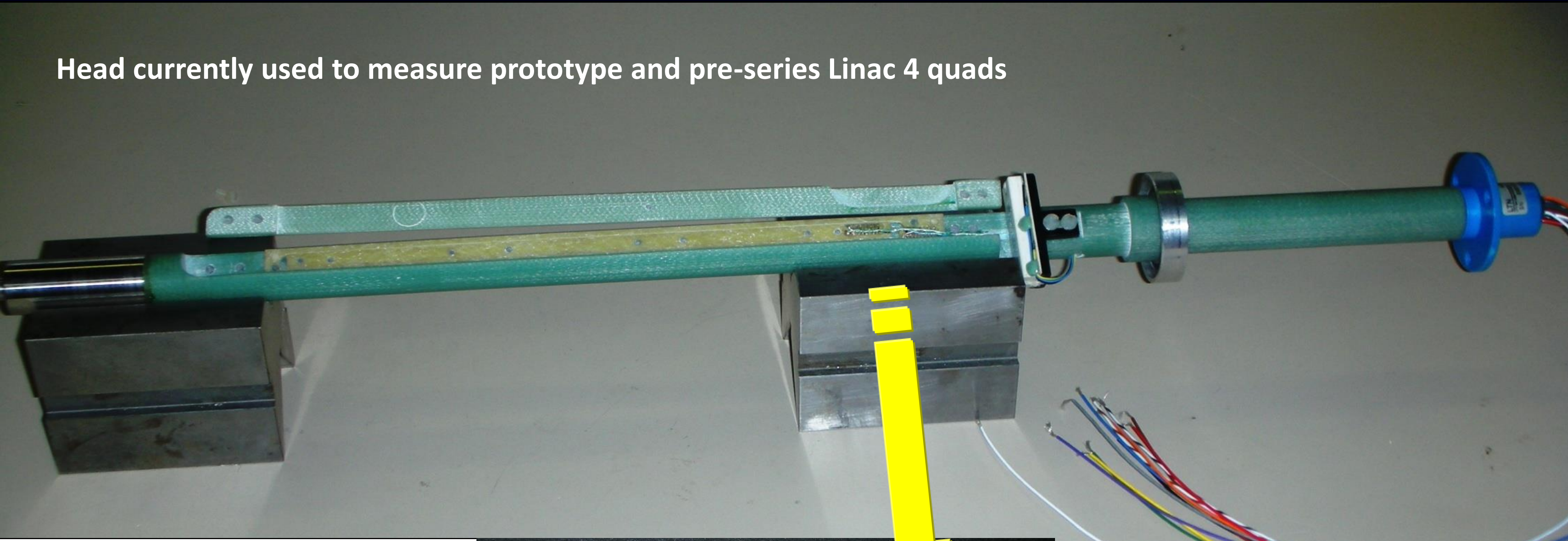
additional size constraint: standard connection PCB

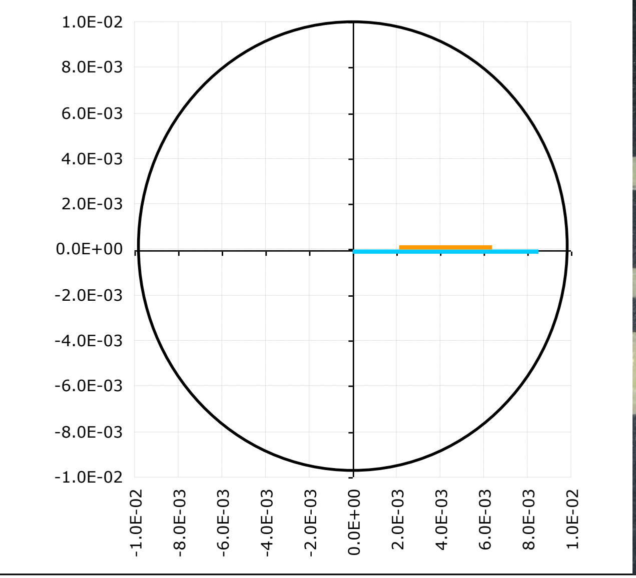


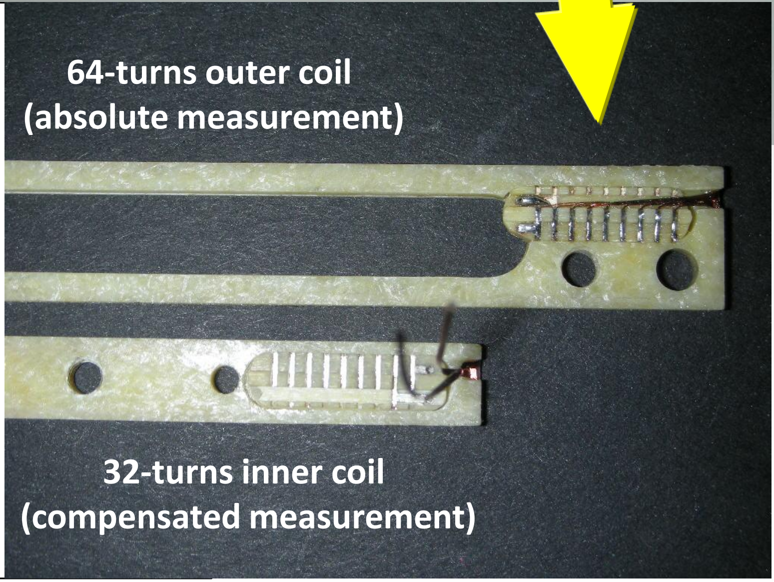
standard 4+1 coil array must be compressed radially

Linac 4 test bench – Coil head prototype #1

Head currently used to measure prototype and pre-series Linac 4 quads





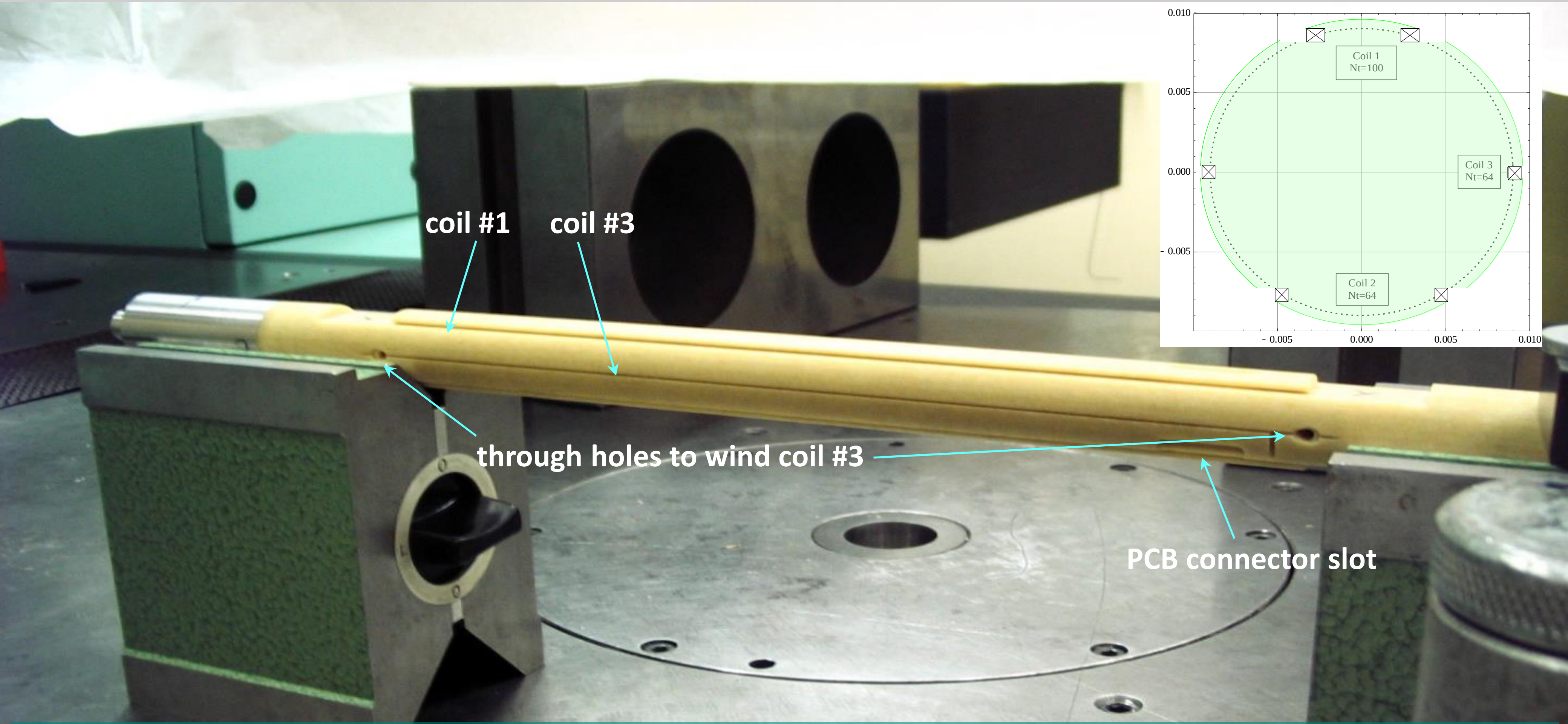


64-turns outer coil (absolute measurement)

32-turns inner coil (compensated measurement)

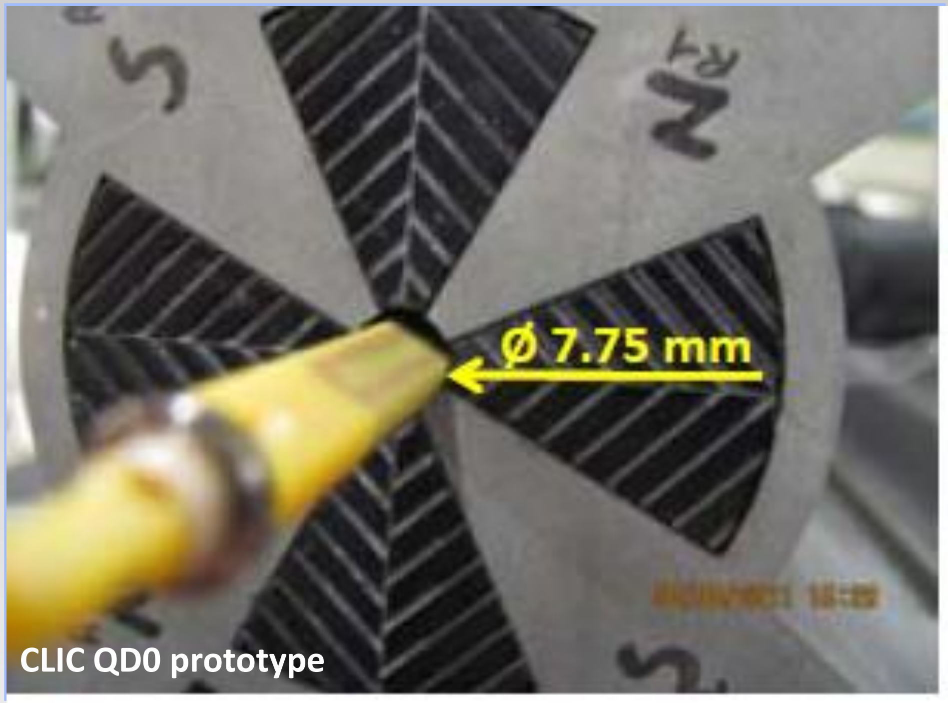
- ∅19 × 200 mm head based on Linac2 design (flat multi-wire cable higher winding density)
- 2 nested coils with B_1 + B_2 bucking (same A_{TOT}, R_0)
- longitudinal variations up to **6% width, 20 mrad twist**

Linac 4 test bench – Coil prototype #2



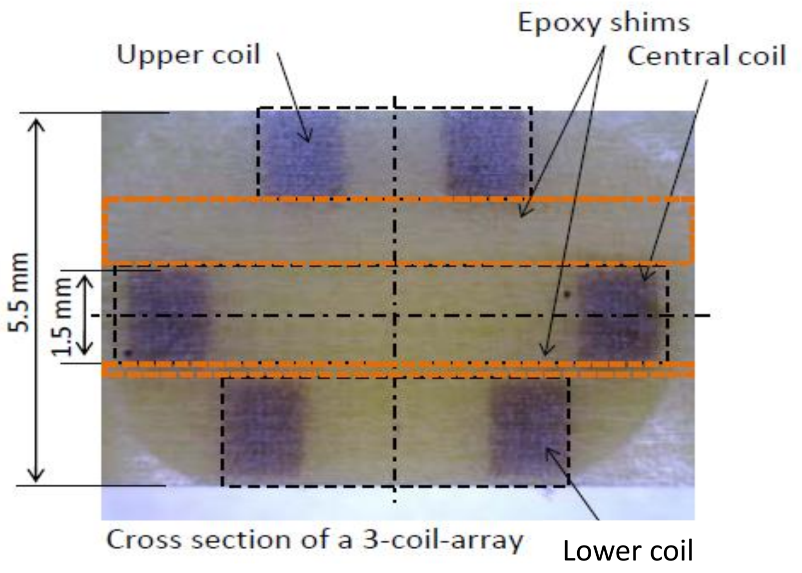
- Skillful manual winding operation required
- Effective area:	longitudinal variations **0.2%**
- Effective radius: longitudinal variations **1%** (outer coils), 0.1 mm (central coils)
- Customary average area/radius calibration does not work very well: a more laborious *in-situ* calibration inside the target magnet is essential to get accurate results

Innovative miniature coils for CLIC quadrupoles



CLIC QD0 prototype

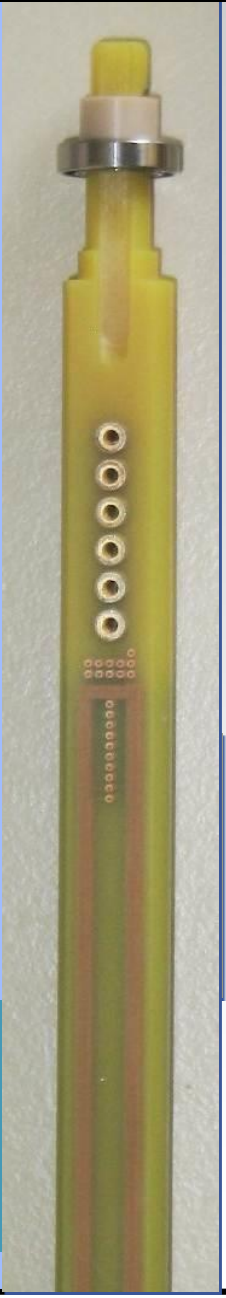
3× 64-layer PCB stack coils



Cross section of a 3-coil-array

200-turn coils (1/6 density w.r.t. 30 μm wire)

3-coil dipole- and quadrupole- bucked array can be chained to measure long magnets at once



- Industrial PCB production; difficult machining to install ball bearings required
- Effective area: reproducibility **$3\cdot10^{-4}$**, longitudinal variations **0.5%** (sag, twist ?)
- Effective radius: variations up to **3%** (outer coils), 0.8 mm (central coil)
- Analog compensation cannot work

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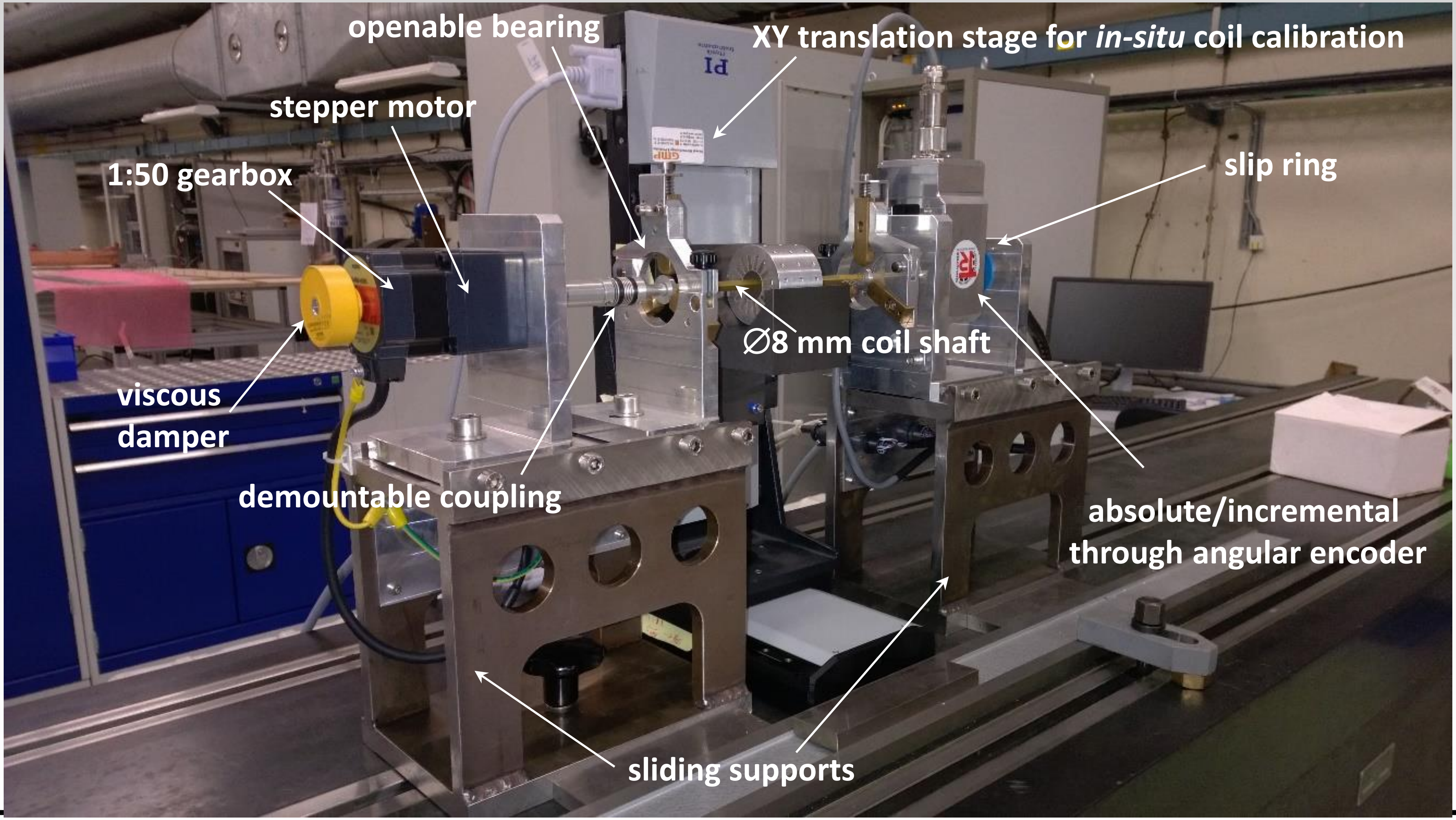
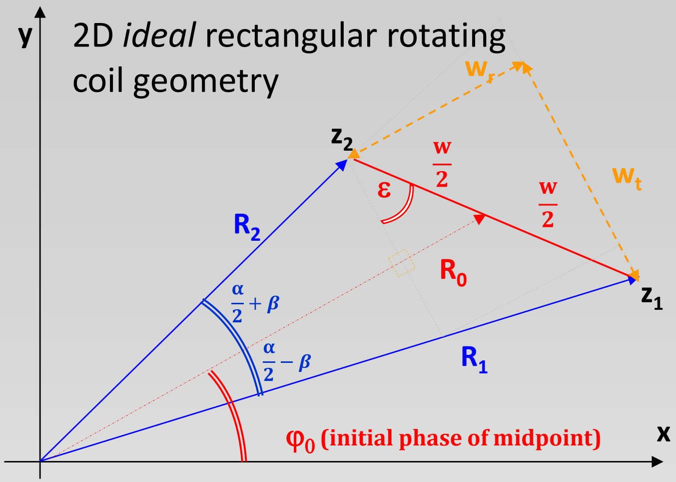
Linac4/CLIC harmonic coil test bench

- Developed for small-aperture permanent-magnet and fast-pulsed quads
- **∅8/19 mm, 150 to 400 mm** long quadrupole-bucked coils
- Harmonic measurements in DC (continuously rotating coil) or fast-pulsed (stepwise rotating) mode.
- *In-situ* calibration technique to improve accuracy despite geometrical coil imperfections



Random errors in rotating coil measurements



2D *ideal* rectangular rotating coil geometry

$$\Phi(\vartheta)=\Phi(0)-\int_{t(0)}^{t(\vartheta)} V_{coil}\,dt=\Re\left(\sum_{n=1}^{\infty}\underbrace{\frac{N_T L}{n}\left(z_2^n-z_1^n\right)}_{\kappa_n}\frac{\mathbf{C}_n}{r_{ref}^{n-1}}e^{in\vartheta}\right)$$

integration constant: <u>lost</u> with fixed coil measurements, <u>irrelevant</u> (unphysical) for rotating coils

integration bounds set by precise angular encoder → rotation speed fluctuations have negligible effects

measured flux depends on both the field and coil geometry

Fourier component of the flux

absolute:

$$C_n=\frac{2}{N}r_{ref}^{n-1}\frac{\Psi_{n+1}}{A_c r_c^{n-1}}\quad [\mathrm{T\ @\ r_{ref}}]$$

Coil area

Coil rotation radius

$$\left(\frac{\sigma_{Cn}}{C_n}\right)^2=\left(\frac{\sigma_{Ac}}{A_c}\right)^2+(n-1)^2\left(\frac{\sigma_{rc}}{r_c}\right)^2+\left(\frac{\sigma_{\Psi}}{\Psi}\right)^2$$

~ 10^{-4}

10^{-3} ~ 10^{-4}

10^{-3} ~ 10^{-4}

dominant term for higher harmonics

normalized:

(from absolute signal)

$$c_n=10^4\frac{C_n}{C_{main}}\quad [\mathrm{units\ @\ r_{ref}}]$$

$$\left(\frac{\sigma_{cn}}{c_n}\right)^2\approx(n-main)^2\left(\frac{\sigma_{rc}}{r_c}\right)^2+\left(\frac{\sigma_{\Psi}}{\Psi_{n+1}}\right)^2$$

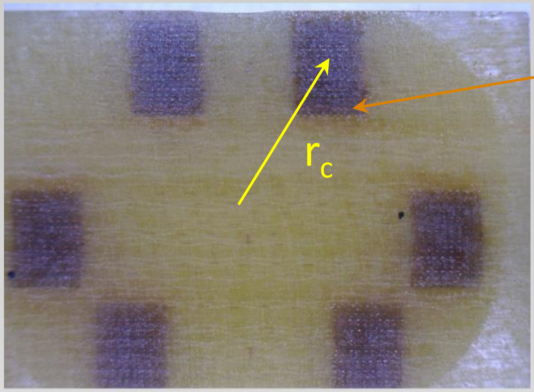
no impact of A_c

10^{-3} ~ 10^{-4}

10^{-2} ~ 10^{-3}

dominant term

Scaling of harmonic uncertainty with gap diameter ∅



number of turns available for the coils i.e.

$A_c \propto \varnothing^2$

mechanical manufacturing tolerances,
static and dynamic deformations, vibrations,
alignment, temperature drifts → σ_{rc} constant

$$\left(\frac{\sigma_{Cn}}{C_n}\right)^2 = \left(\frac{\sigma_{Ac}}{A_c}\right)^2 + (n-1)^2\left(\frac{\sigma_{rc}}{r_c}\right)^2 + \left(\frac{\sigma_{\Psi}}{\Psi}\right)^2$$

$r_c \approx \frac{\varnothing}{3}$ (typically)

Integrated flux change ~ constant
(peak pole field, rotation/translation speed,
magnet length being equal)

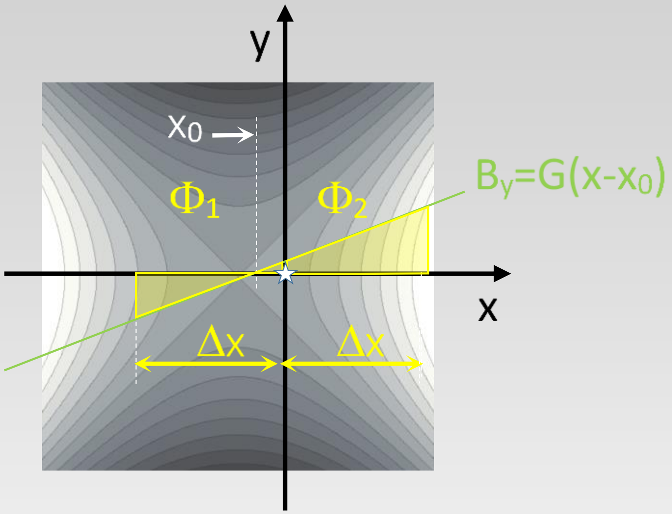
absolute harmonic coefficient uncertainty scales with:
harmonic order, $\varnothing^{-1} \sim \varnothing^{-2}$

Errors in stretched wire measurements

Wire moved in two steps of width Δx ∝ ∅ inside a quadrupole of unknown gradient *G*

Coordinate frame offset from magnetic axis by unknown amount x_0

Flux *Φ* integrated over the wire length L_w



$$\begin{cases}\Phi_1 = L_w \displaystyle\int_{-\Delta x}^{0} B_y\,dx \\ \Phi_2 = L_w \displaystyle\int_{0}^{\Delta x} B_y\,dx\end{cases}$$

$$G = \frac{\Phi_1 - \Phi_2}{\Delta x^2}$$

$$x_0 = \frac{\Delta x}{2}\frac{\Phi_1 + \Phi_2}{\Phi_1 - \Phi_2}$$

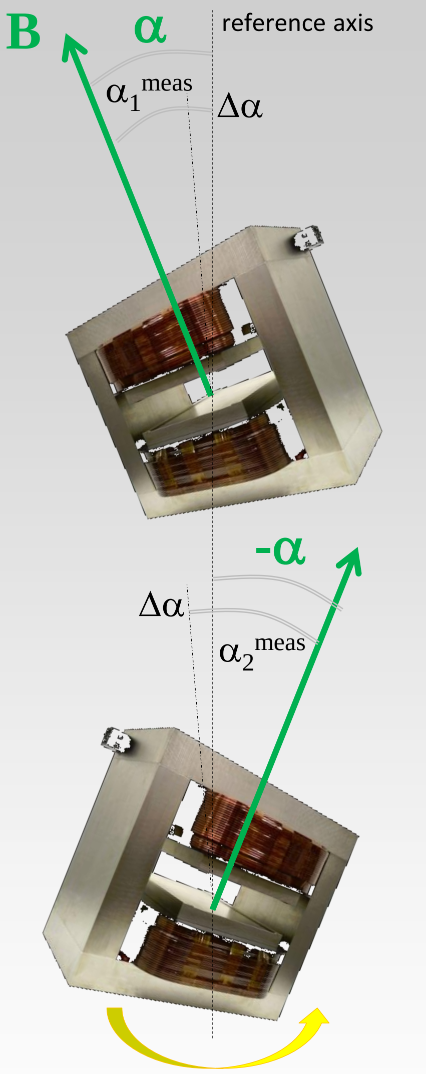
$$\begin{cases}\left(\dfrac{\sigma_G}{G}\right)^2 = \dfrac{1}{2}\left(\dfrac{\sigma_\Phi}{\Phi}\right)^2 + 2\left(\dfrac{\sigma_{\Delta x}}{\Delta x}\right)^2 \\ \left(\dfrac{\sigma_{x_0}}{x_0}\right)^2 = \left(\dfrac{\sigma_\Phi}{\Phi}\right)^2 + \left(\dfrac{\sigma_{\Delta x}}{\Delta x}\right)^2\end{cases}$$

uncertainty of gradient and magnetic axis scales with $\varnothing^{-1}$

Caveat: increasing too much Δx → get too close to the poles, harmonic errors perturb the result:

$$\frac{\frac{1}{2}\left(\int G_x\,dl + \int G_y\,dl\right)}{\int G\,dl} = 1 + \frac{2}{3}\left(\frac{\Delta x}{r_{ref}}\right)^4 \frac{b_6}{10^4} + \frac{2}{5}\left(\frac{\Delta x}{r_{ref}}\right)^8 \frac{b_{10}}{10^4} + \cdots$$

Estimation of systematic errors



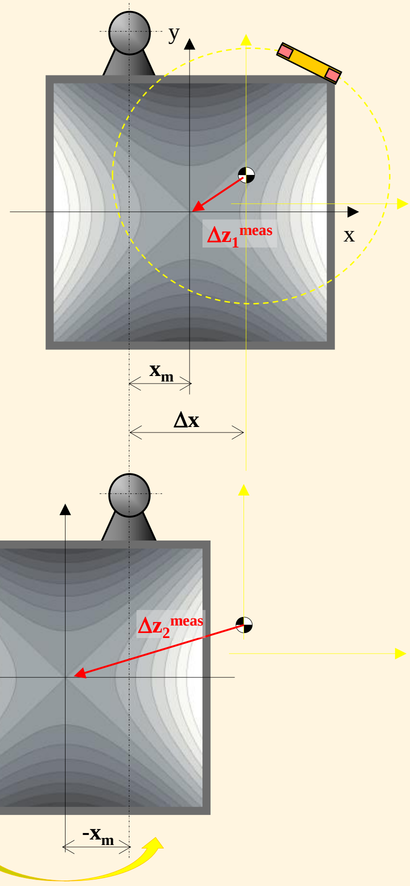
example of field direction calibration:
180° rotation around reference axis
(gravity *or* mechanical support)

- Simple cases: transverse and angular offsets
- Repeat the measurement by flipping the magnet around a vertical axis
- Reversing y is seldom possible, vertical offset is much harder to determine

$$\begin{cases}\alpha_1^{meas} = +\alpha - \Delta\alpha \\ \alpha_2^{meas} = -\alpha - \Delta\alpha\end{cases} \Rightarrow$$

$$\begin{cases}\alpha = \dfrac{\alpha_1^{meas} - \alpha_2^{meas}}{2} \\ \Delta\alpha = -\dfrac{\alpha_1^{meas} + \alpha_2^{meas}}{2}\end{cases}$$

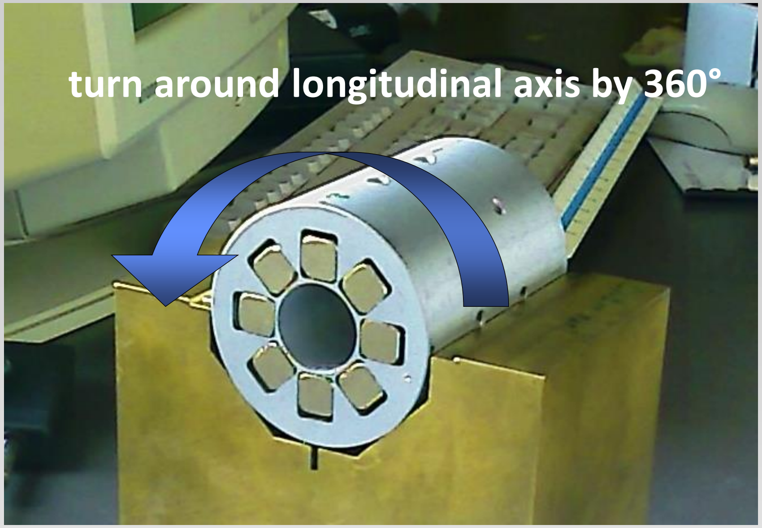
Systematic axis offset correction



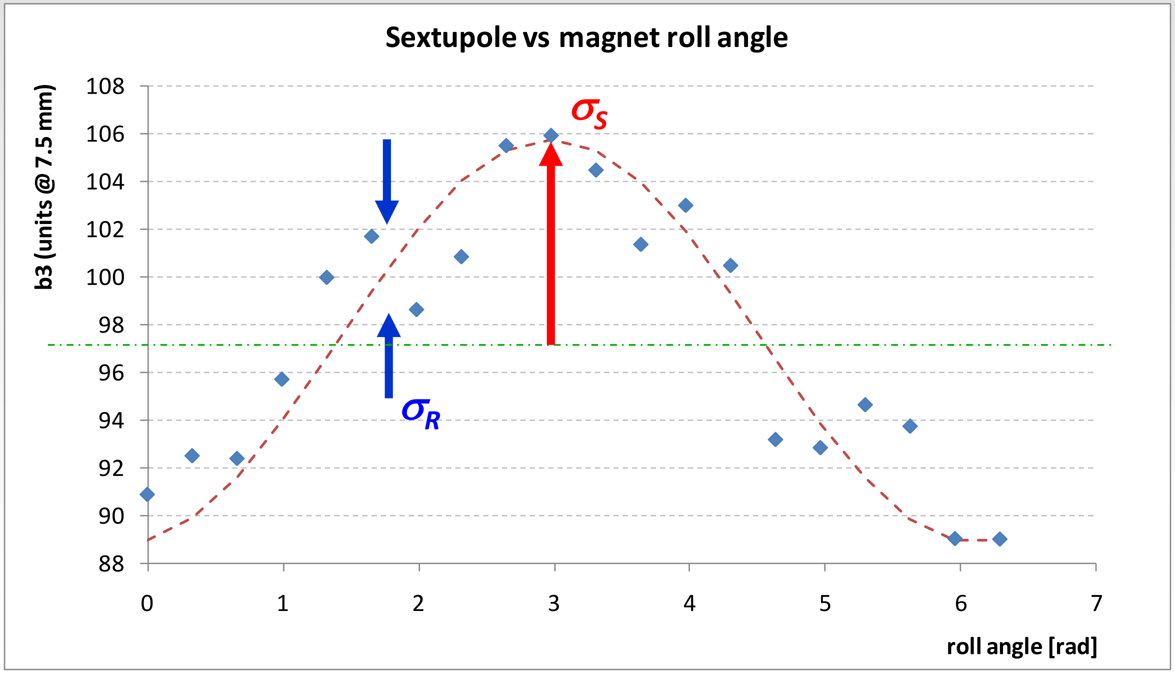
180° rotation around reference axis

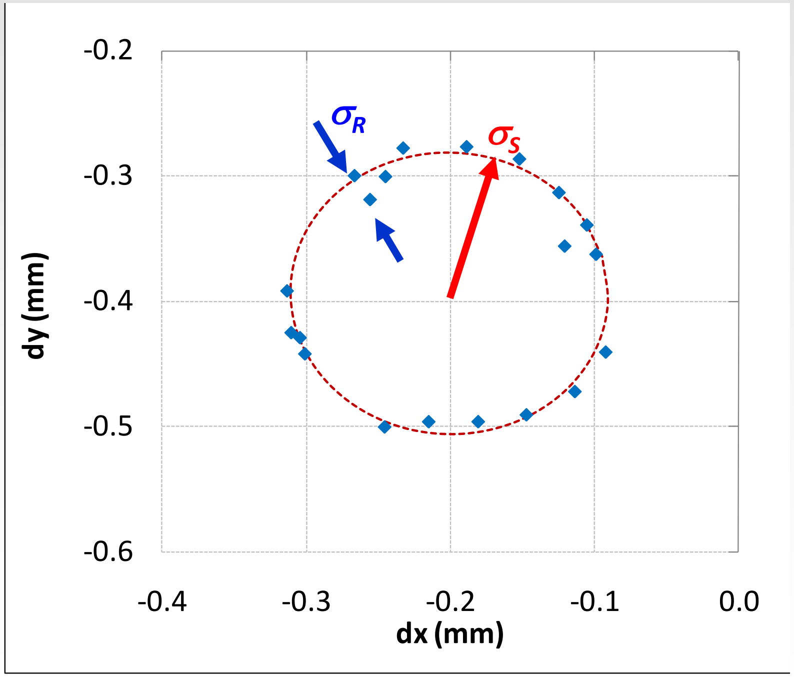
$$\begin{cases}\Delta x_1^{meas} = \Delta x - x_m \\ \Delta x_2^{meas} = \Delta x + x_m\end{cases} \Rightarrow \begin{cases} x_m = \dfrac{\Delta x_2^{meas} - \Delta x_1^{meas}}{2} \\ \Delta x = \dfrac{\Delta x_2^{meas} - \Delta x_1^{meas}}{2}\end{cases}$$

Estimation of systematic errors



- random uncertainty:
  electrical and mechanical noise
- systematic uncertainty: mechanical coil imperfections = f(θ) (weight-induced sag, ball-bearing eccentricity, torsional vibrations …)
- "true" value – <u>may be averaged from any two measurements 180° apart</u>





Low RMS

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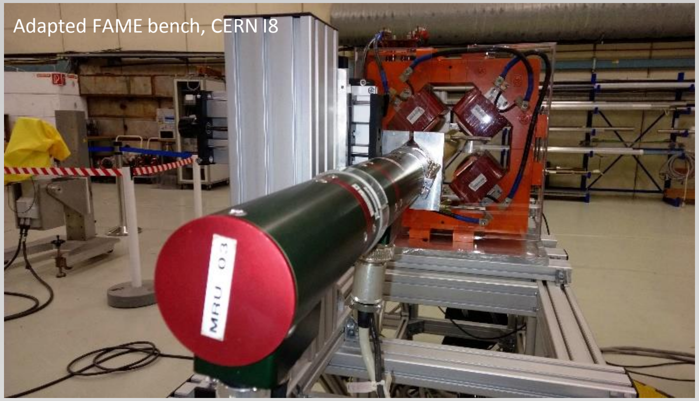
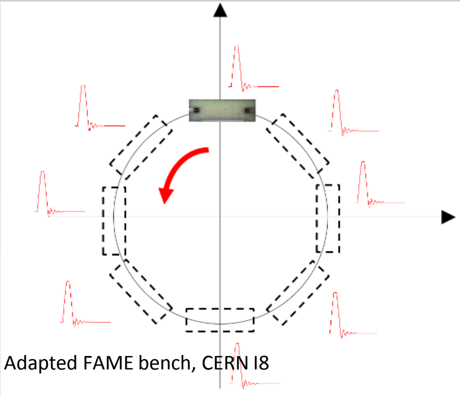
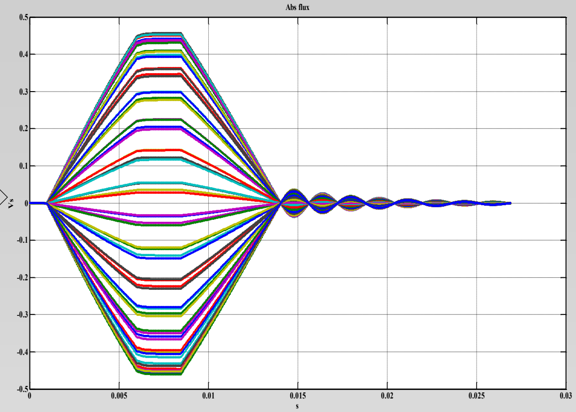
Stepwise pulsed-mode harmonic coils

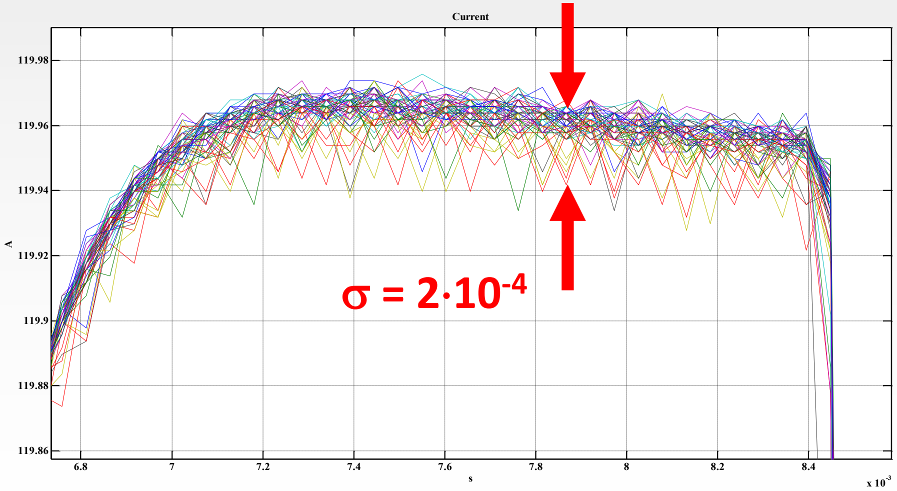

Adapted FAME bench, CERN I8


Adapted FAME bench, CERN I8

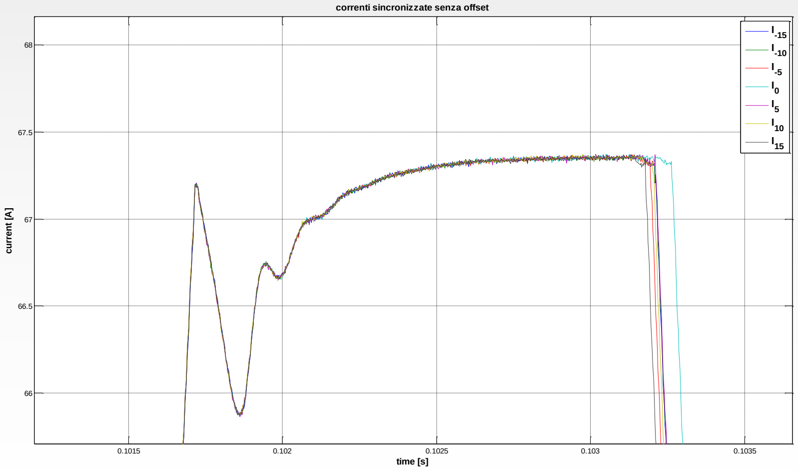
$\Phi(\theta,t)$



- New technique being developed to measure dynamically in the nominal powering conditions
- Requires: precise angular positioning, repeatability of power cycles
- Alternative solutions being evaluated:
  - scaling/time shifting I(t) and Φ(t) to recover errors by post-processing
  - differential mode measurement (additional fixed coil as a reference for scaling)
  - simultaneous rotation/current pulsing (reasonable for pulse lengths 0.1~1 s)

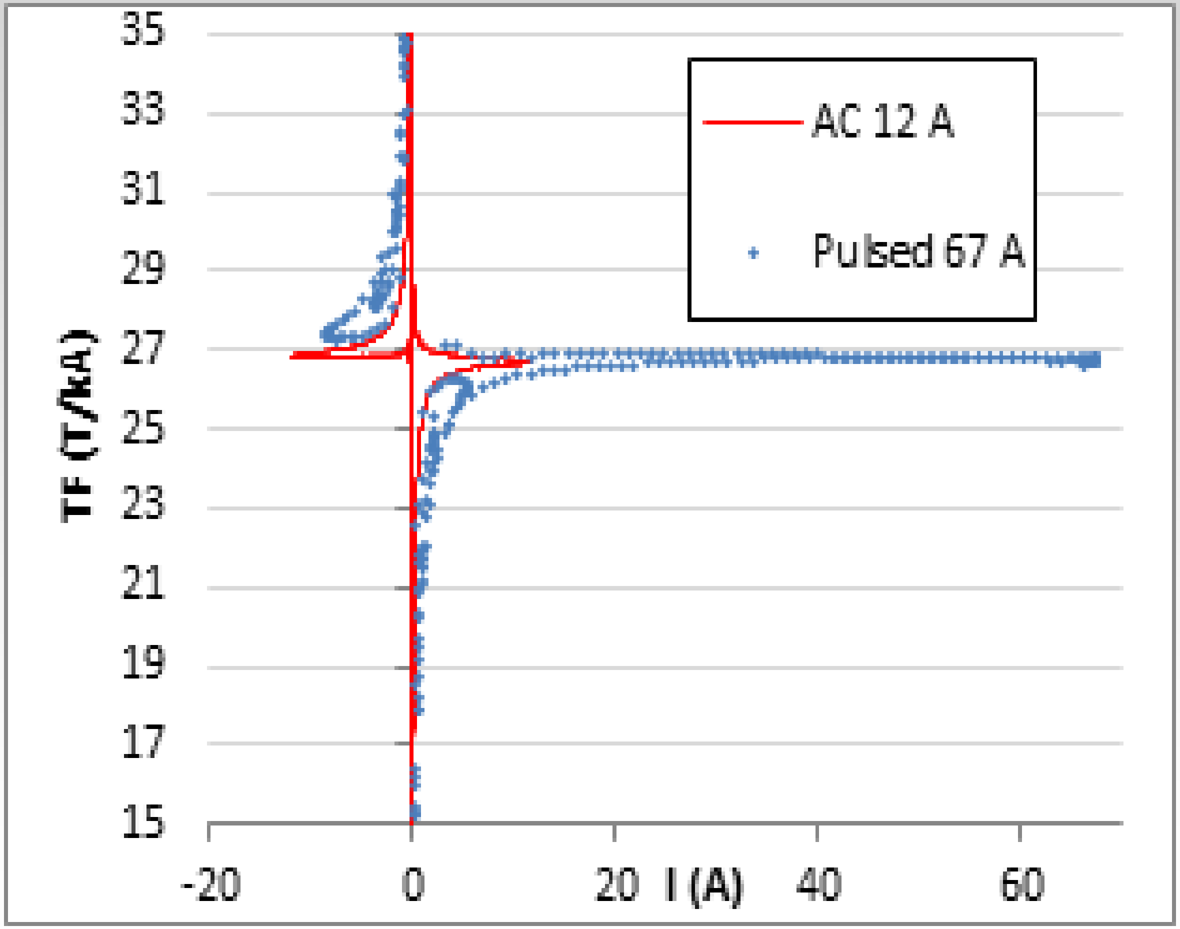


$\sigma = 2{\cdot}10^{-4}$



Extrapolation of low-field measurements

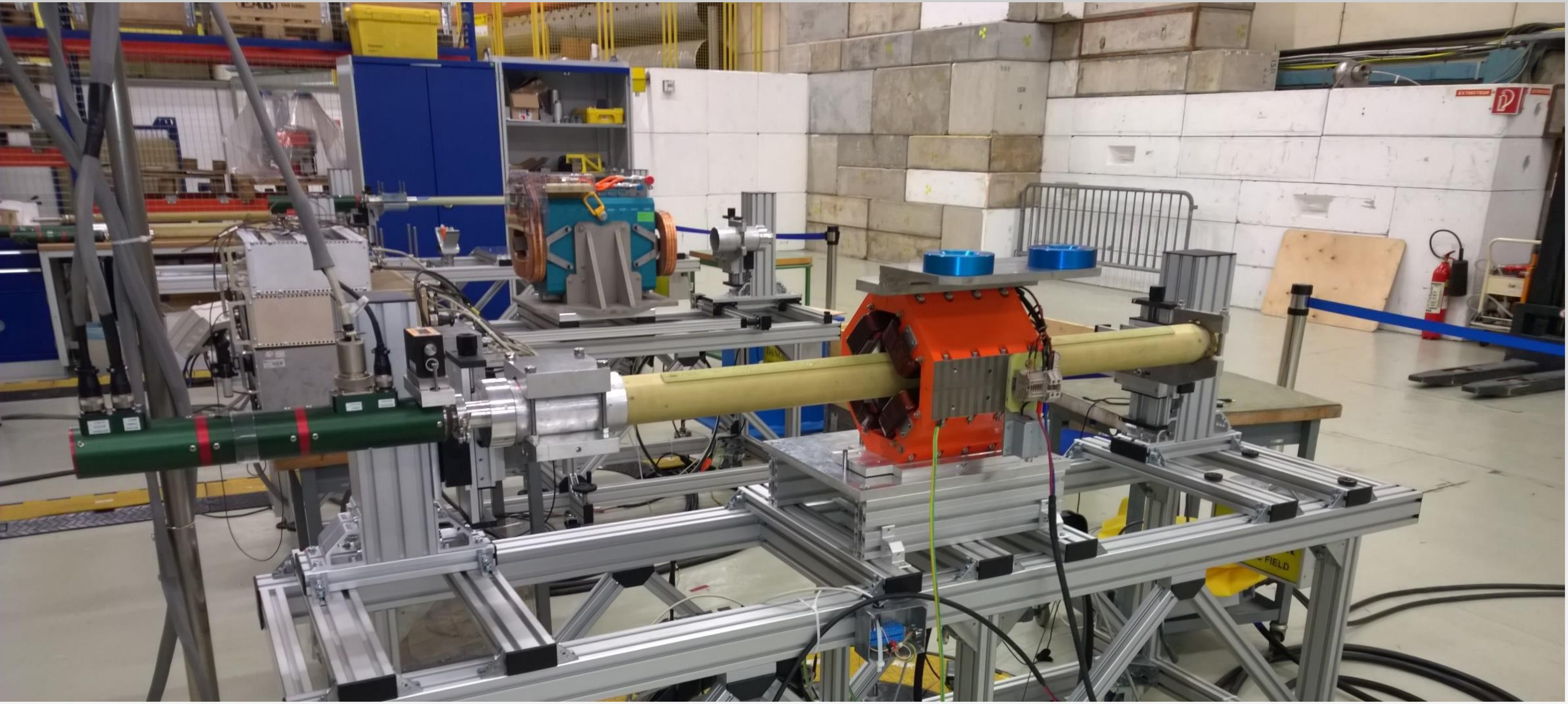
- Simplest solution: use standard DC rotating coils or DC/AC stretched wire → extrapolate to high fields (flat-top conditions must be equivalent to DC when the beam passes i.e. eddy current must decayed)
- Transfer function is perturbed by eddy current losses + remanent field effects
- So far used only for Linac4 EMQs (±0.5% tolerance)



Example:

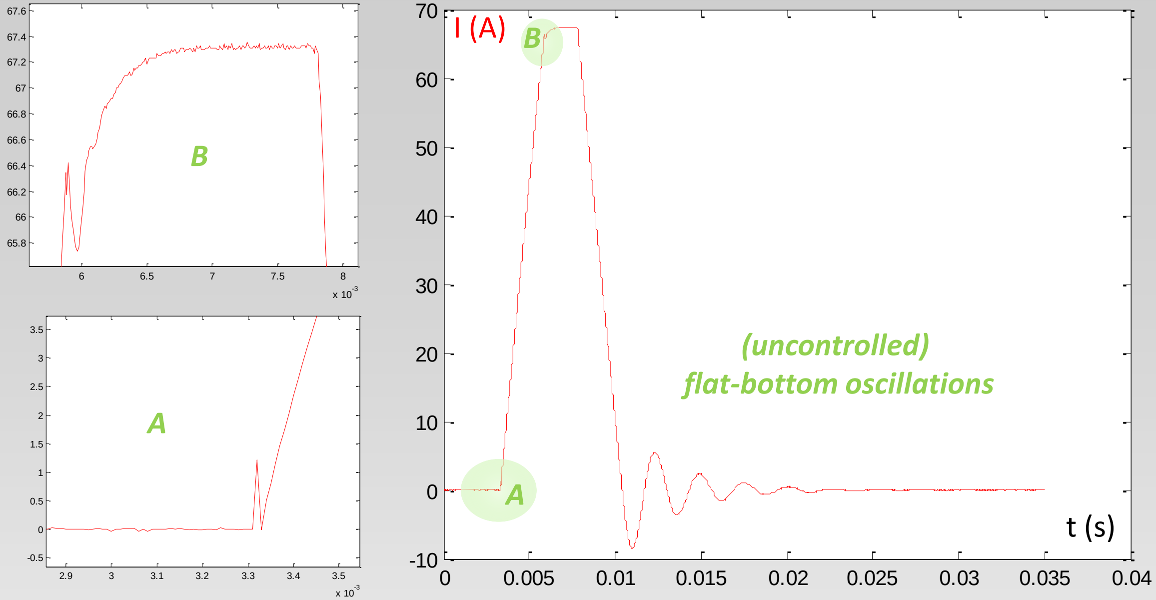
GdL transfer function of Linac4 EMQ

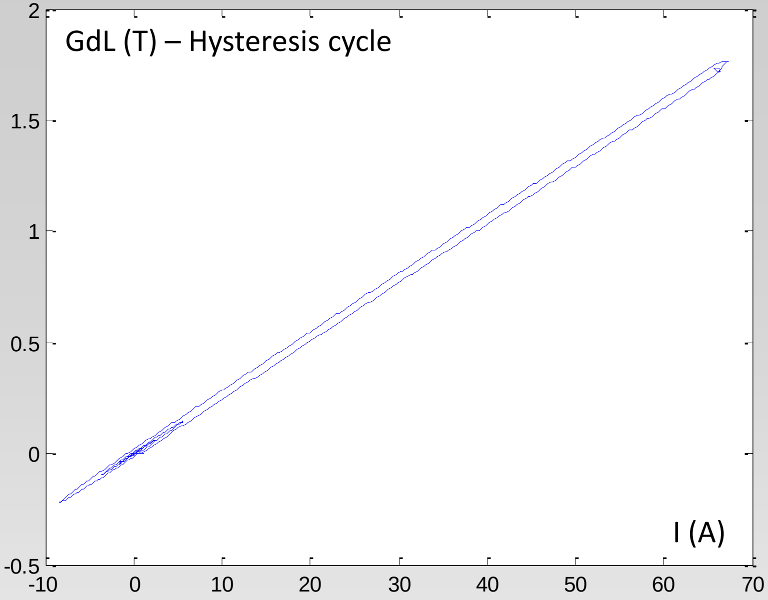
Impact of background fields on low-field DC measurements



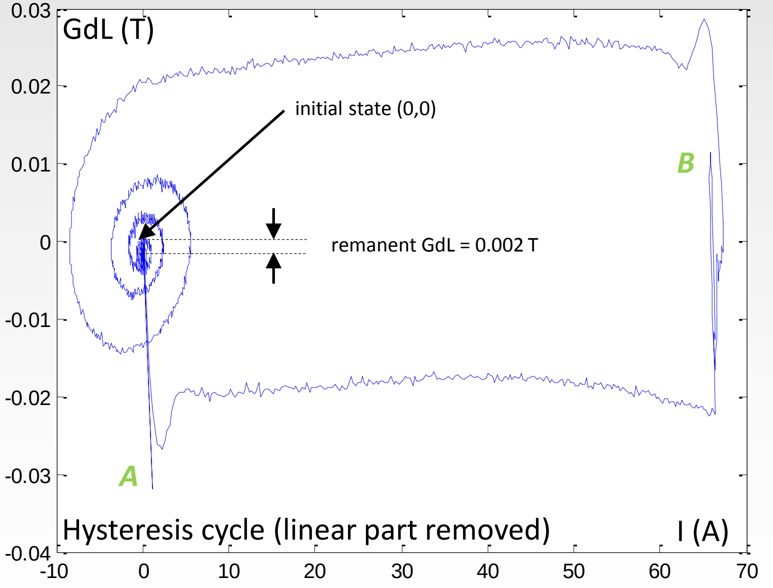
- Example: CERN linac4 TL EMQs: $B_0 \approx 0.05$ mT, $\int G d\ell = 0.14$ T @ 9 A (nominal 120 A), $L_c = 1.2$ m, $L_m = 0.3$ m $\rightarrow \Delta z \approx \frac{B_0 (L_c - L_M)}{\int G d\ell} \approx 0.3$ mm
- Can be suppressed by flipping around the magnet/inverting the current
- Remanent field in the poles adds up: the ffect can also be suppressed taking care about cycling

Cycling issues in fast-ramping magnets





- Example: fast capacitive discharge powering of Linac4 inter-tank EMQs
- current spikes lead minor hysteresis loops → field reproducibility degradation
- oscillations at the end of the ramp-down may provide a beneficial free de-gaussing, *if* symmetrical
- the overshoot at the end of the ramp-up may give a more stable flat-top, but makes it less reproducible



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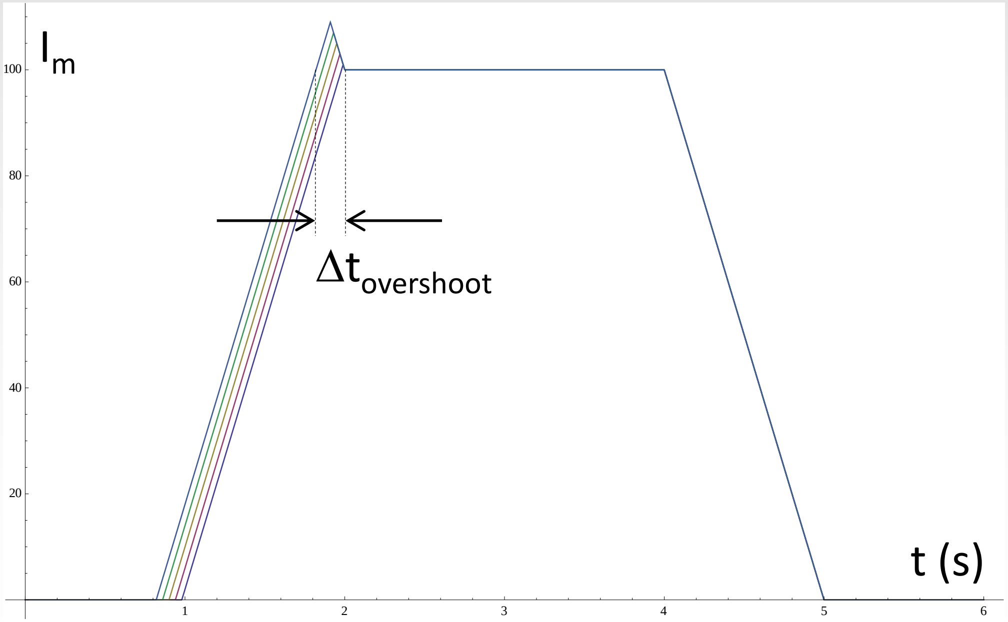
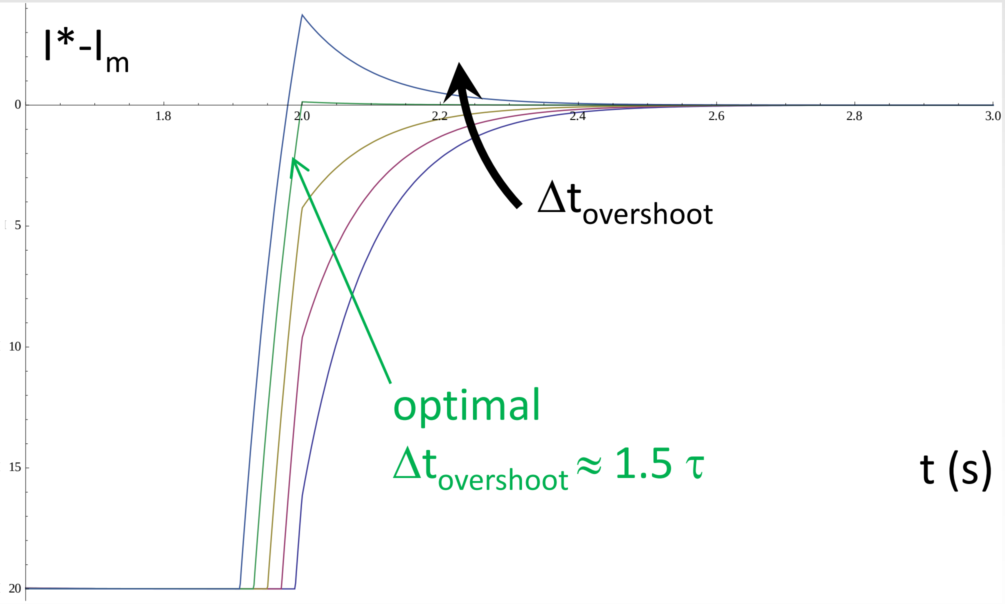
Feed-forward control of eddy currents

- Eddy currents can be partially, totally or over-canceled by a linear excitation current overshoot at the end of ramp-up
- Example: stable flat-top reached at the time cost of ~1.5τ (to be compared with exponential decay time ~3τ)
- Caveats:
  - power converter needs high dV/dt;
  - the maximum working point is increased considerably, at the risk of saturation

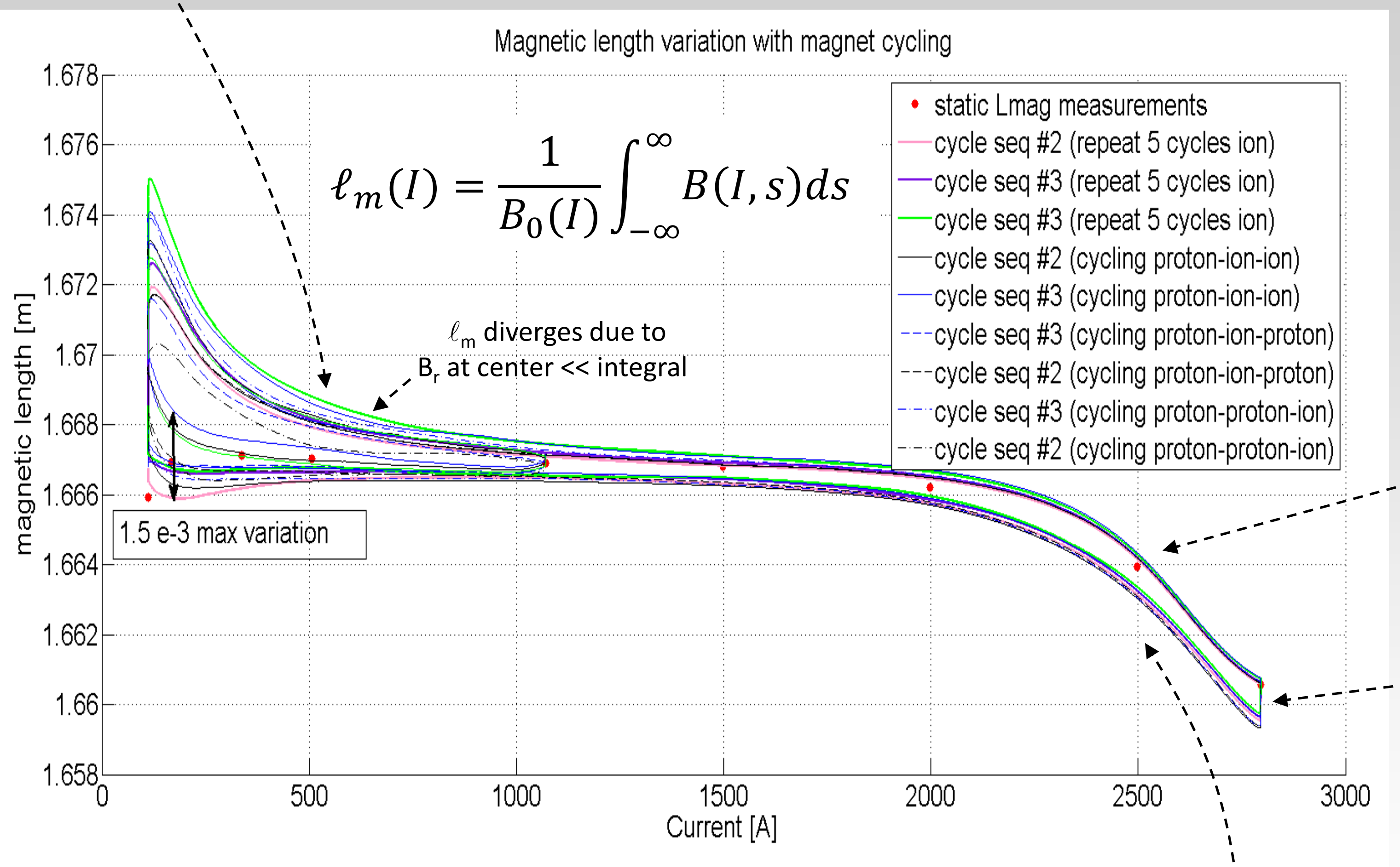




Cycle reproducibility in MedAustron main bending dipole

large fluctuations due to history-dependent residual field

reproducibility degrades at low field



$$\ell_m(I) = \frac{1}{B_0(I)} \int_{-\infty}^{\infty} B(I,s)\,ds$$

ℓ_m diverges due to B_r at center << integral

ℓ_m drops due to saturation in the ends

eddy current decay (τ=0.2 s)

saturation tends to erase previous magnetic history

→ better reproducibility at high field

Courtesy G. Golluccio

Summary

Summary

- Measurement systems for **small gaps** (∅<40 mm) currently being developed at CERN
- Main limitations:
  - mechanical tolerances for rotating coil systems
  - mechanical tolerances and various non-linear effects for stretched-wire systems
- reasonable performance at ∅20 mm, still work to do at ∅8 mm
- many sources of systematic errors can be corrected by flipping the magnet around or upside/down

- Techniques for **fast cycled magnets** are being developed too (Linac EMQs)
- Open issues: precise extrapolation of main component, dynamic behavior of field harmonics/magnetic center
- The impact of new current waveforms on magnetic performance should be evaluated early in the design cycle:
  - extending dynamic range at the bottom degrades reproducibility
  - uncontrolled transients degrade the reproducibility
  - prototype magnets should ideally be tested along with their prototype power supplies !

References

[1] M. Buzio, S. Sanfilippo *et al.*, SMALL-DIAMETER ROTATING COILS FOR FIELD QUALITY MEASUREMENTS IN QUADRUPOLE MAGNETS, XX IMEKO TC-4 International Symposium, September 15–17, 2014, Benevento, Italy

[2] S. Kasaei *et al.,* MAGNETIC CHARACTERIZATION OF FAST-PULSED ELECTROMAGNETIC QUADRUPOLES FOR LINAC4 AT CERN, Proceedings of Linac14, CERN, September 2014