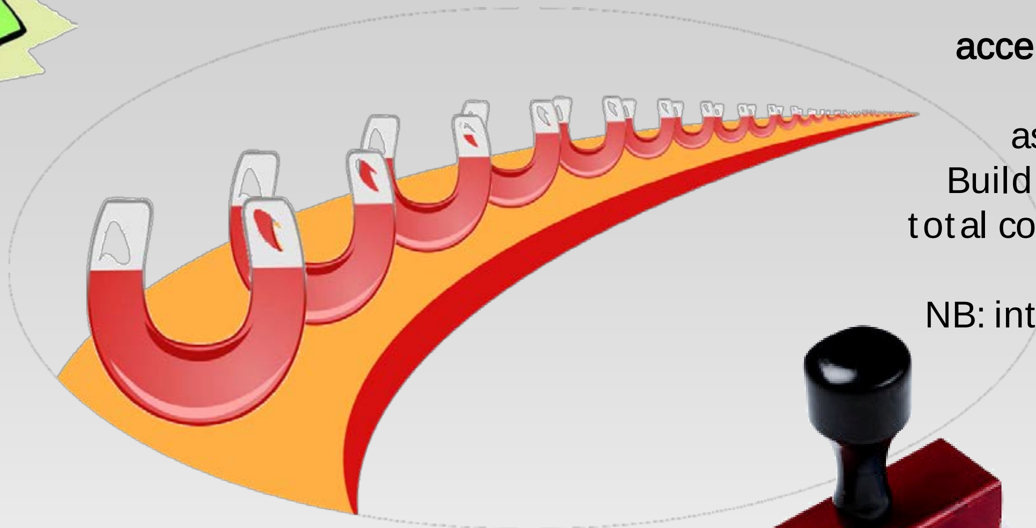
Overview of Magnetic Measurements for Particle Accelerators

Marco Buzio on behalf of the Magnetic Measurement Section
Magnet, Superconductors and Cryostat Group, Technology Department, CERN

Introduction

design phase: test material samples for permeability, coercivity etc…
test prototypes or models (scaled down versions) to validate computer simulations
and specific design choices (e.g. chamfers, shims, many other details …)



acceptance tests: monitor production quality, trap errors, tooling wear …
as early as possible to steer manufacturing.
Build up statistics to reduce tests and minimize total cost. Get all data required for fiducialization (installation) and beam optics.
NB: internal acceptance criteria might be elastic, but legal acceptance is binary (and may be even obligatory !)

prototypes/pre-series: test field quality to verify the respect of mechanical tolerances (inverse problem),
give feedback to designer and manufacturing firms.
Carry out a fully detailed magnetic characterization (often the time to do so will not be available during series tests)

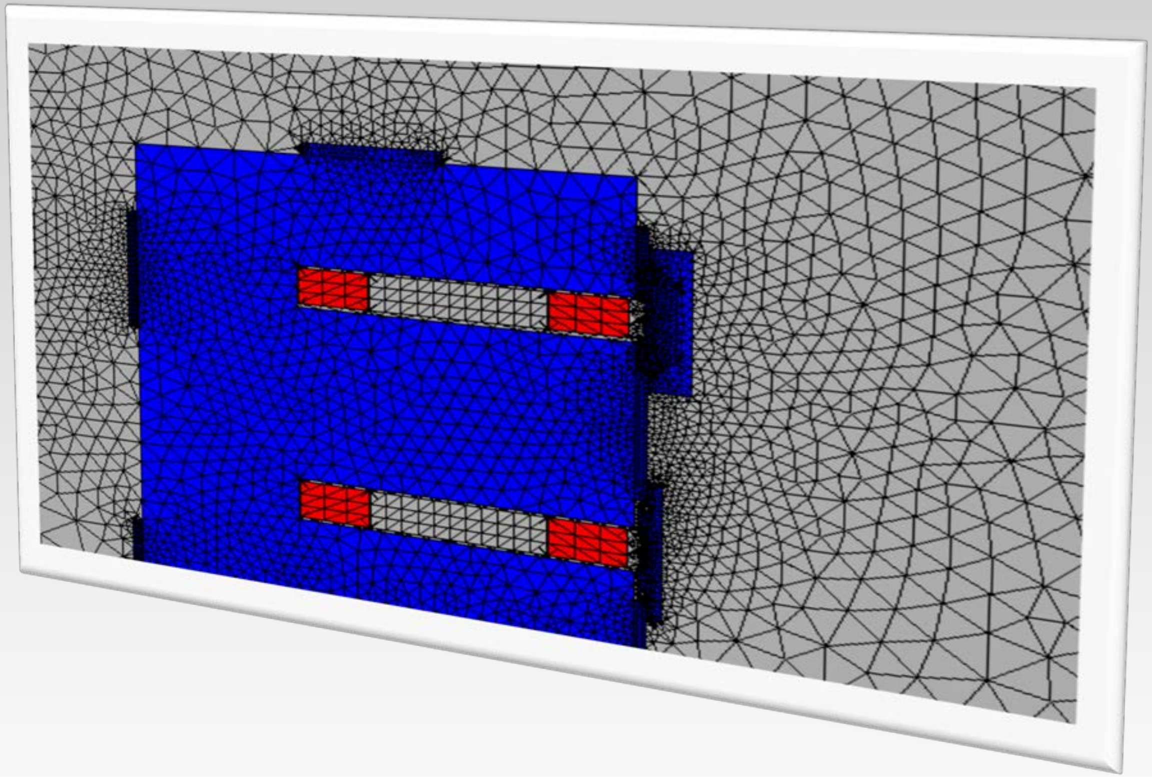
throughout lifetime: characterize magnets after repairs, or to allow use in different ways than originally intended

different trade-offs between accuracy and resources at different times

Mathematical models

Advantages

- **predict behaviour without having the physical object** (!!!)
- **fast and inexpensive** for relatively simple cases; allow parameter space searches, optimization
- virtually **unlimited resolution** and precision



Limitations

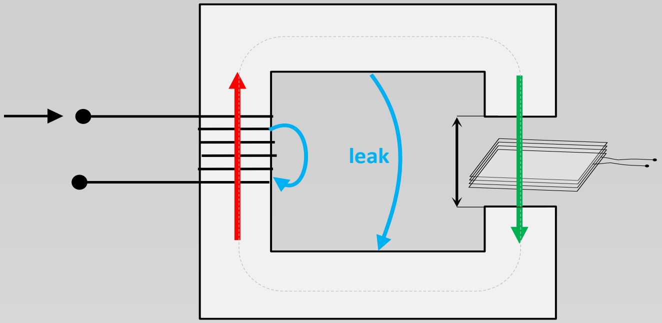
- **partial physical model**: including all couplings (thermal, mechanical) and phenomena (magnetostriction, magnetoresistivity …) that *may* be relevant is extremely expensive
- **numerical errors**: e.g. singularities in re-entrant corners, boundary location of open regions; these may spoil results. Special techniques (special corner elements, BEM) require skill and time
- **high cost** of detailed 3D models $\propto \Delta x^{2\sim3}, \Delta t^{-1}$ (2D simulations not always sufficient …)

marco.buzio@cern.ch

Impact of model uncertainties

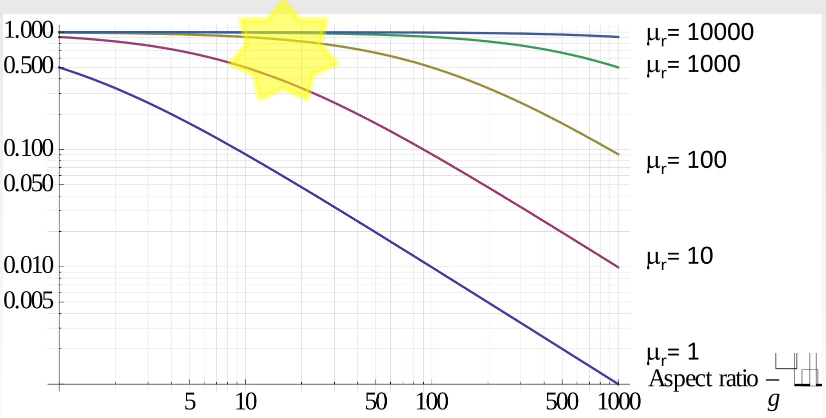
Analytical 1D model (assume no leakage, constant sross-section), typical accuracy 10^{-1}~10^{-2}

$$B = \frac{\mu_0 N_t I}{g\left(\frac{1}{\mu_r}\frac{\ell}{g}+1\right)}$$



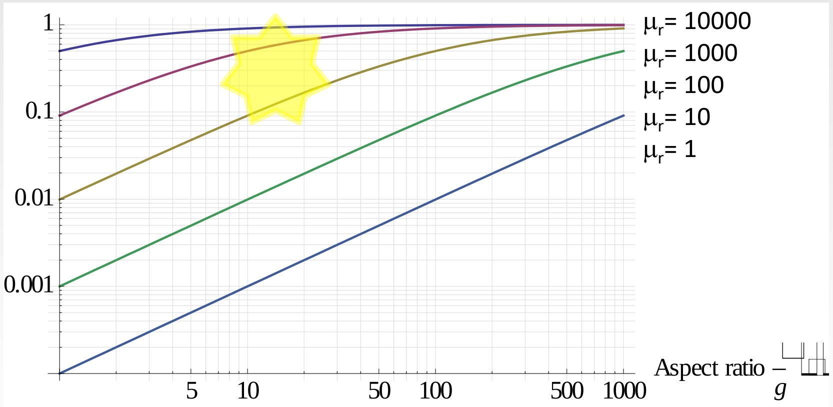
impact of geometrical uncertainty (mechanical tolerances, assembly errors)

$$\frac{g}{B}\frac{\partial B}{\partial g} = -\frac{1}{\frac{1}{\mu_r}\frac{\ell}{g}+1}$$



impact of material property uncertainties

$$\frac{\mu_r}{B}\frac{\partial B}{\partial \mu_r} = \frac{1}{1+\mu_r\frac{g}{\ell}}$$



10 μm/100 mm gap error→ 10^{-4} field error at high field
5% μ_r error → $5\cdot10^{-3}$ field error at low field (typical values)

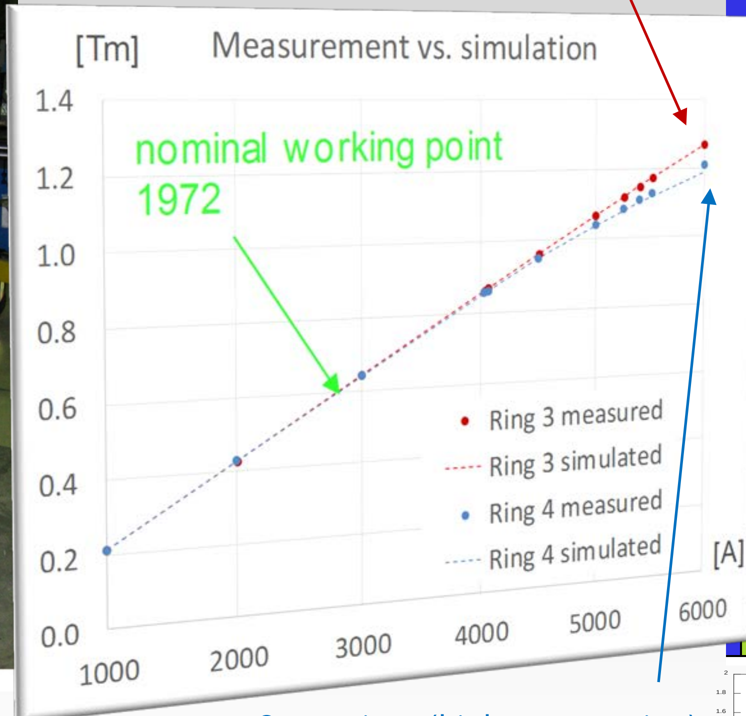
FE/MM comparison (1/2): CERN PS Booster Dipole

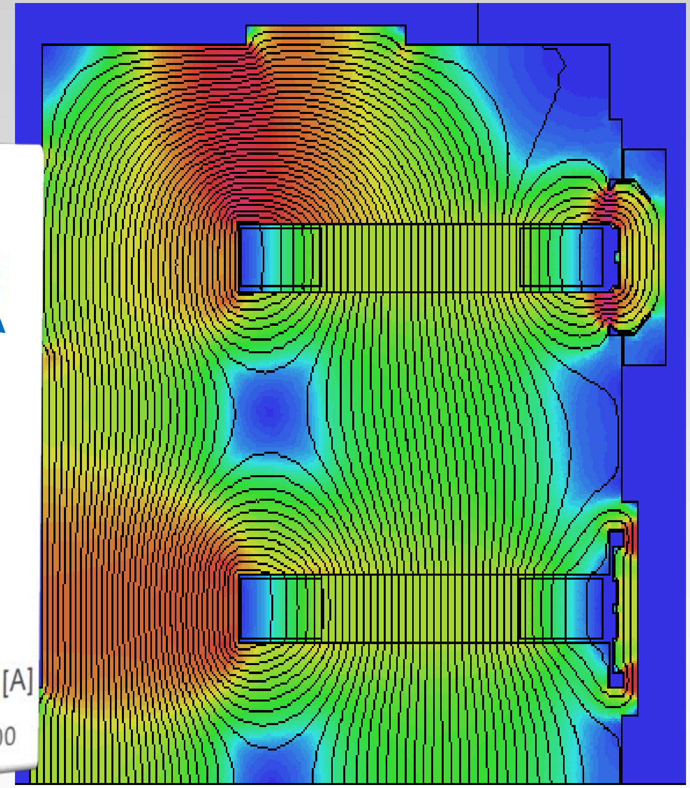
steel plates to be reinforced to equalize the rings at high field (+110% @ 2 GeV w.r.t. design value !)

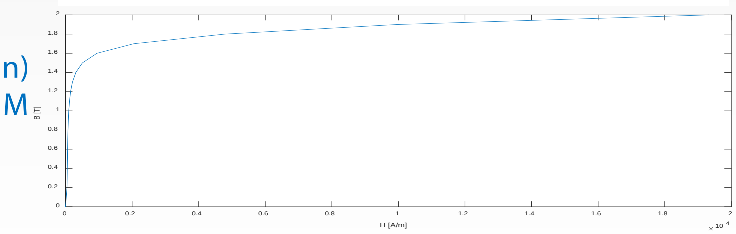
2D FE with nominal *B(H)* (tweaking the curve does not work !)

4-ring main bending dipole of CERN PS Booster

Inner rings (high field, little saturation) 0.3% mismatch FE/MM







Outer rings (higher saturation) 2% mismatch FE/MM

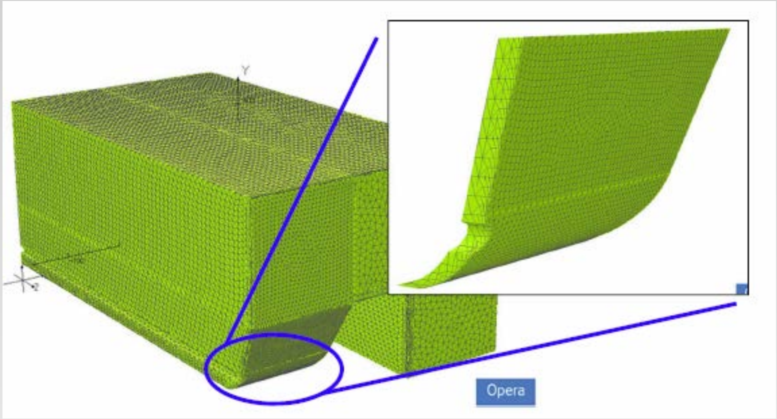
Courtesy A. Newborough, R Chritin

marco.buzio@cern.ch

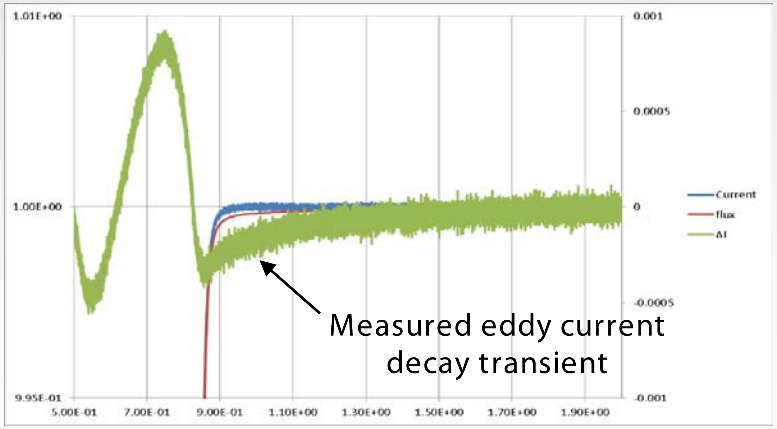
FE/MM comparison (2/2): MedAustron Bending Dipole

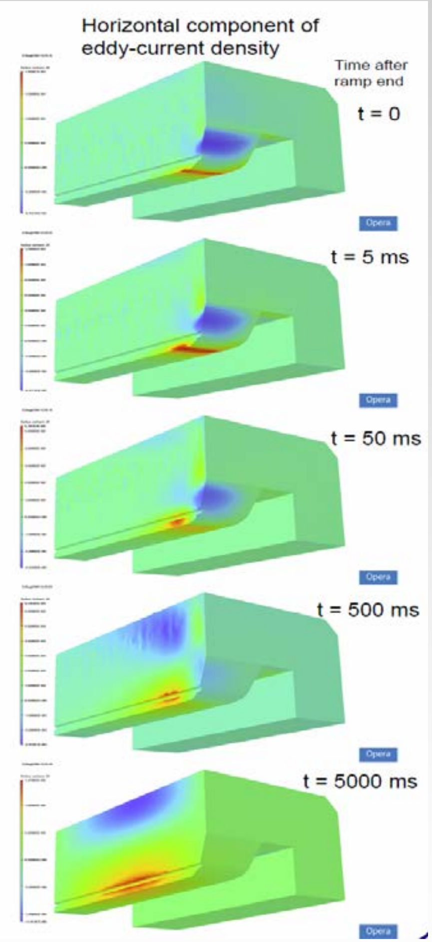
- modelling issues more complex for dynamic phenomena (eddy currents)
- medical hadrontherapy machine requirements: fast energy changes, high accuracy and stability
- settling time: measured 200 ± 20 ms, computed 150 ms

Integral PCB fluxmeter



~ 2M elements, 80 h running time

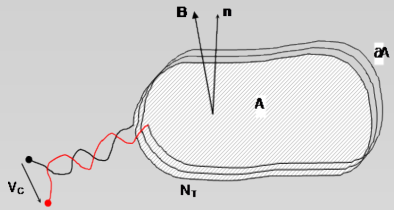




G. Golluccio, A. Beaumont *et al.*, Overview of the magnetic measurements status for the MedAustron project, IMMW18
T. Zickler *et al.*, Design and Optimization of the MedAustron Synchrotron Main Dipoles, IPAC11

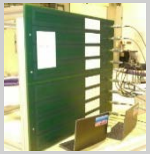
Measurement methods

Induction sensors



$$-V_c = \frac{\partial \Phi}{\partial t} = \frac{d}{dt}\iint_{\mathcal{A}} \boldsymbol{B}\cdot\boldsymbol{n}\,dA =$$
$$\iint_{\mathcal{A}} \frac{\partial \boldsymbol{B}}{\partial t}\cdot\boldsymbol{n}\,dA + \oint_{\partial\mathcal{A}} \boldsymbol{v}\times\boldsymbol{B}\,d\ell$$

$$A_c\frac{\partial B}{\partial t}$$ Fixed coil in a time-changing field (fluxgate, AC stretched wire)



$$l_w B\frac{\partial x}{\partial t}$$ Wire translating in a DC field (classical DC stretched wire)

see Z. Wolf IMMW19

$$A_c B\frac{\partial \theta}{\partial t}$$ Coil rotating in a DC field

see J. Di Marco IMMW19

$$A_c\frac{\partial B}{\partial x}\frac{\partial x}{\partial t}$$ Coil translating in a DC field

see G. Caiafa IMMW20

- Sensitive to the **flux** rather than the field
- Intrinsically **linear transducer**
  (some nonlinearity indirectly due to acquisition electronics e.g. finite input impedance → small currents circulate in the coil)
- **Voltage integration** generally required, with attendant advantages (noise abatement proportional to frequency) and drawbacks (drift, results depend on integration time)
- Direct post-processing of the voltage also possible
  (relies on accurate speed control and measurement)

Lorentz force-based sensors

$$\frac{\boldsymbol{F}}{q} = \boldsymbol{E} + \boldsymbol{B} \times \boldsymbol{v}$$

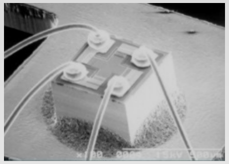
$$\frac{\partial \boldsymbol{F}}{\partial l} = \boldsymbol{B} \times \boldsymbol{I}$$

Vibrating wire

see Z. Wolf, IMMW19

$$V_H = k_H B\ I$$

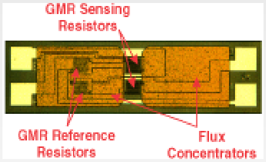
Hall effect sensor



see Prof. Popovic, M. Calvi IMMW20

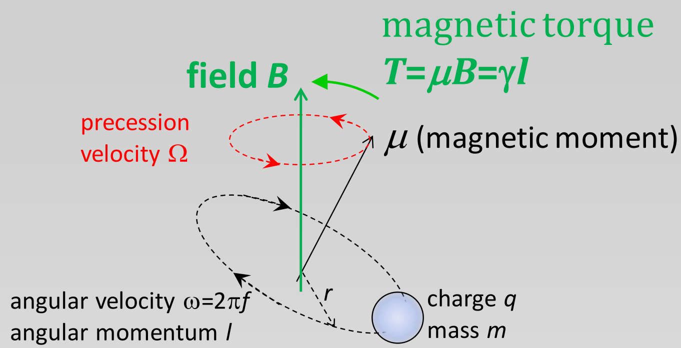
$$\frac{\Delta\rho}{\rho} = kB^2$$

Magneto-resistive sensor
(hardly used in our field)



- Sensitive to a **single field component** (with higher order correction terms)
- Mechanical/solid state phenomena → stronger non linearity → **more difficult calibration**

Magnetic resonance sensors



$$B = \frac{2\pi}{\gamma} f$$

see P. Keller, IMMW19
G. Boero, IMMW20

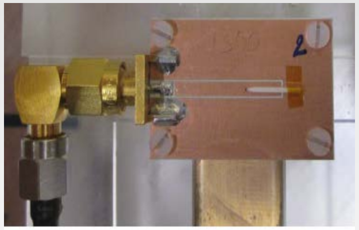
$$\gamma = g\frac{q}{4\pi m} = \begin{cases} \mathrm{H^+ (proton)} & 42.577 \\ \text{free electron} & 28\,015.737 \end{cases} \quad MHz\, T^{-1}$$

Gyromagnetic ratio

Zeeman (quantum) correction factor

NMR (Nuclear Magnetic Resonance)
γ constant known to better than 1 ppm

EPR/ESR (Electron Paramagnetic/Spin Resonance), FMR (FerriMagnetic Resonance)
actual value in materials depends on: chemical composition, temperature, direction …



- Resonant absorption/re-emission of RF waves in a sample within a uniform field
  (field gradient spreads the resonance, impact depends on sample size and shape)
- Transducer sensitive to the **field vector norm**
  (some impact of temperature, orientation of transducer, chemical nature of sample: < 10^{-6} for NMR, much stronger for EPR)
- Gyromagnetic ratio depends on fundamental constants → **metrological golden standard**

Magnetic measurement dataflow

CALIBRATION → **DATA REDUCTION**

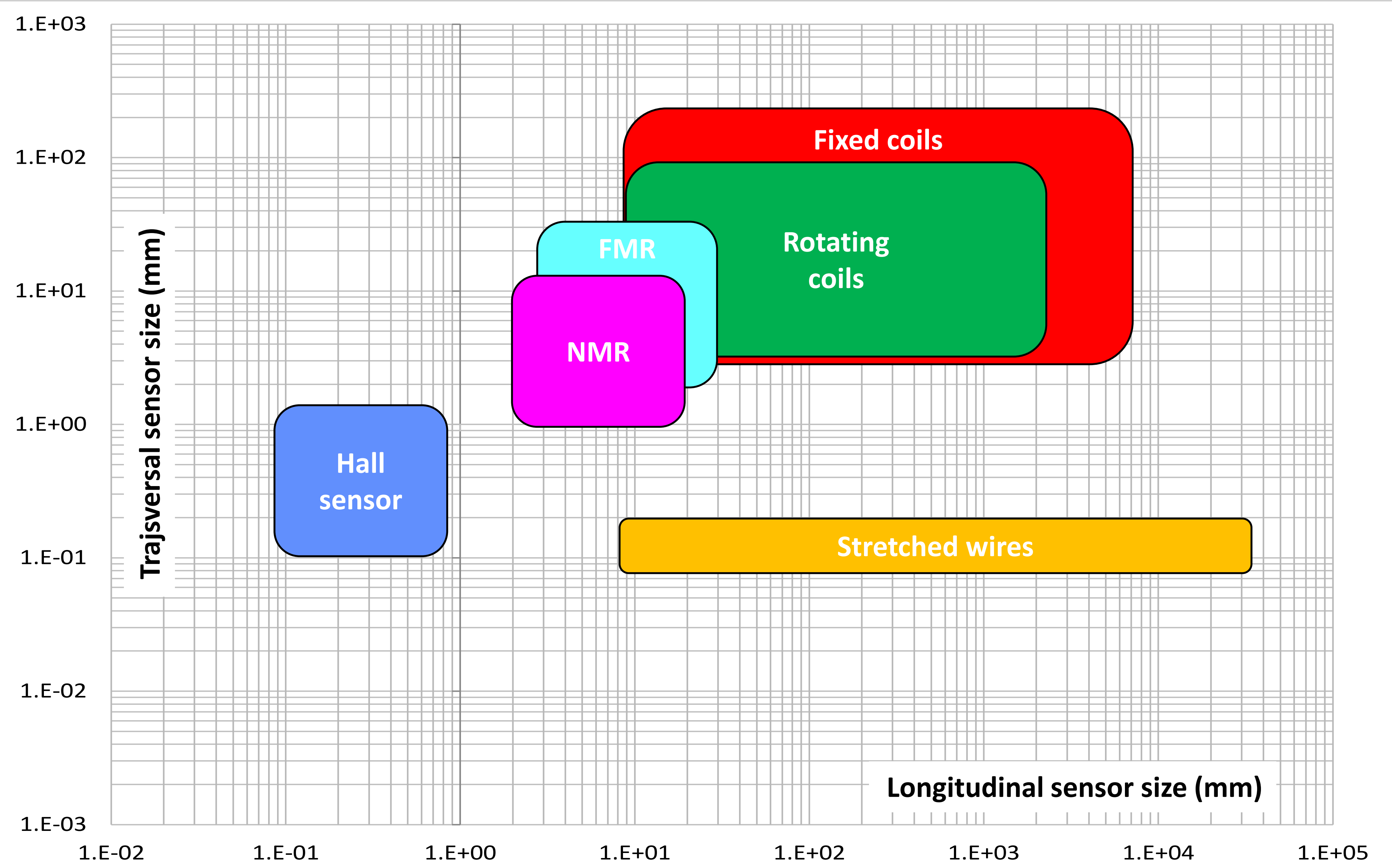
Physical principle	Method	Raw data	Intermediate result	Field representation	Final results
Induction $V_c = \frac{\partial \Phi}{\partial t}$	fixed coil $V_c = A_c \dot{B}$	$V_c(t)$	$\Delta\Phi(t)$	long. field integral vs. time, transv. pos. $\frac{1}{w_c \ell_c} \iint \Delta B(x,t,s) ds\, dx$	Commonly required results: • field polarity • integrated/local field strength (main harmonic) • field direction (phase of main harmonic), • integrated/local field errors (higher harmonics) • magnetic axis (transversal position) • magnetic axis (pitch and yaw angles) • magnetic center (longitudinal) vs. time, current, excitation history, environmental conditions etc.
	rotating coil $V_c = \omega A_c B$	$V_c(\vartheta)$	$\int_0^{2\pi} \Phi(\psi)\kappa(\vartheta - \psi) d\psi$	avg. field expansion coefficients $C_n = B_n + i A_n$	
	translating coil $V_c = \dot{s} A_c \frac{\partial B}{\partial s}$	$V_c(s)$	$\int_{-\infty}^{\infty} \Phi(u)\kappa(s-u) du$	long. avg. field profile vs. transv. pos. $\frac{1}{w_c} \int B(s,x) dx$	
	moving wire $V_c = \dot{x} A_c \frac{\partial B}{\partial x}$	$V_c(x)$	$\Delta\Phi(x)$	long. avg. field integral $\frac{1}{\Delta x\, \ell_w} \iint \Delta B(x,s) ds\, dx$	
Lorentz force $\frac{\partial F}{\partial s} = B(s) I(t)$	vibrating wire	$\delta_x(\bar{s},t)$ $\delta_y(\bar{s},t)$	eigenmode amplitudes $\delta_{xn} sin(2\pi n \frac{s}{\ell_w})$ $\delta_{yn} sin(2\pi n \frac{s}{\ell_w})$	$\frac{1}{\delta_{yn}} \int B_{xn}(s) sin(2\pi n \frac{s}{\ell_w}) ds$ $\frac{1}{\delta_{xn}} \int B_{yn}(s) sin(2\pi n \frac{s}{\ell_w}) ds$	
Hall effect $V_H = k_H I_H B$	1D/2D/3D probes	$V_H(t)$		$B(t)$	
Magnetic Resonance $f = \gamma \lVert \boldsymbol{B} \rVert$	NMR/EPR probes	$V_{RF}(t)$	$V_{LF}(t)$	$\lVert \boldsymbol{B} \rVert = \frac{f(t_{res})}{\gamma}$	

s: longitudinal coordinate; x,y: transversal coordinates. B: magnetic field component normal to the coil, the movement of the wire and to the Hall sensor

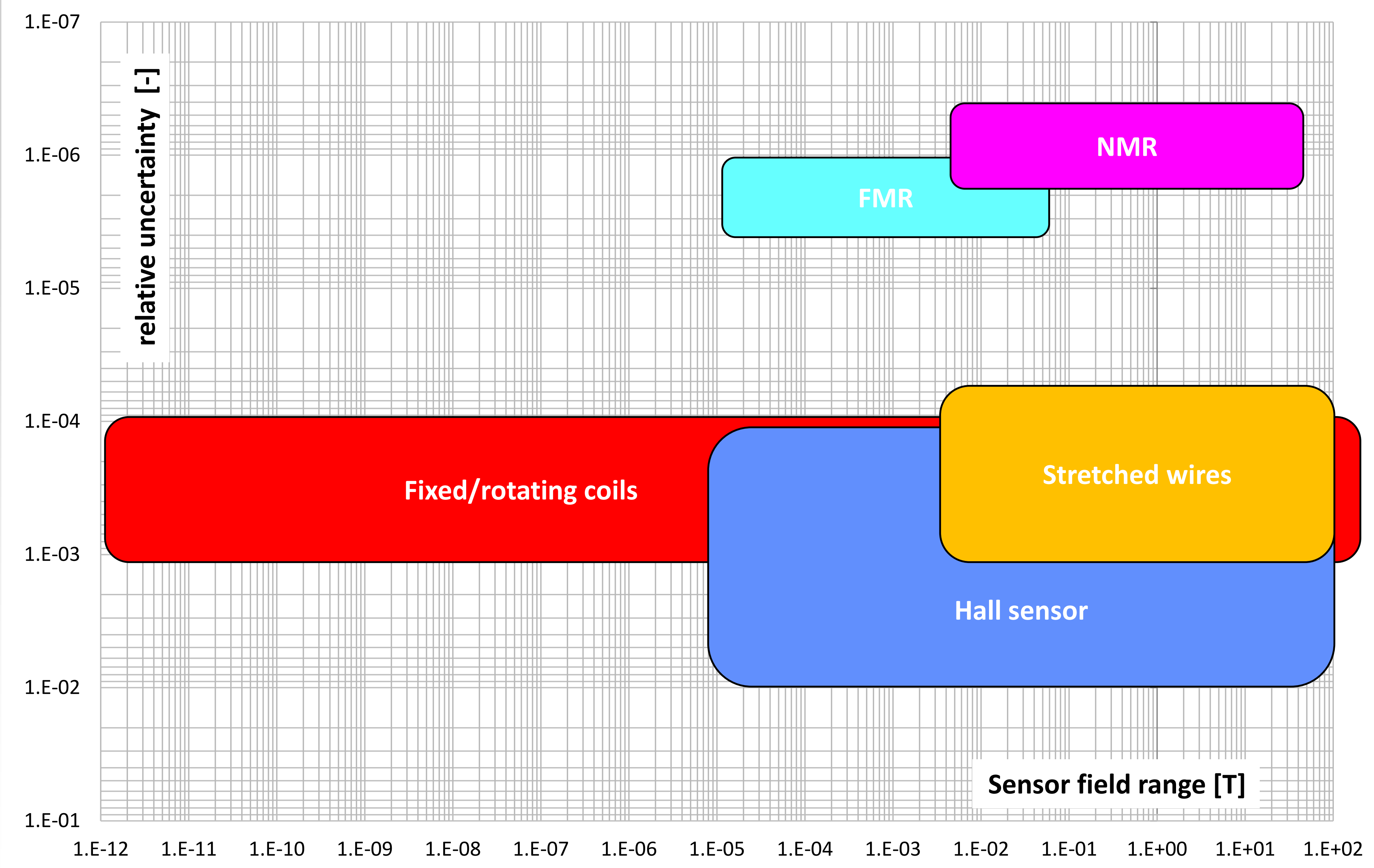
Overview of magnetic instruments

Instrument	B [T]	B.W. [Hz]	$\frac{\sigma_B}{B}$	Sensor size	Remarks
Rotating-coil fluxmeter	$>10^{-4}$	~DC	10^{-4}	∅8-350 mm 30 – 1300 m	• full 2 D field information (absolute and relative, integral or local): strength, multipoles, axis and direction • coil bucking → higher multipoles at ppm resolution, decreased sensitivity to mechanical imperfections • time resolution up to ~0.1 s
Fixed-coil fluxmeter	$>10^{-4}$	$>10^{-2}$	10^{-4}	< 7 m	• natural (and only) option for very fast pulsed magnets • allows easy dynamics studies (eddy current and history-dependent effects) • integration constant requires separate measurement
Translating-coil fluxmeter	$>10^{-4}$	DC	10^{-4}	~100 mm	• adaptable to curved or very long magnets • longitudinal field profile requires deconvolution
Stretched wire (moving)	$>10^{-3}$	DC	10^{-4}	∅ 0.1 mm < 20 m	• calibration reference for integral field strength, direction and axis (precision of the XY stages) • equivalent to 1-turn variable-geometry coil • best geometrical flexibility (long magnets, narrow gaps)
Stretched wire (vibrating)	$>10^{-3}$	DC	10^{-4}	∅ 0.1 mm < 20 m	• extremely sensitive for axis (at resonance) • only option for harmonics in small gaps • longitudinal resolution possible via FFT (λ>0.1 m)
Hall probe	$>10^{-4}$	$<10^{4}$	$\sim10^{-3}$	<1 mm^2	• widespread, vast range of commercial options • high accuracy requires laborious calibration
NMR probe	>0.043	<20	10^{-6}	1 cm^3	• metrological golden standard • works only in highly uniform fields • limited bandwidth; provides field vector norm
Fluxgate	$>10^{-8}$ $<10^{-3}$	$<10^{2}$	10^{-3}	1 cm^3	• geomagnetic and environmental field applications • fringe fields, residual field, safety

Typical transversal vs. longitudinal size

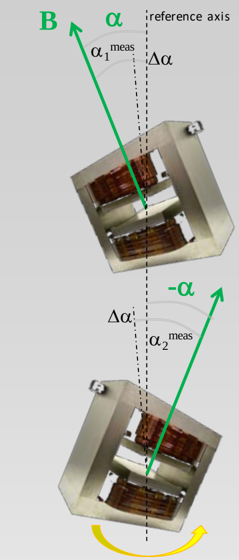


Typical accuracy vs. field range

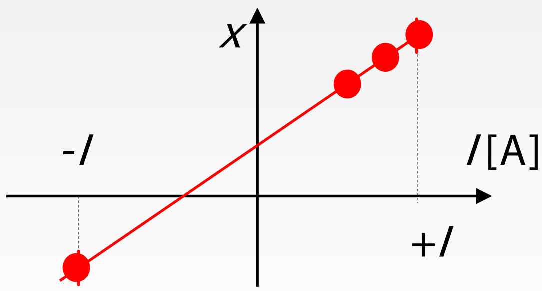


The **standard uncertainty** of an instrument is a certified function of the **operating conditions** (field range/frequency, gradient, temperature etc. …) can be further improved based on the **time and effort** taken

- Repeat to get rid of random errors: $\sigma(\langle x \rangle) = \frac{\sigma(x)}{\sqrt{n}}$
  (diminishing returns for large *n*)
- Oversample (time/angle) to reduce aliasing
  (e.g. MHz sample rate for kHz bandwidth → much improved drift correction)
- Flip and repeat to estimate and subtract systematic errors
  either the magnet or the instrument, as is more practical
- Reverse polarity to recover ambient or intrinsic offsets
  (e.g. remanent field)
- Redundant takes will give you confidence !



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



$$x(0) = \frac{x(I) + x(-I)}{2} \qquad \frac{dx}{dt} = \frac{x(I) - x(-I)}{2}$$

Instrument selection criteria

"hard" criteria

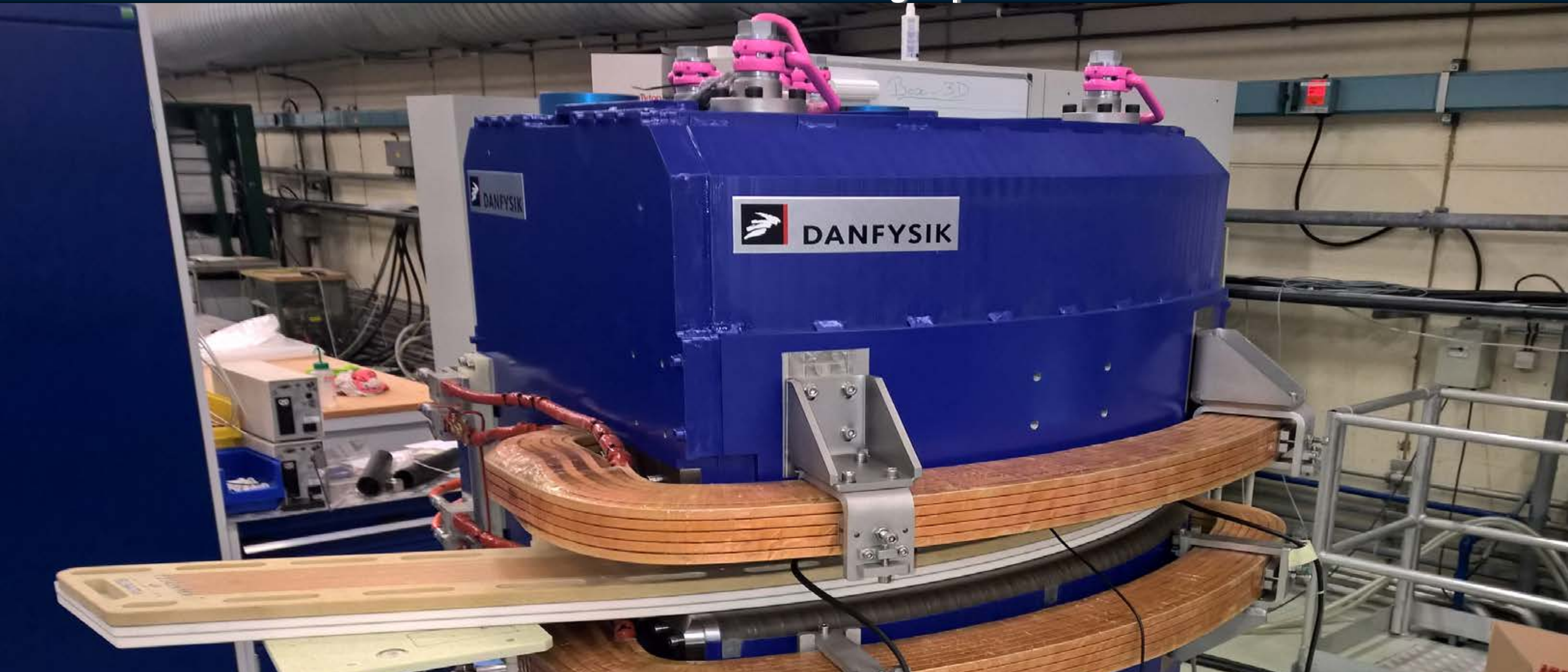
1) **Compatibility** with field level/gradients (could not work at all!)
2) **Transverse size** (it must fit, and should reach as wide as possible)
   - local ripple close to the pole may degrade the accuracy of harmonics
   - extrapolation further from the axis can be applied, at a cost

"soft" criteria

3) **Bandwidth**
   - sensitivity may drop above cutoff
   - additional errors e.g. from inductive cable loops
4) **Longitudinal size**
   - the integral can be computed by scanning longitudinally (time-consuming)
   - de-convolution of longitudinal scans done with a longer probe → low-pass filter, noise
5) **Accuracy**
   - uncertainty can be reduced by repetition, changing orientation, cross-checks …
6) **Result format**: harmonics vs. map (1D/2D/3D)
   - can be translated into one another, with caveats
7) **Practical considerations**: cost, measurement time, output signal format, cabling length, commensurate size of sensors and magnet, availability of trained personnel …

Example: cross calibration of a curved fluxmeter

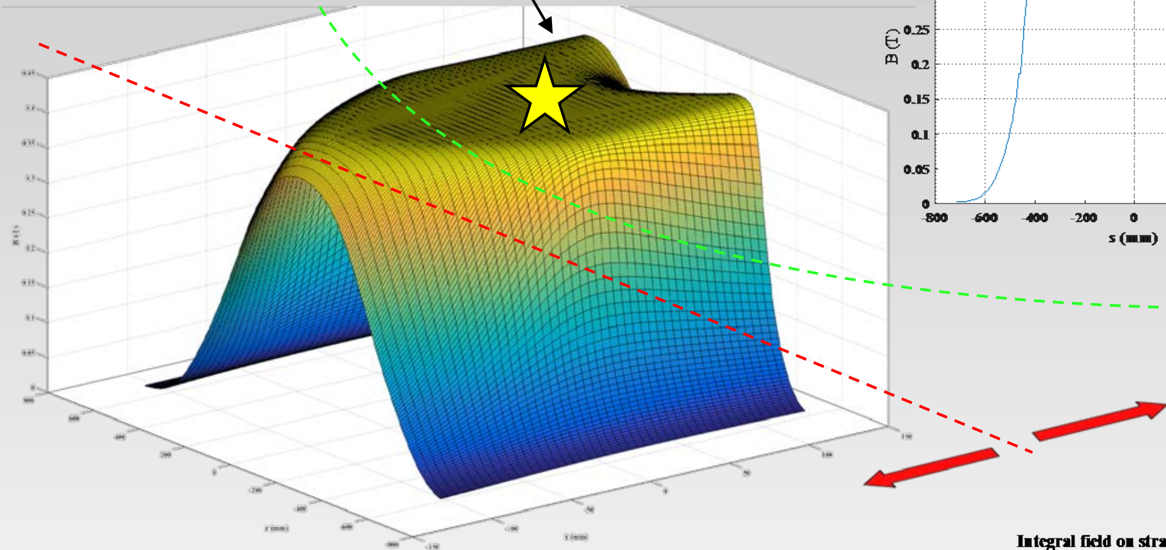
CERN ELENA bending dipole



- Difficult case: 60° bending, low-energy pbar ring → low field (50 to 420 mT), accelerating & decelerating cycles, 2 min-long long e-cooler plateaux
- 0.5 mm laminations with high dilution 2:1 electrical steel M270-50 A HP/304 L to reduce hysteresis; 13° cut angle for focusing
- Measured with Litz-wire fluxmeter (see O. Dunkel, IMMW19), with 2% coil area uncertainty originally intended as a backup for higher quality PCB unit

Multi-reference cross-calibration

(2) Central NMR for high-field calibration

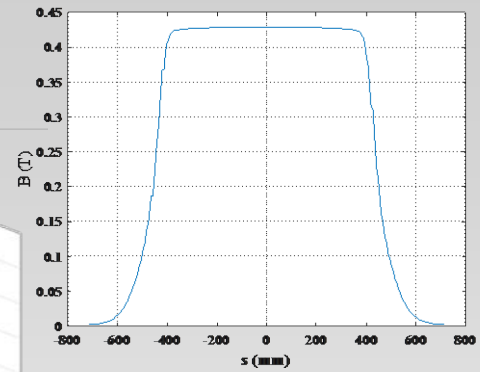


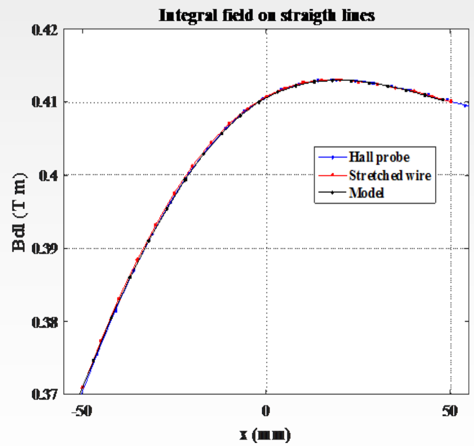
(1) 2D Hall probe map on the mid-plane

(4) Hall probe gain and offset calibration

$$B' = \Delta B + (1 + \varepsilon)B$$

(5) Integral of B' interpolated on a curved path to match fluxmeter coil



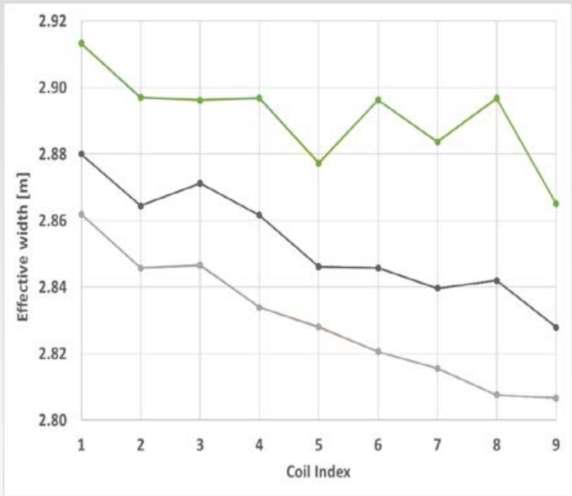


(3) Integral calculated along straight lines matched to Stretched Wire

independent remanent field measurement

pulsed-mode fluxmeter coil measurement

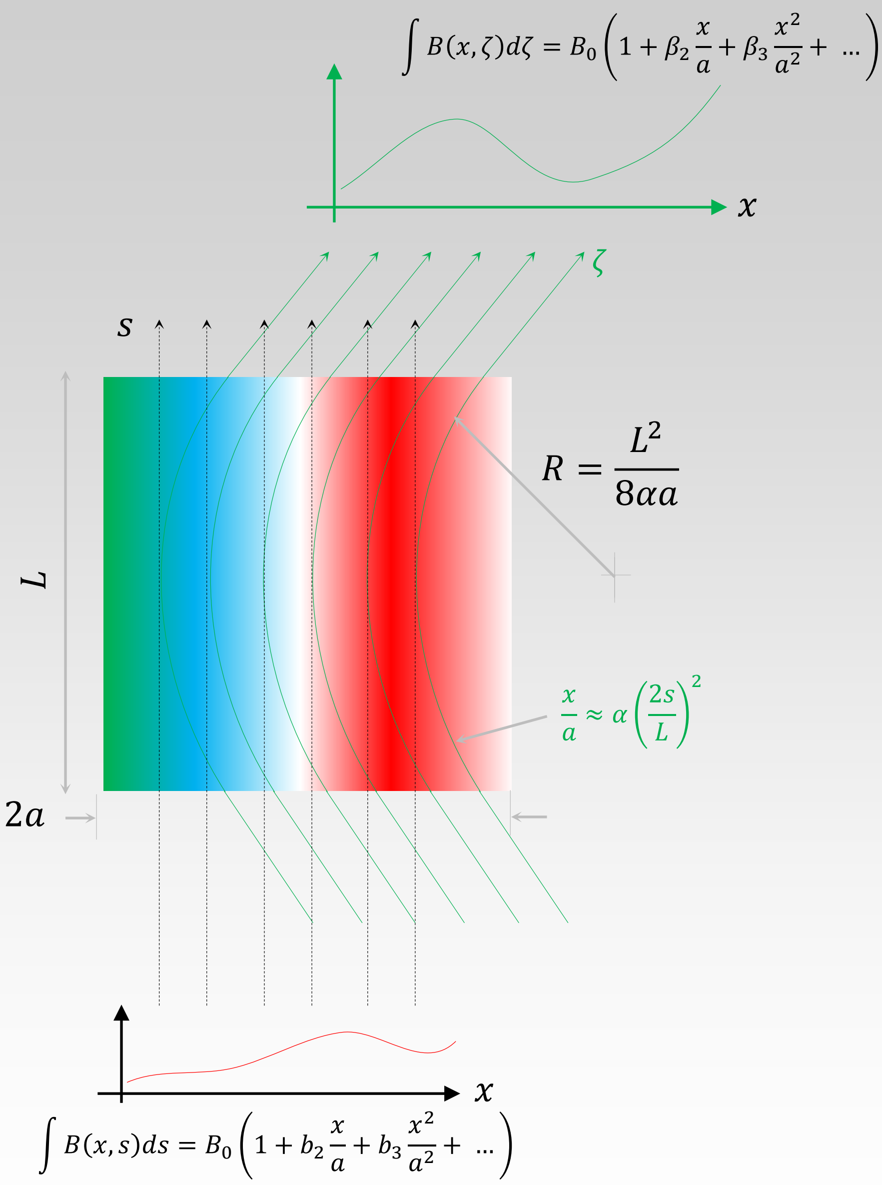
$$w_{eff} = \frac{\Phi_0 + \int_0^t V_c dt}{\int_{-\infty}^{+\infty} B'(s) ds}$$



final result (3× 9-coil fluxmeters)

Courtesy of Lucio Fiscarelli

Is measuring along a curve truly necessary ?



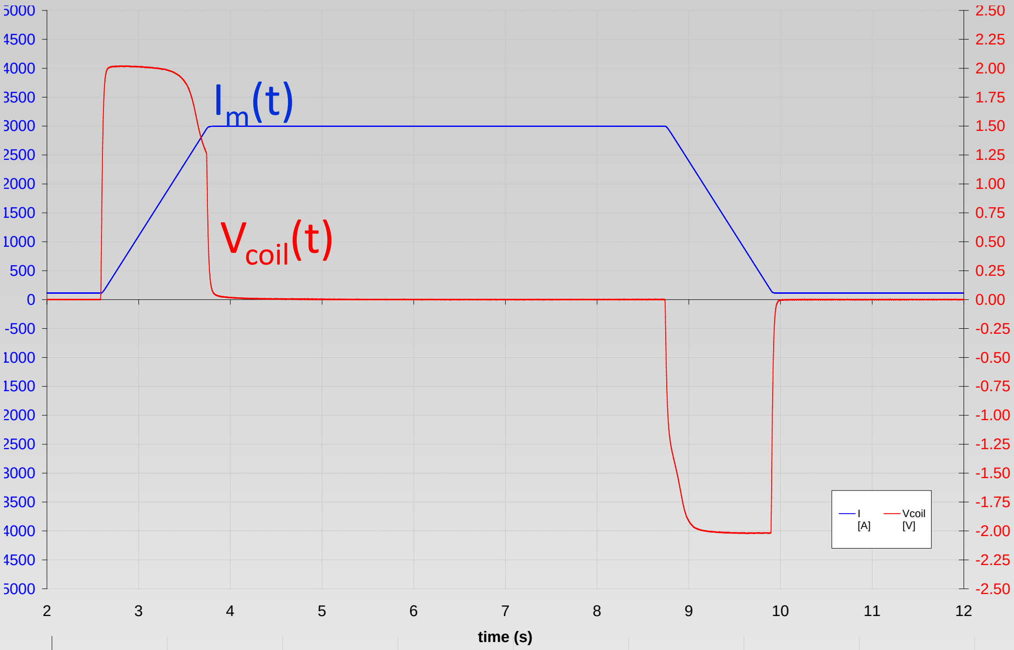
- Simplest example: hard-edge dipole field distribution, uniform along *s*
- Let $\{b_n\}$ be the transversal harmonic expansion of the integral along straight lines
- Let $\{\beta_n\}$ be the transversal harmonic expansion of the integral along arcs of radius *R*
  (approximated by parabolas with negligible loss of accuracy)
- $\{b_n\}$ and $\{\beta_n\}$ are connected by a feed-down-like linear relation:

$$\begin{Bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \\ b_5 \\ b_3 \end{Bmatrix} = \begin{bmatrix} 1 & \frac{\alpha}{12} & \frac{\alpha^2}{80} & \frac{\alpha^3}{448} & \frac{\alpha^4}{2304} & \frac{\alpha^5}{11264} \\ 0 & 1 & \frac{\alpha}{6} & \frac{3\alpha^2}{80} & \frac{\alpha^3}{112} & \frac{5\alpha^4}{2304} \\ 0 & 0 & 1 & \frac{\alpha}{6} & \frac{3\alpha^2}{40} & \frac{5\alpha^3}{224} \\ 0 & 0 & 0 & 1 & \frac{\alpha}{3} & \frac{\alpha^2}{8} \\ 0 & 0 & 0 & 0 & 1 & \frac{5\alpha}{12} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \\ \beta_4 \\ \beta_5 \\ \beta_3 \end{Bmatrix}$$

field integrals along straight and curved paths contain the same amount of information

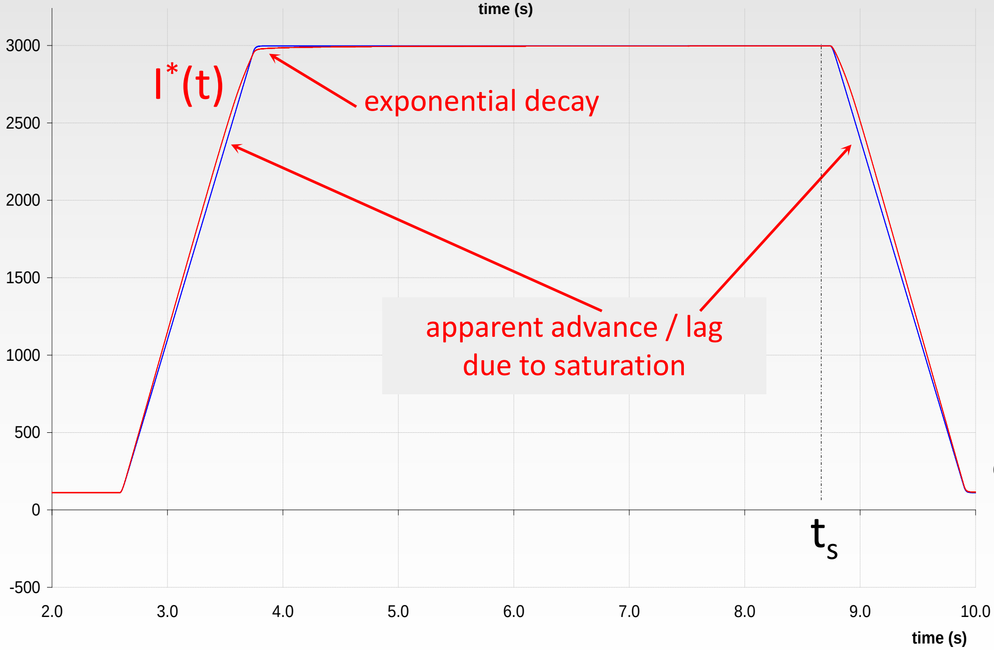
Measurement and control of dynamic & cycling effects

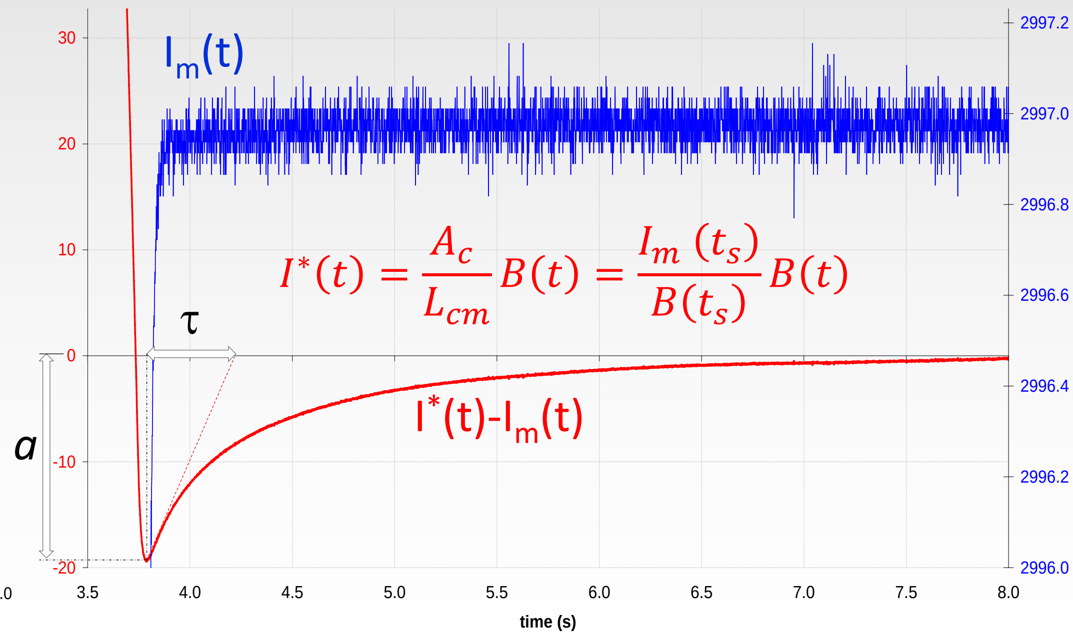
Measurement of eddy current effects

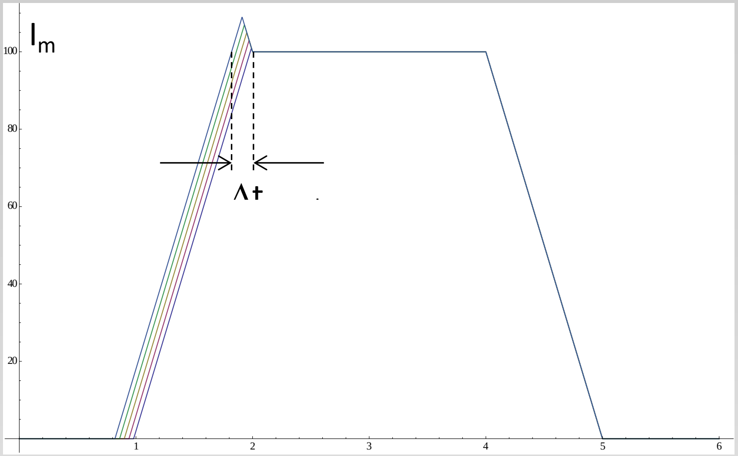


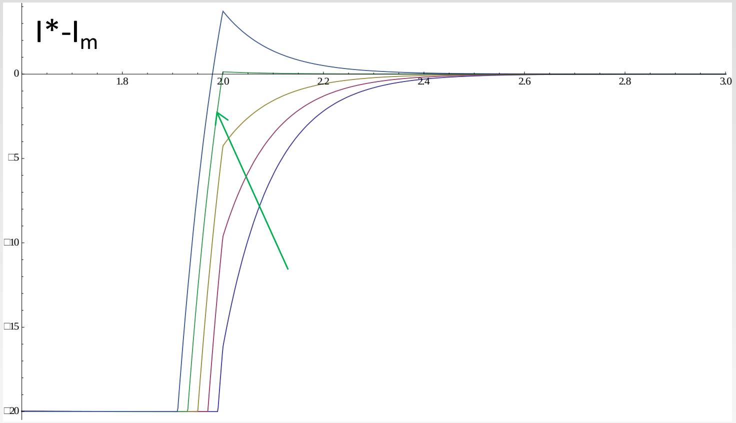
- Method: current plateaux of duration >> expected τ
- High-speed acquisition of integral coil voltage → detailed profile of I^*-I_m
- The relative amplitude $a/I_m(t_s)$ and logarithmic decay ratio τ of the exponential starting at the end of the ramp = eddy current effect
- Scaling law for the time constant:

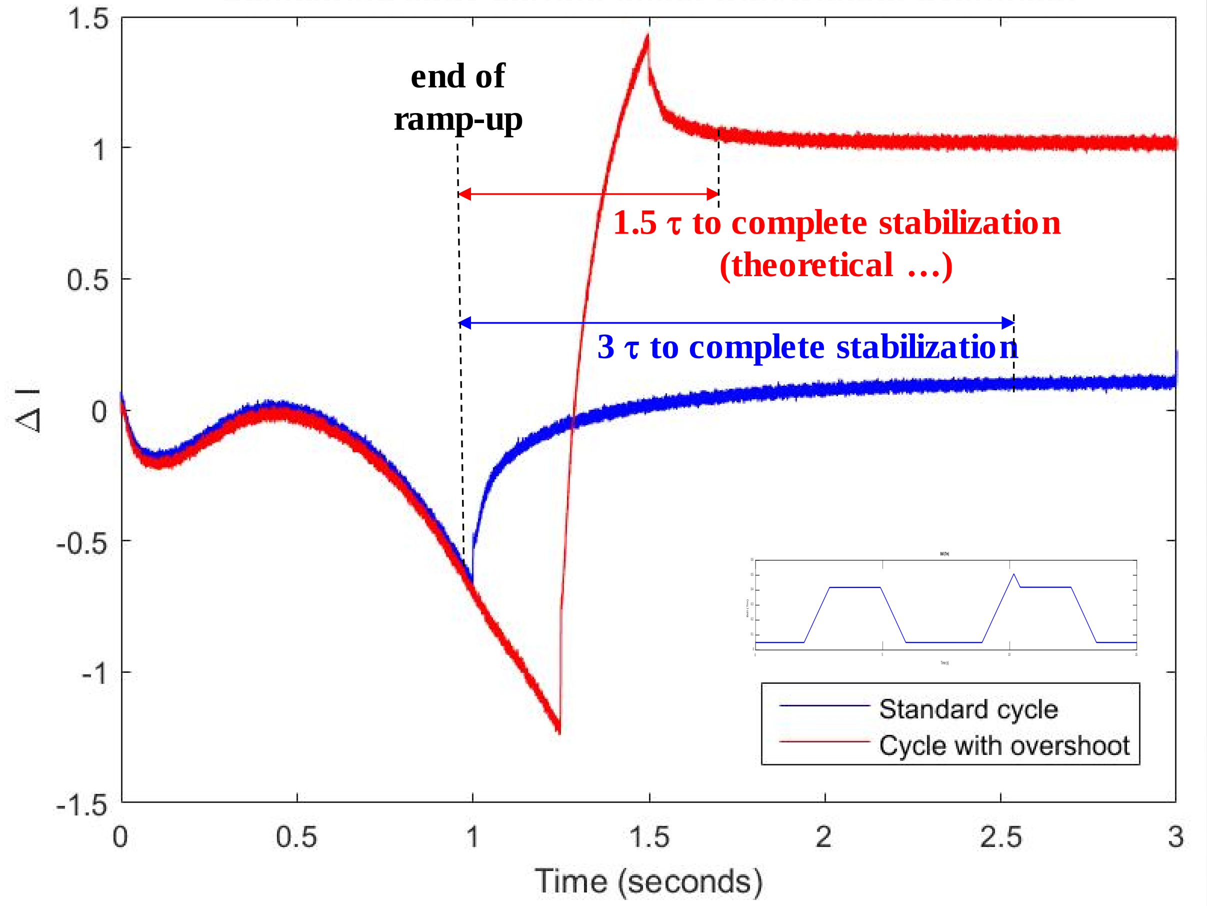
$$\tau = \frac{L_e}{R_e} \propto \frac{\ell}{\ell/\ell^2} = \ell^2$$





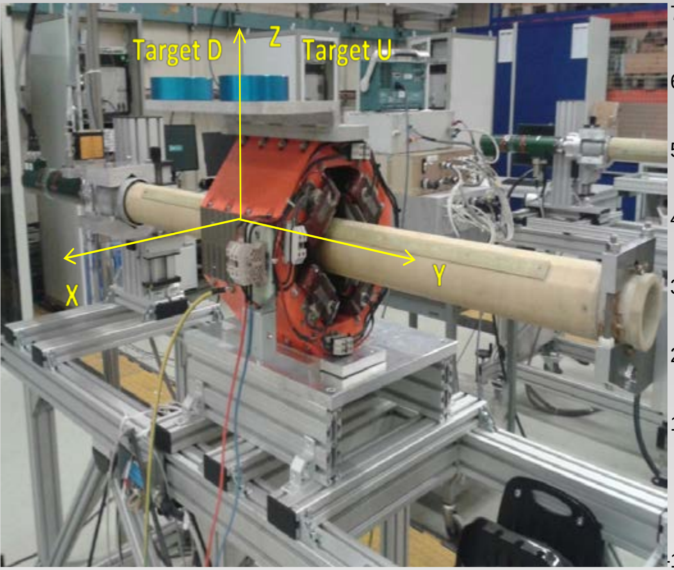


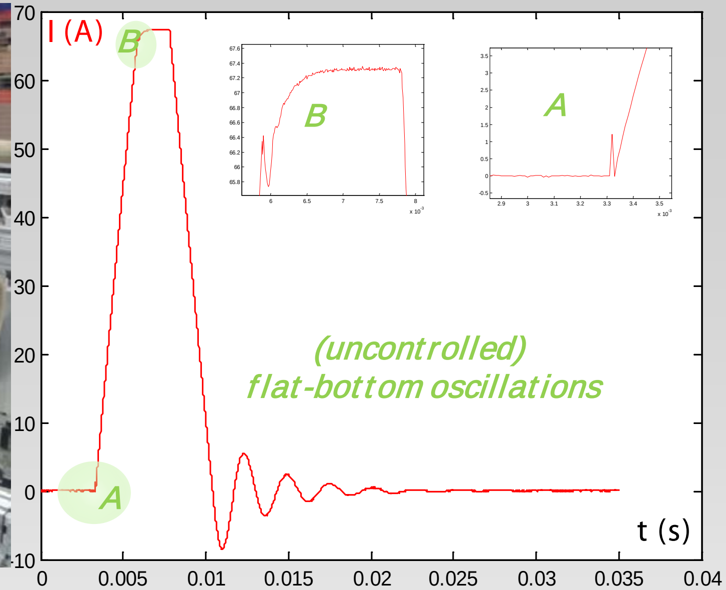


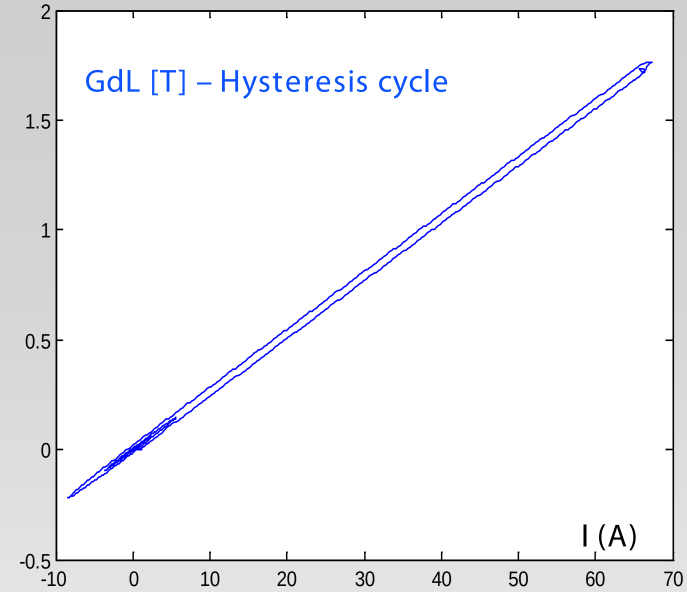


- Eddy currents can be partially, totally or over-canceled by a triangular current overshoot at the end of ramp-up
- Example: stable flat-top reached at the time cost of ~1.5τ (to be compared with exponential decay time ~3τ)
- Caveats: - power converter needs high dV/dt;
  - the maximum working point may increase considerably, at the risk of saturation
  - hysteresis → final field level changes (new limit cycle, still OK if stable)

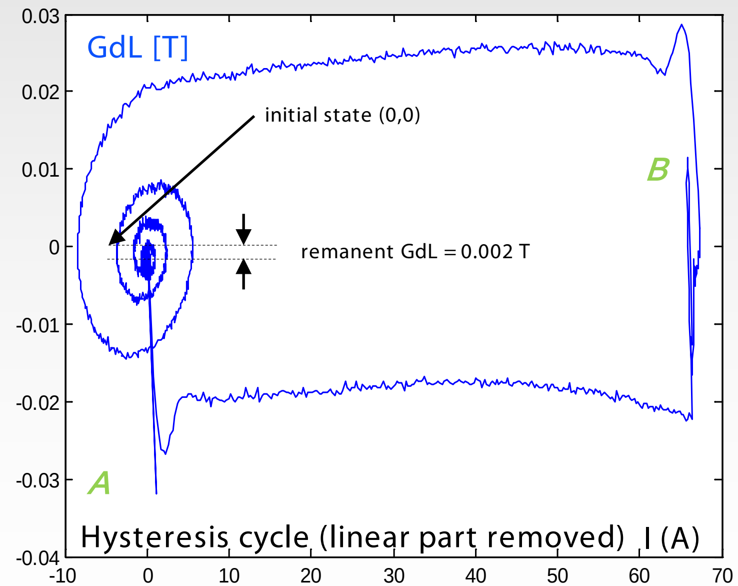
Fast-cycled quads







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



Courtesy Samira Kasaei```

- Magnetic after-effect (**magnetic viscosity**): class of relaxation phenomena linked to the magnetoelastic interaction between ferromagnetic domain walls and crystal lattice leading to a lag between H and M
- Logarithmic time-dependence is a function of relaxation times distribution and is valid at intermediate time scales

$$\Delta M \propto k_B T \log t$$

- All ferromagnetic metals are affected
- does not depend on the geometry (unlike eddy currents)
- weakly correlated with field level and initial ramp rate
- strongly dependent upon temperature
- In soft steels: small effect, large time constant → can usually be ignored

- **Disaccommodation:** after-effect on the initial permeability

- Magnetic ageing: irreversible phenomena affecting the metallurgical nature of the steel (precipitation, diffusion, crystal phase transition) on long time scales

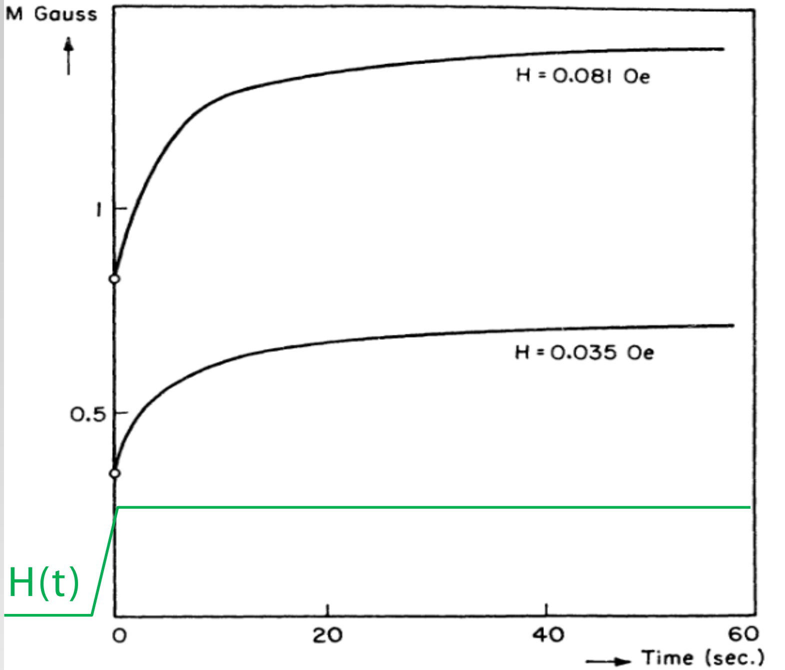


Fig. 1—Magnetic Viscosity As Measured on a Wire of Wrought Iron. Demagnetization ended at t = o. (After Ewing)

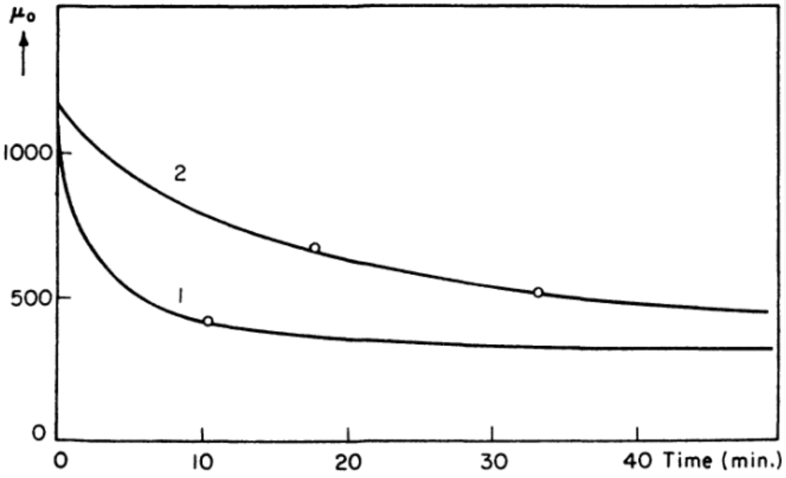


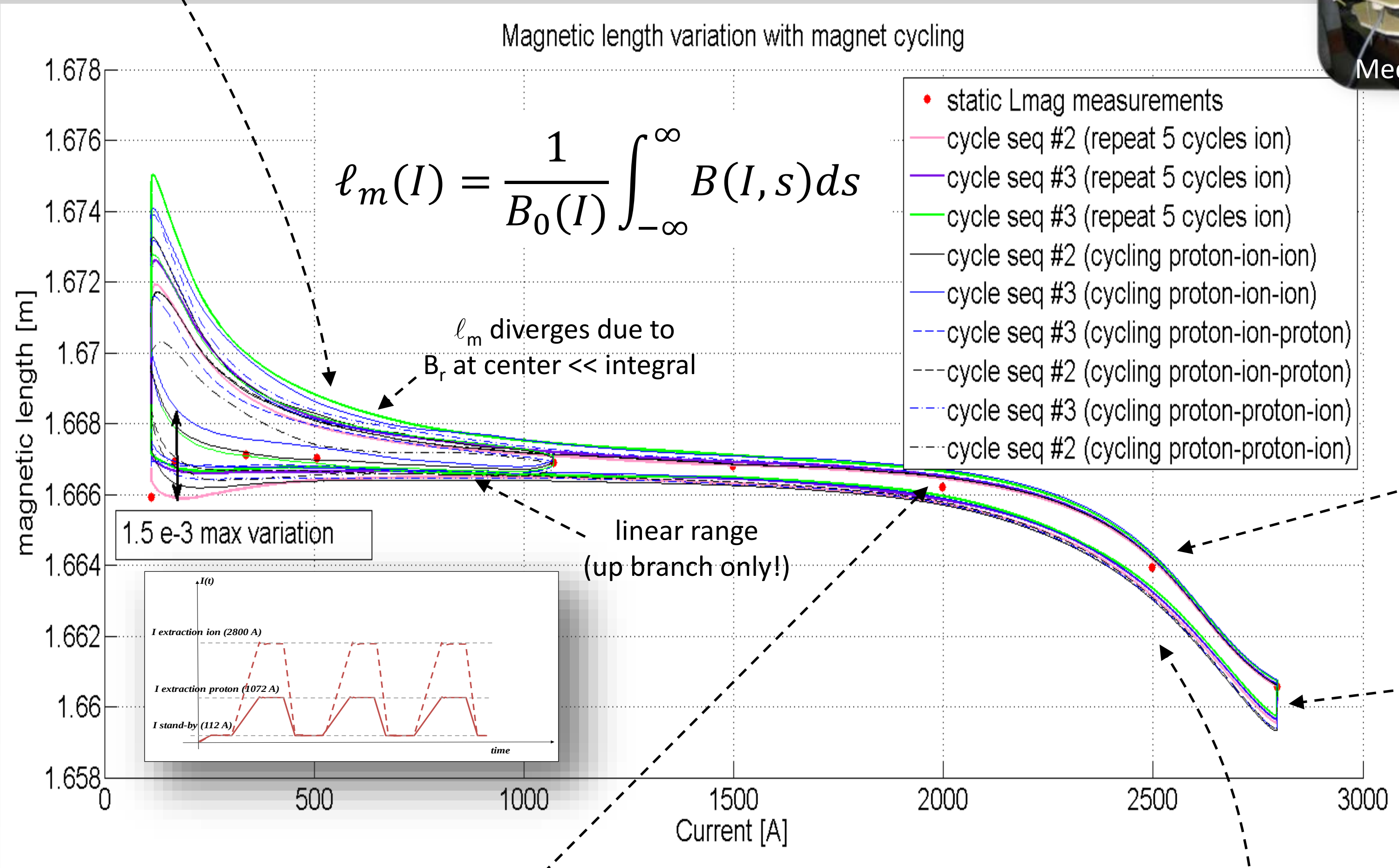
Fig. 3—Time Decrease of Initial Permeability (Disaccommodation) for Carbonyl Iron Containing Interstitials. Demagnetization at t = o. Curve 1: 249 °K. Curve 2: 236.4 °K. (After Snoek)

marco.buzio@cern.ch

Non-linear features in iron-dominated magnets (1/2)

large fluctuations due to history-dependent residual field

reproducibility degrades at low field



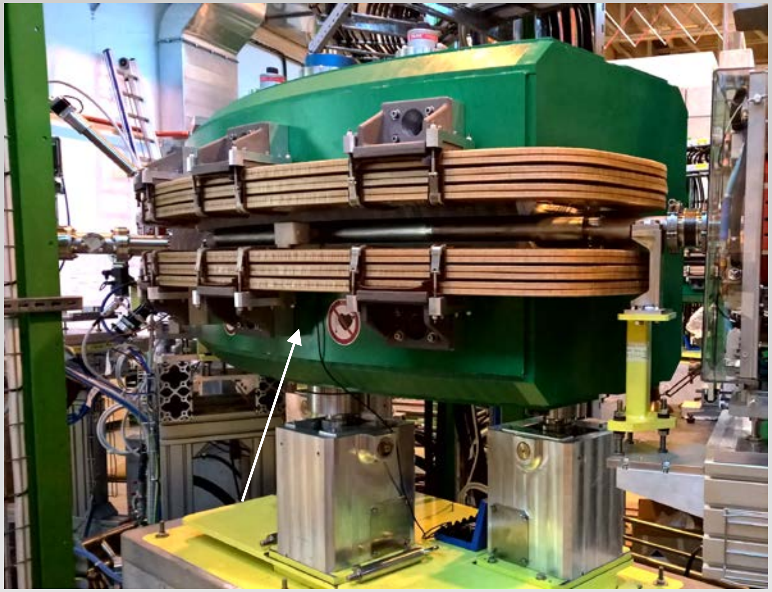
central coil replaced by NMR (DC cross-check)

saturation tends to erase previous magnetic history

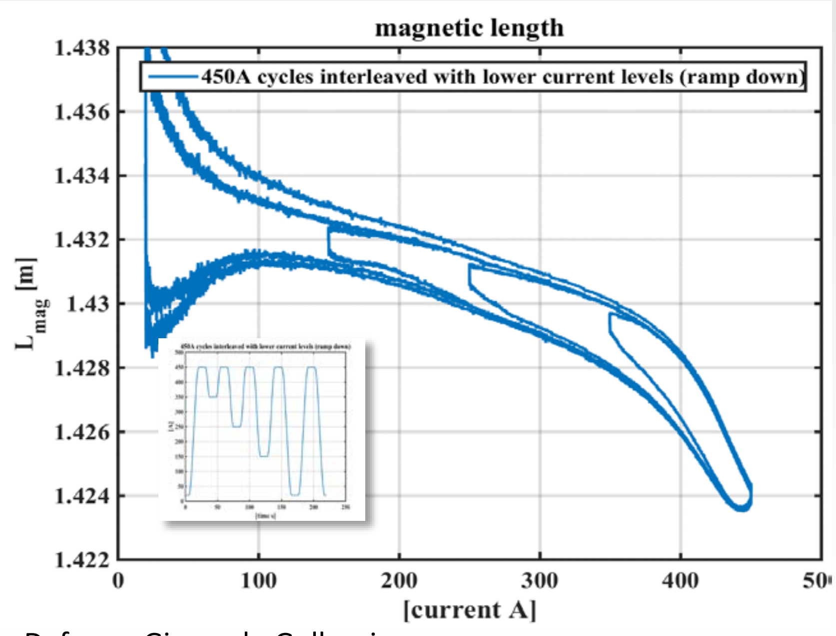
→ better reproducibility at high field

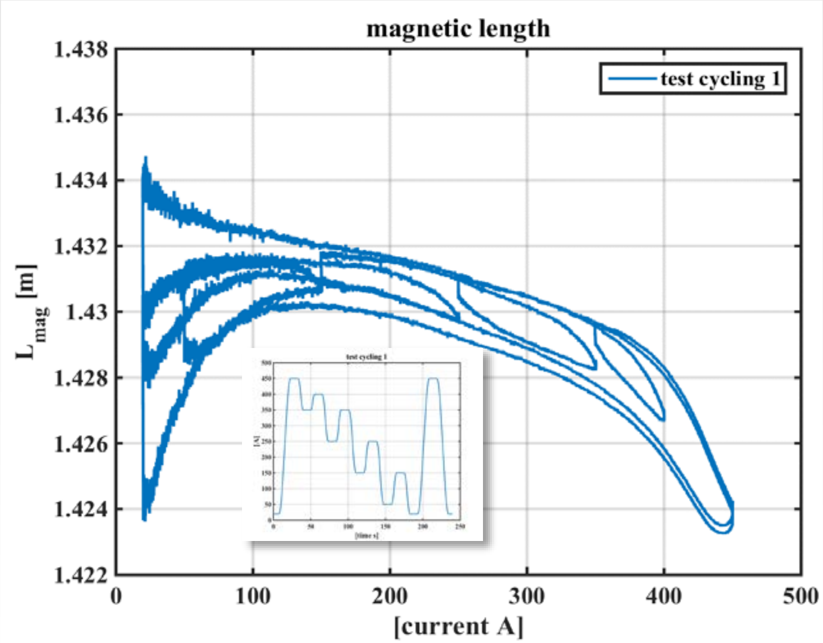
Courtesy Anthony Beaumont, Giancarlo Golluccio

Non-linear features in iron-dominated magnets (2/2)



- Transfer line bending in the ISOLDE heavy isotope test facility
- Minor loops span the whole width of the major hysteresis cycle
- Open loop control: « random » cycling → 0.7% errors
- Missing linear range ?!

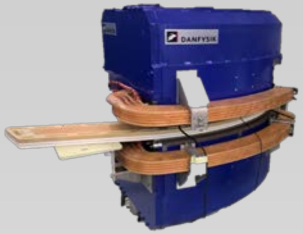




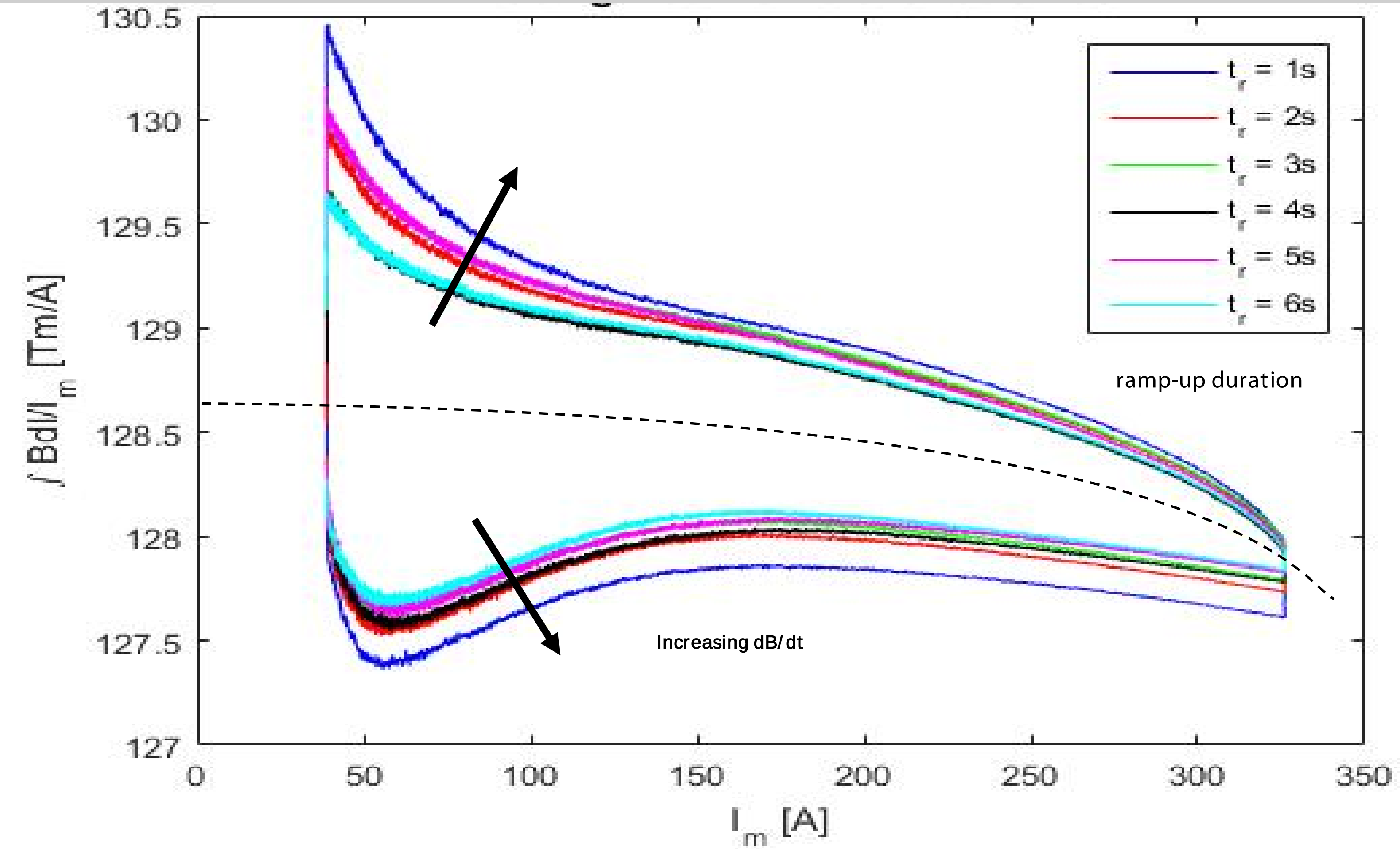
Courtesy Guy Deferne, Giancarlo Golluccio

Hysteresis + eddy currents

ELENA
bending dipole



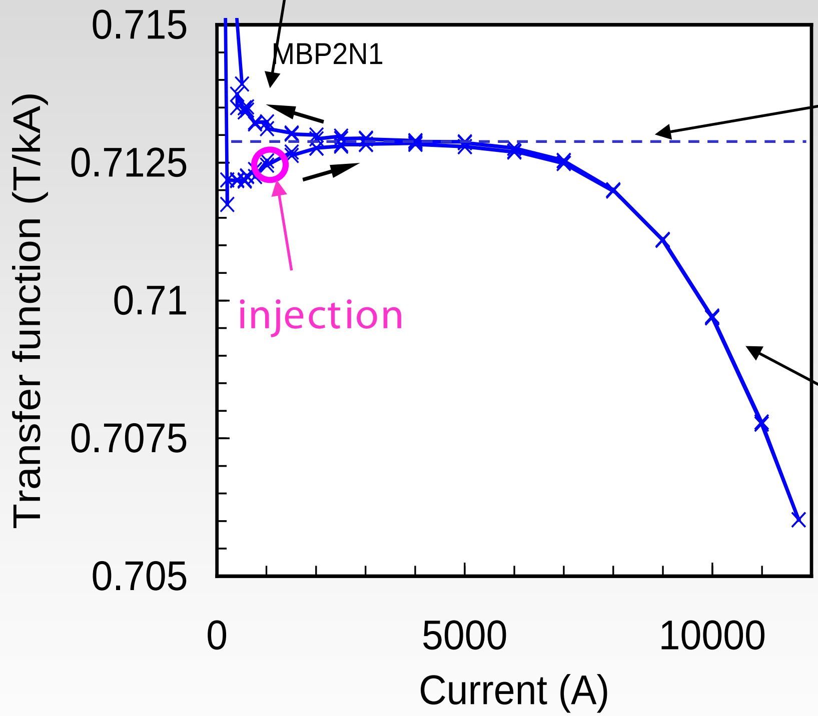
fixed-coil
measurement



- Aim: extrapolate dynamic measurements to DC to predict behavior at arbitrary dB/dt
- Eddy currents $\propto$ dB/dt $\rightarrow$ both field lag and dissipation (hysteresis loop area) $\propto$ dB/dt
- Measurement result not so ideal … loops cross each other, more drift on slower cycles
- hysteresis/drift effects need to be corrected by absolute measurements on the plateaux

Superconducting filament magnetization (persistent eddy currents)

- large hysteresis with relative errors of the order of 10^{-3} at low field (injection)
- hysteresis depends on temperature, current and current history (negligible at high field)
- main field and multipoles affected in different ways



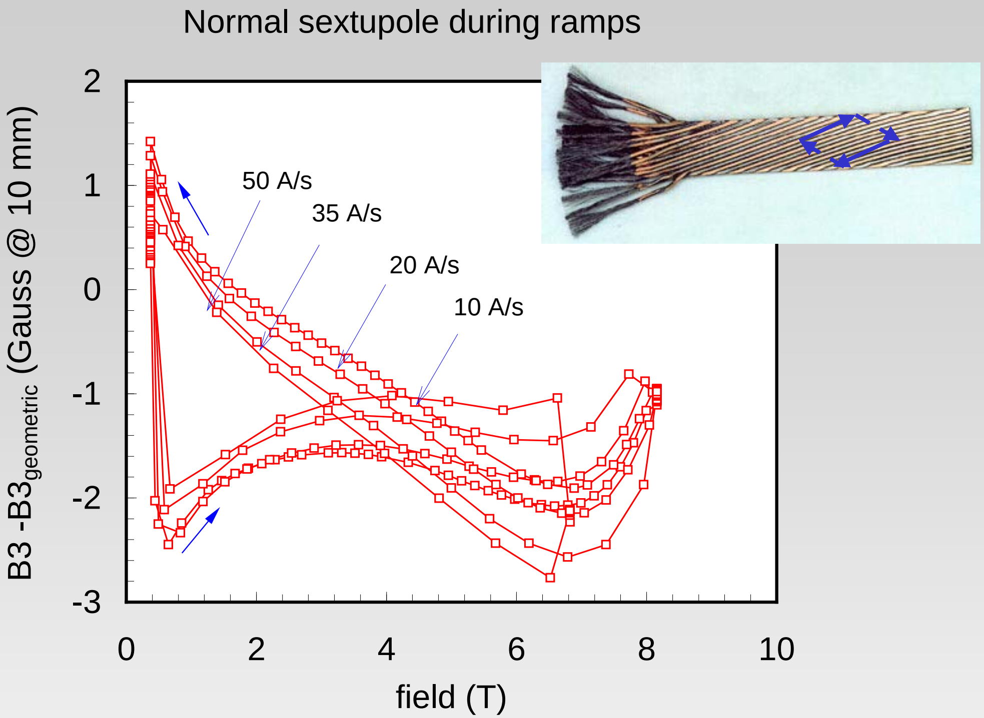
Linear regime (geometric contribution)

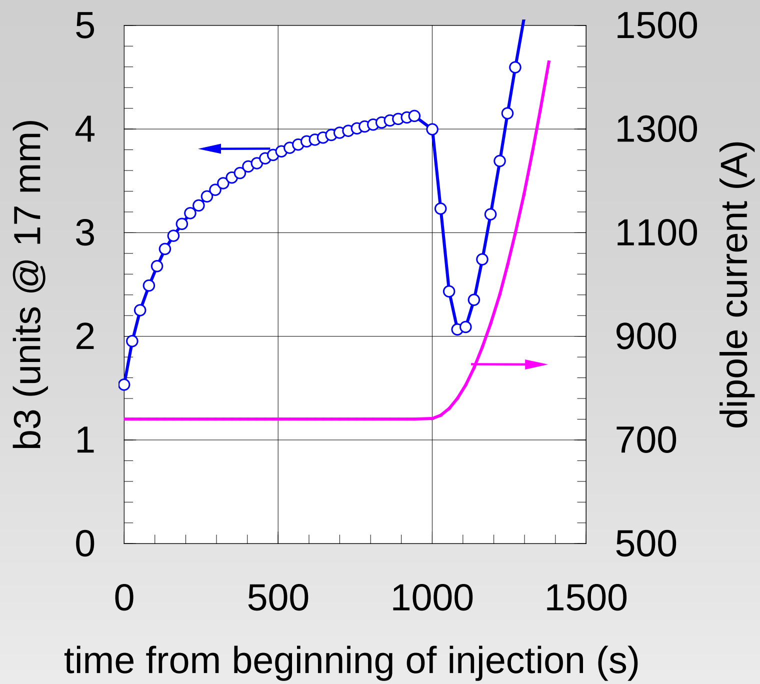
- field is proportional to the current (can be computed with Biot-Savart's law)
- the T.F. depends only on the coil geometry

Iron saturation

- affects only small area in the collar (B>2T)
- relative errors ~ 1% at high field
- additional multipoles generated

marco.buzio@cern.ch





Coupling currents

- finite inter-filament and inter-strand resistance (R_C) gives rise to loops linked with changing flux
- multipole errors $\propto \dot{B}, R_C^{-1}$
- hysteresis depends upon field level, temperature and powering history

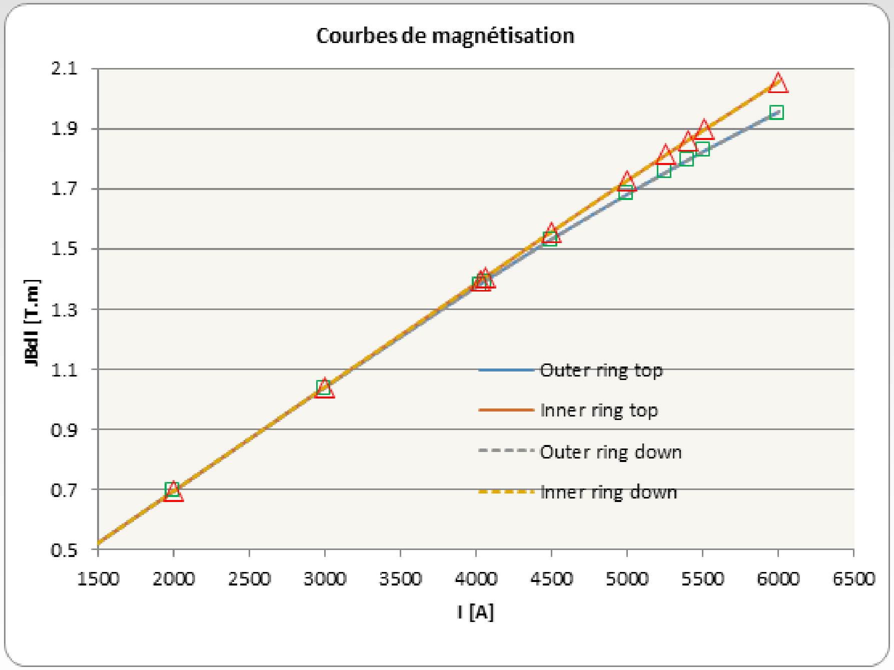
Decay and snap-back

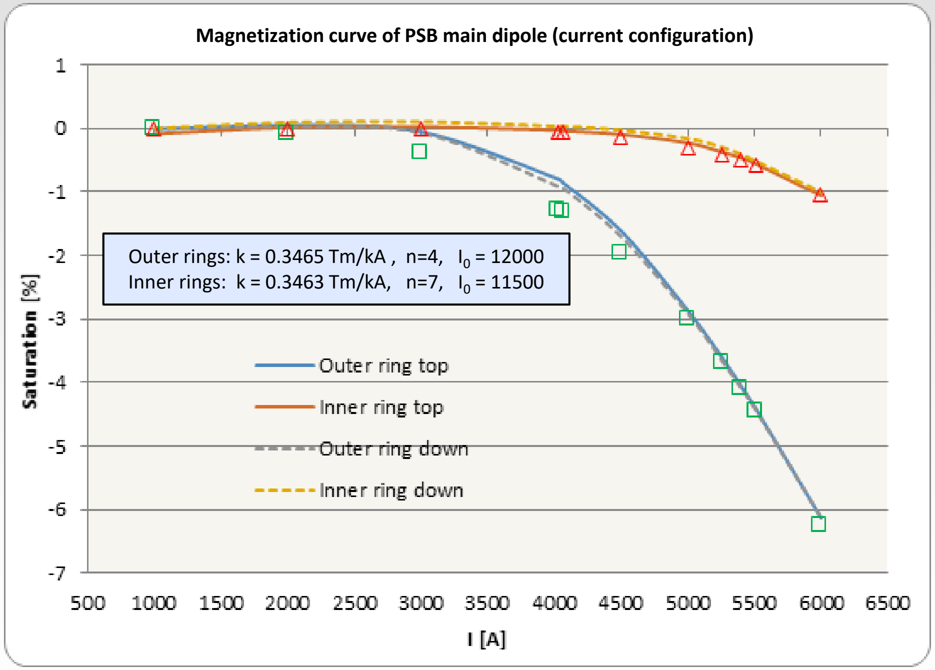
- superconductor magnetization and coupling currents interact in a complex way → long-term logarithmic time dependence effects (field decay)
- hysteresis branch switching at the end of decay → sudden current redistribution and additional multipole errors (snap-back)

Saturation modelling

- Qualitative example: anhysteretic transfer function
- Simple analytical interpolation, too coarse for open-loop field control but adequate for inner-loop power converter control

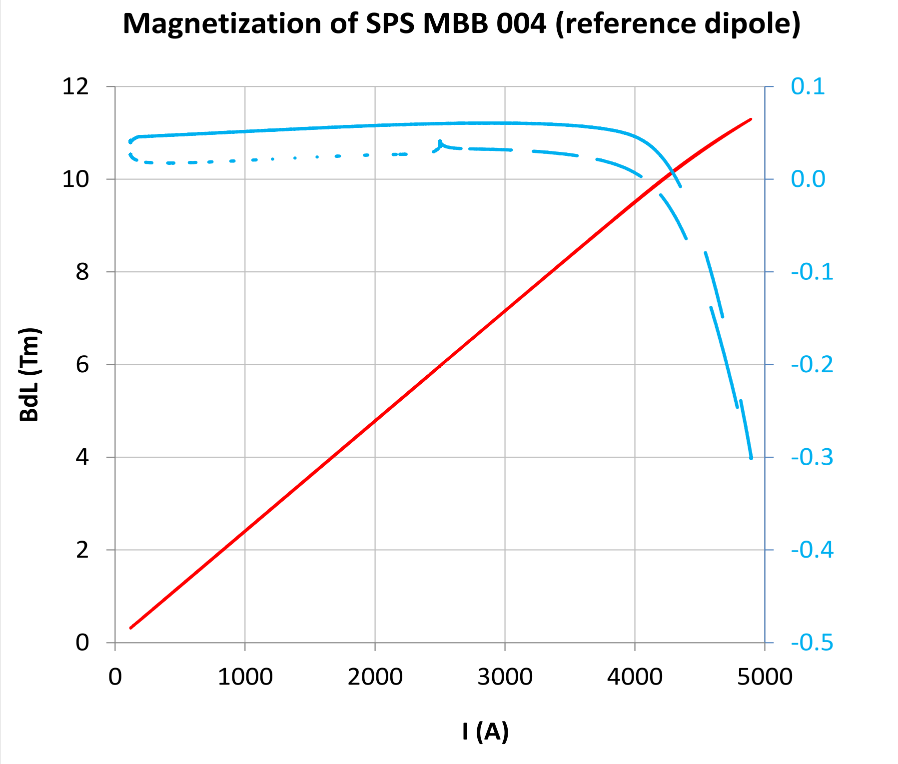
$$\frac{\int Bd\ell}{I} = k\left(1 - \left(\frac{I}{I_o}\right)^n\right) \qquad L = \frac{\Phi}{I} = N_t\, w_p \frac{\int Bd\ell}{I} = L_0\left(1 - \left(\frac{I}{I_o}\right)^n\right)$$

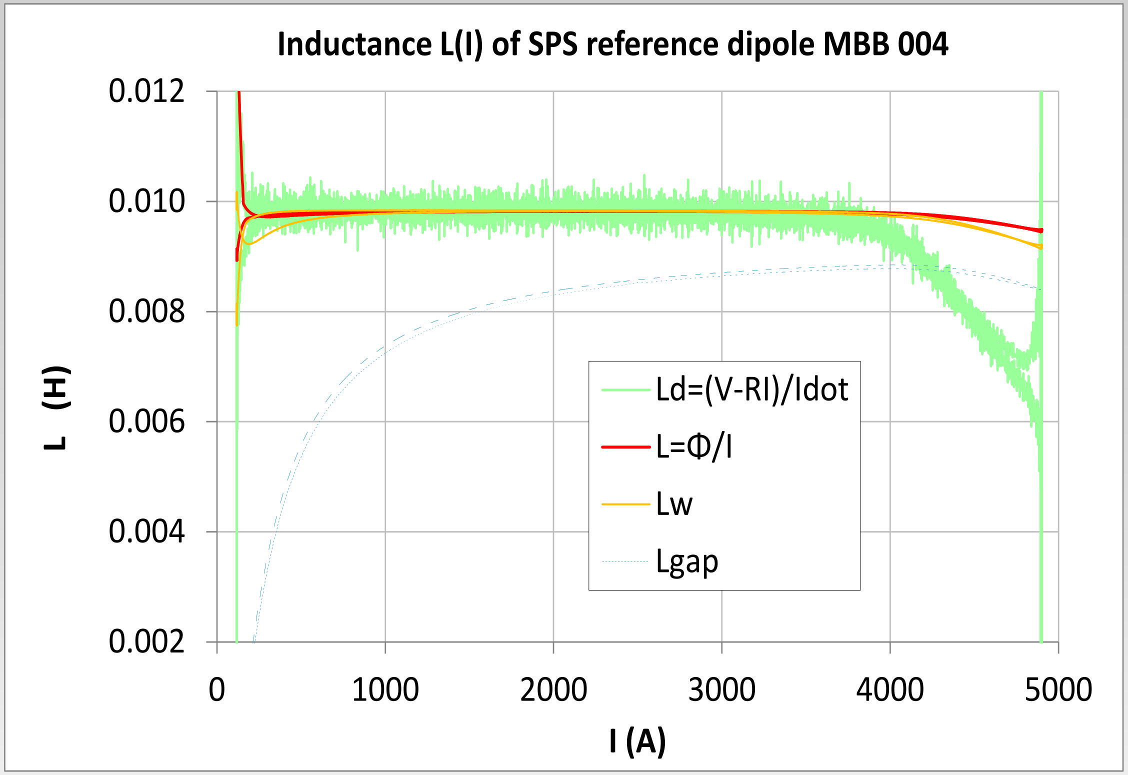




Regos

Inductance modeling





$$V = RI + \frac{d\Phi}{dt} = \mathrm{RI} + L_d \frac{dI}{dt}$$

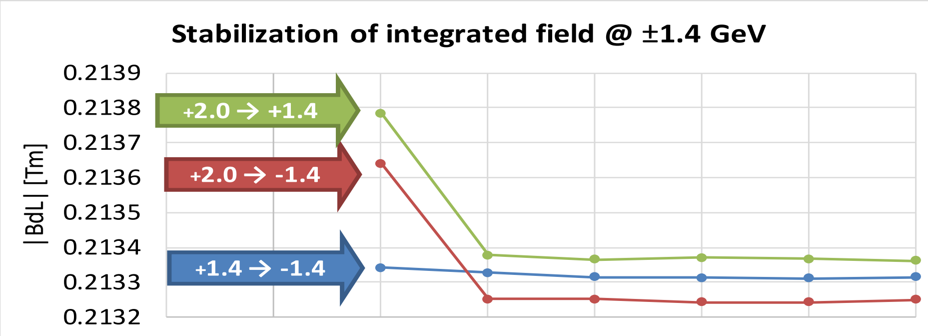
$$L_d = L + I\frac{dL}{dI} = L_0\left(1 - (1+n)\left(\frac{I}{I^*}\right)^n\right)$$

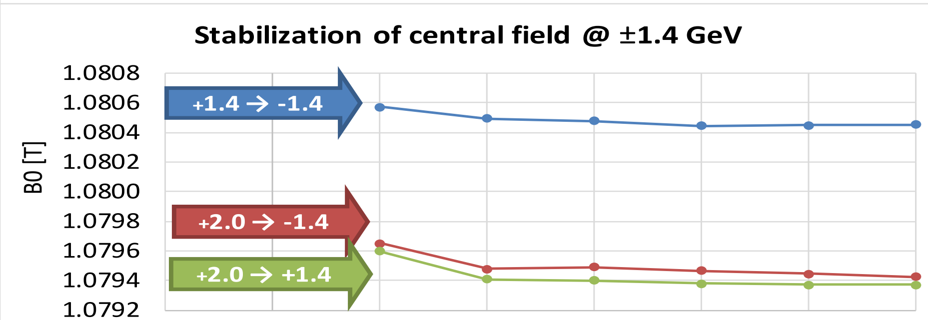
- A large drop of the differential inductance at saturation is to be expected even for mildly saturated magnets. E.g. SPS main dipoles: field saturation 3.4% differential inductance saturation of 40%.
- Measurement of the inductance curves can be easily done in parallel with standard magnetic tests.
- If this is not possible, the drop of differential inductance may be estimated from the model of field saturation

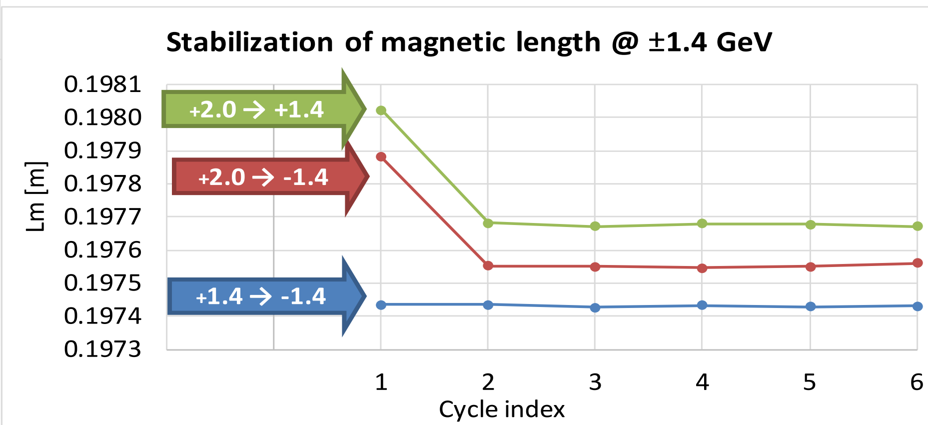
Rapid Cycling Synchrotron bending prototype

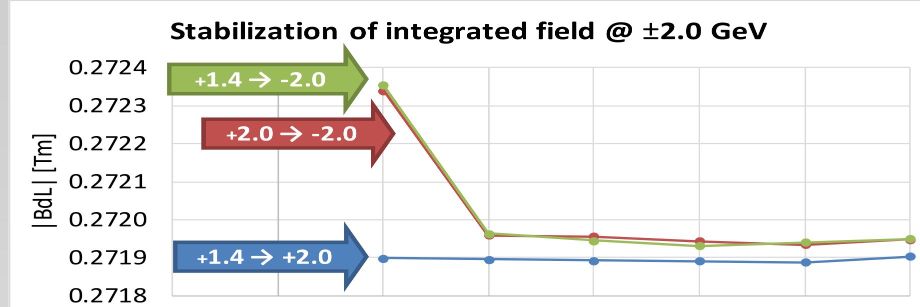
- Dipole prototype optimized for a possible future RCS with 100 ms cycle time
- 0.3 mm Si-steel laminations
- ideal testbed to decouple hysteresis from dynamics

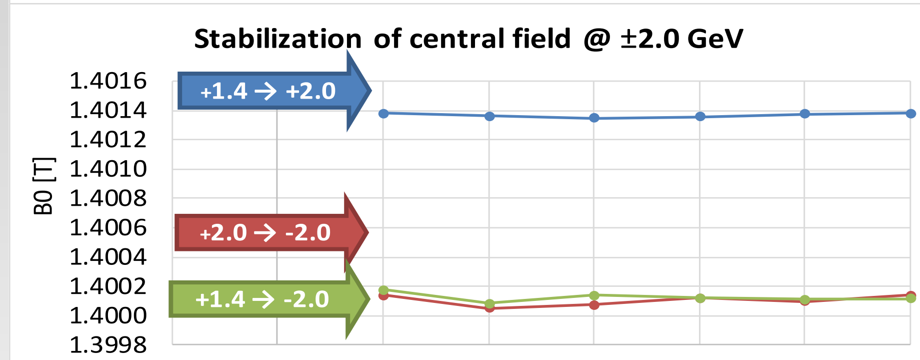
Bipolar repeatability on RCS

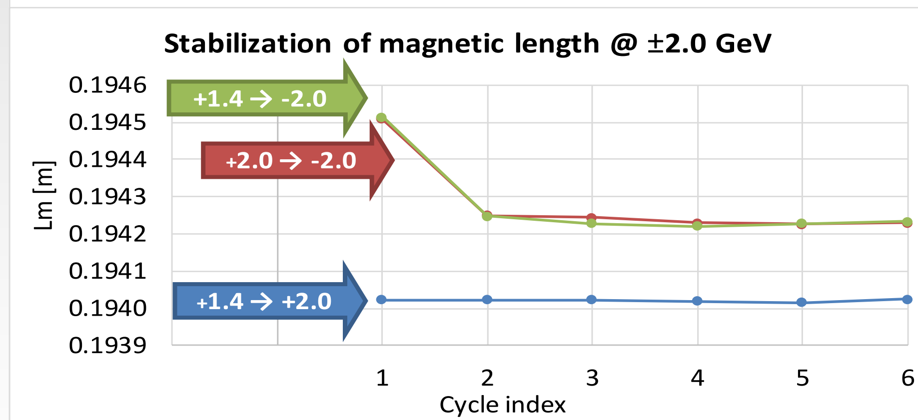






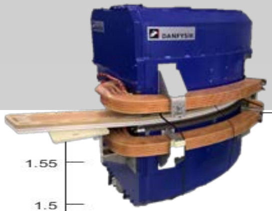




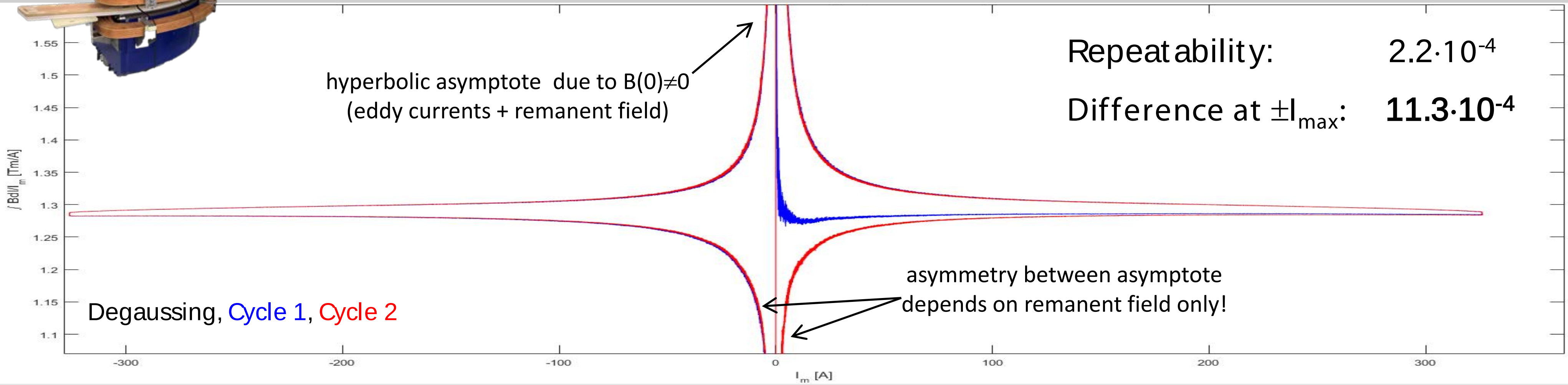


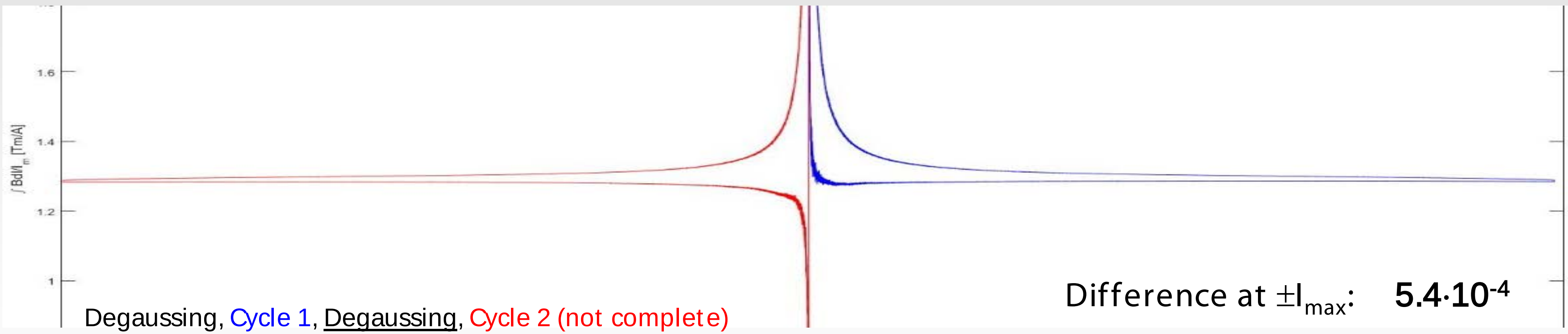
- cycles simulating all possible transitions between ±1.4 and ±2.0 GeV beams in the new PSB extraction switch
- field errors up to **$2{\cdot}10^{-3}$** just after a transition
- field errors **down to $4{\cdot}10^{-5}$ after two repeated cycles**

Bipolar reproducibility



Integral transfer function in ELENA bending dipole: $\frac{\int B d\ell}{I}$





- Example: bipolar operation of ELENA bending dipole
- An additional intermediate degaussing cycles improves repeatability by a factor 2 (but constrains and delays operation !)

Magnetic stabilization

- Reproducibility of magnetic field improves by resetting the magnetic state with current pre-cycles
- The operating mode of the magnet should be respected:

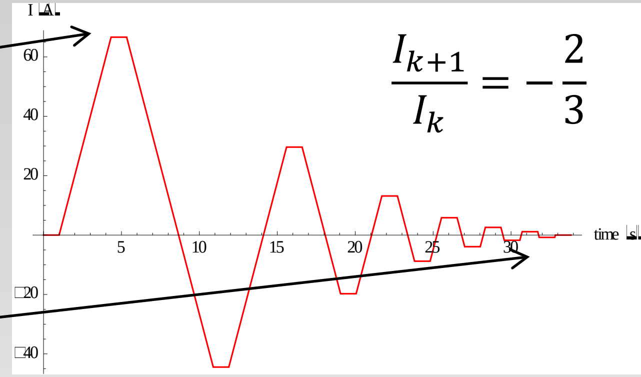
Bipolar magnets

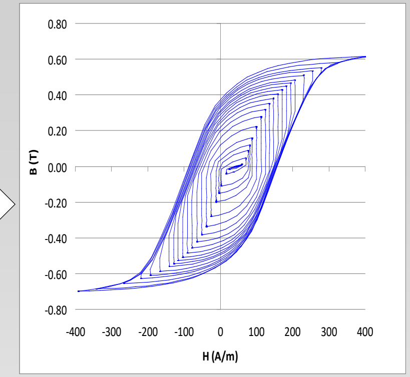
- steerers
- correctors
- switching dipoles
- experimental magnets

→ **degaussing**

maximum current injected

power supply resolution





NB: “real” demagnetization requires T≥T_{curie} ≈ 948 °C !!

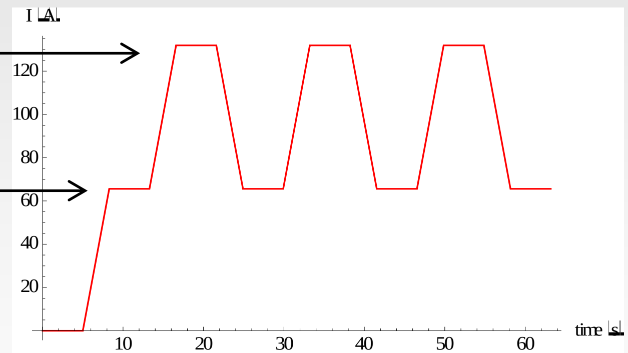
Unipolar magnets

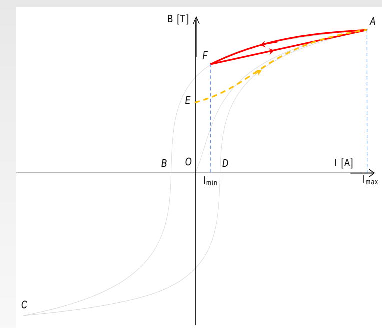
- main ring bending/quads

→ **pre-cycles**

maximum current in operation

minimum current in operation





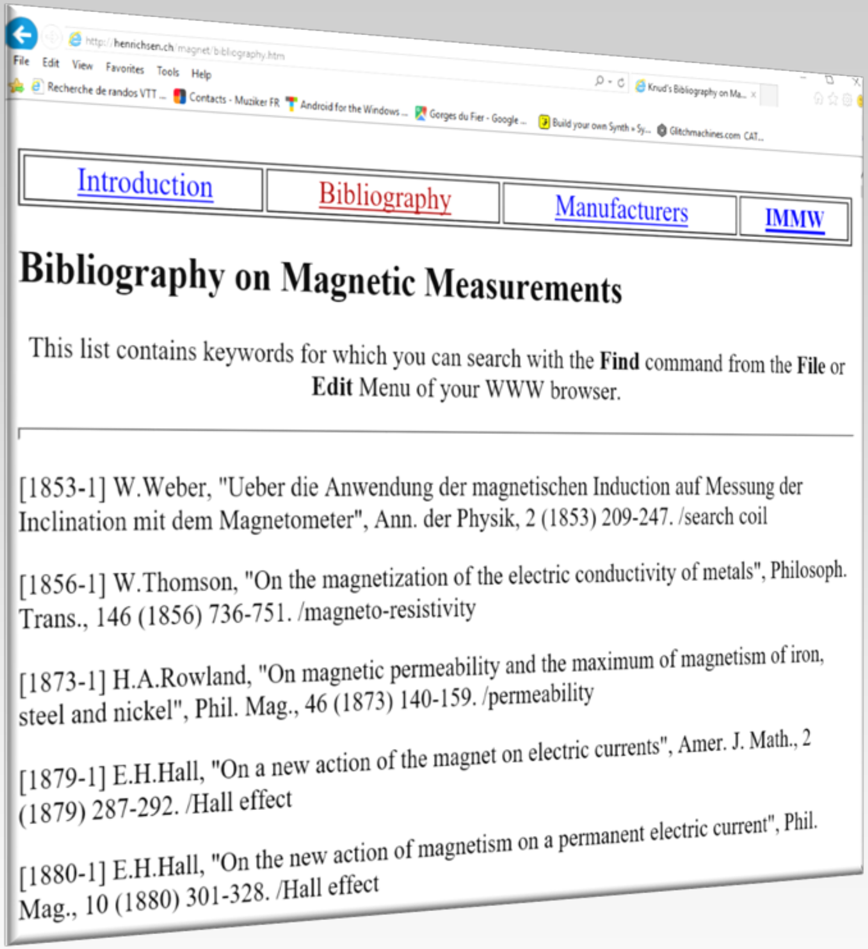
- Random cycling → minor cycles → unpredictable errors within the envelope of the limit cycle
- Enforce monotonic cycling for critical magnets (at the cost of more time spent ramping)
- Stay as high as possible above zero to improve reproducibility

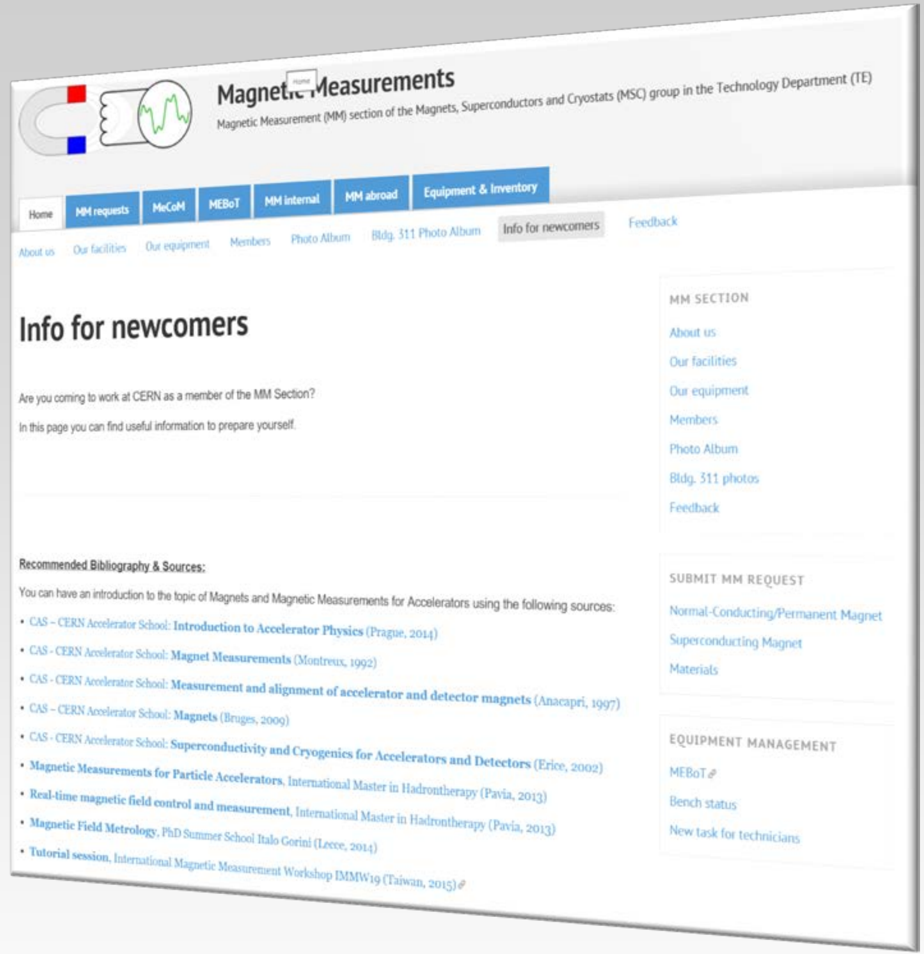
marco.buzio@cern.ch

Conclusions

Summary

- we must **measure** because mathematical prediction at the level of precision we need is in many cases more expensive or impossible
- measuring under **reproducibility conditions** allows estimation and correction of systematic errors → convince your management to take more data points
- there is no universal method ! **combine complementary tools** to optimize resources
- commercial choices increasing but still limited – in-house or (better) **collaborative R&D** often necessary





An extensive bibliography by one of our founding fathers, including links to the whole IMMW series:

http://henrichsen.ch/magnet/default.htm

List of CERN Accelerator School proceedings and other resources covering the fundamentals:

https://te-msc-mm.web.cern.ch/

Thanks for your attention

... and good luck with new discoveries !

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