Flux-metric methods, rotating coils, static coils, and wires

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Outline

- Introduction
- Voltage integrators
- Search coils
  - Design
  - Fabrication
- Flux-metric methods
  - Rotating coils
  - Static-coil arrays with examples
  - Stretched wire
- Conclusions

Fluxmeters, not a novel technique…

“Earth inductor” from Weber, University of Göttingen

Start » Stadtführungen » Von Gauß bis Measurement-Valley

STADTFÜHRUNG: VON GAUSS BIS MEASUREMENT-VALLEY

Advertisement of the statue of Weber and Gauss, Göttingen tourism office

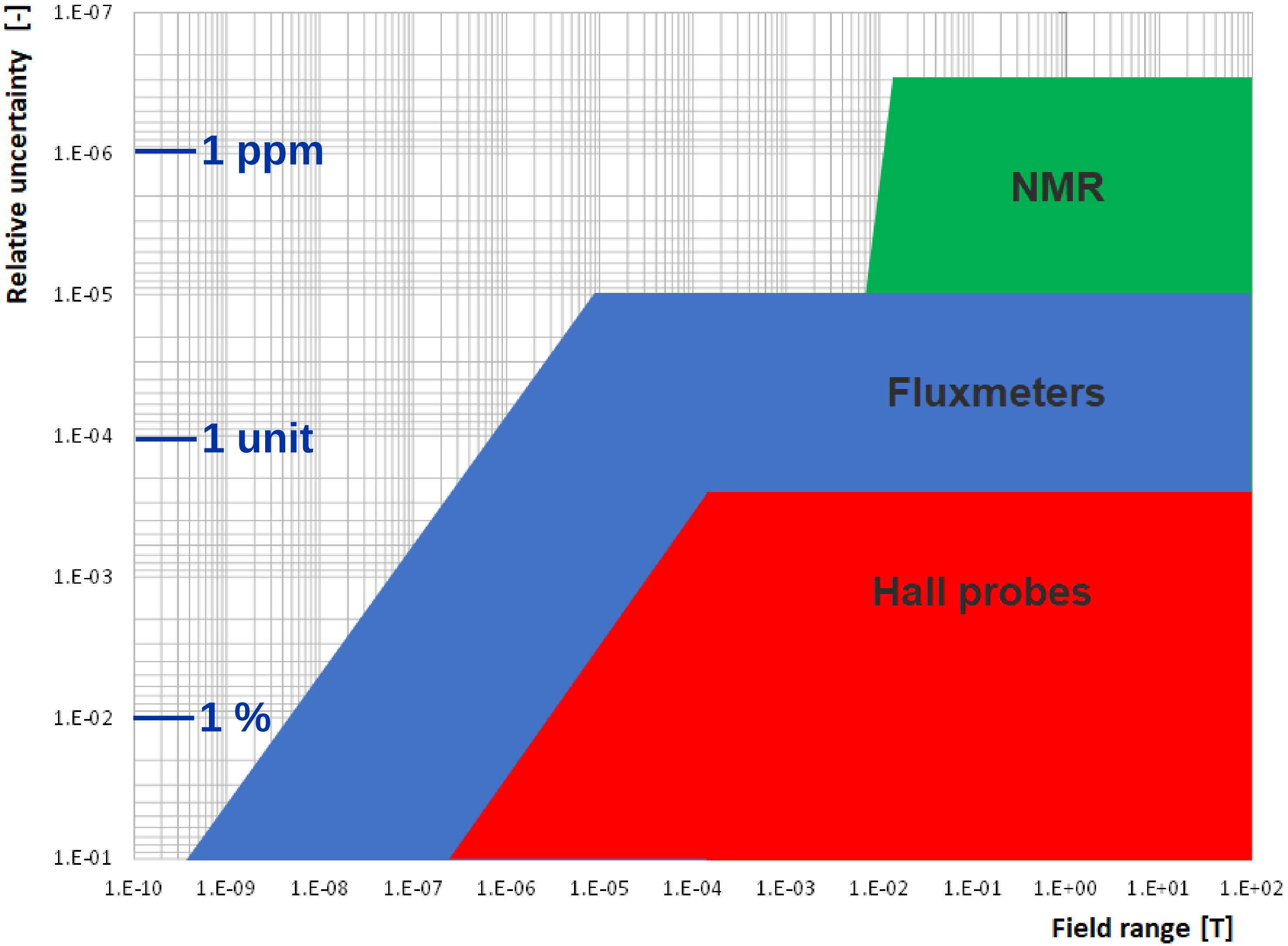
Weber and Gauss were using induction sensors to study the Earth magnetic field already in ~1850.

They not only invented the magnetic measurements, but they also introduced the absolute system of units.

- The SI unit for the magnetic flux is the *weber*
- The CGS unit for the magnetic flux density is the *gauss*

“In 1839, Gauss pioneered the use of spherical harmonic analysis to provide a useful quantitative description of the magnetic field.”

Why flux-metric methods?



Flux metric methods cover the requirements of accelerator magnets both in terms of accuracy and field levels.

Other complementary methods are:

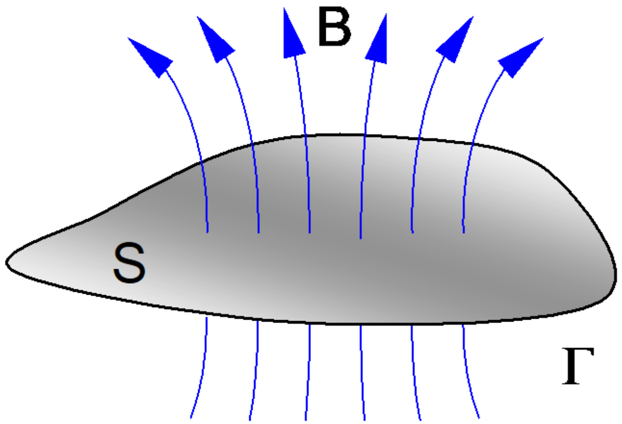
- NMR for absolute calibration in dipolar field
- Hall probes for detailed mapping

Many other methods can be used for measuring fields but are not relevant for accelerator magnets.

Basics of flux-metric methods

Magnetic flux $$\varphi = \int_S \mathbf{B}\,d\mathbf{S}$$

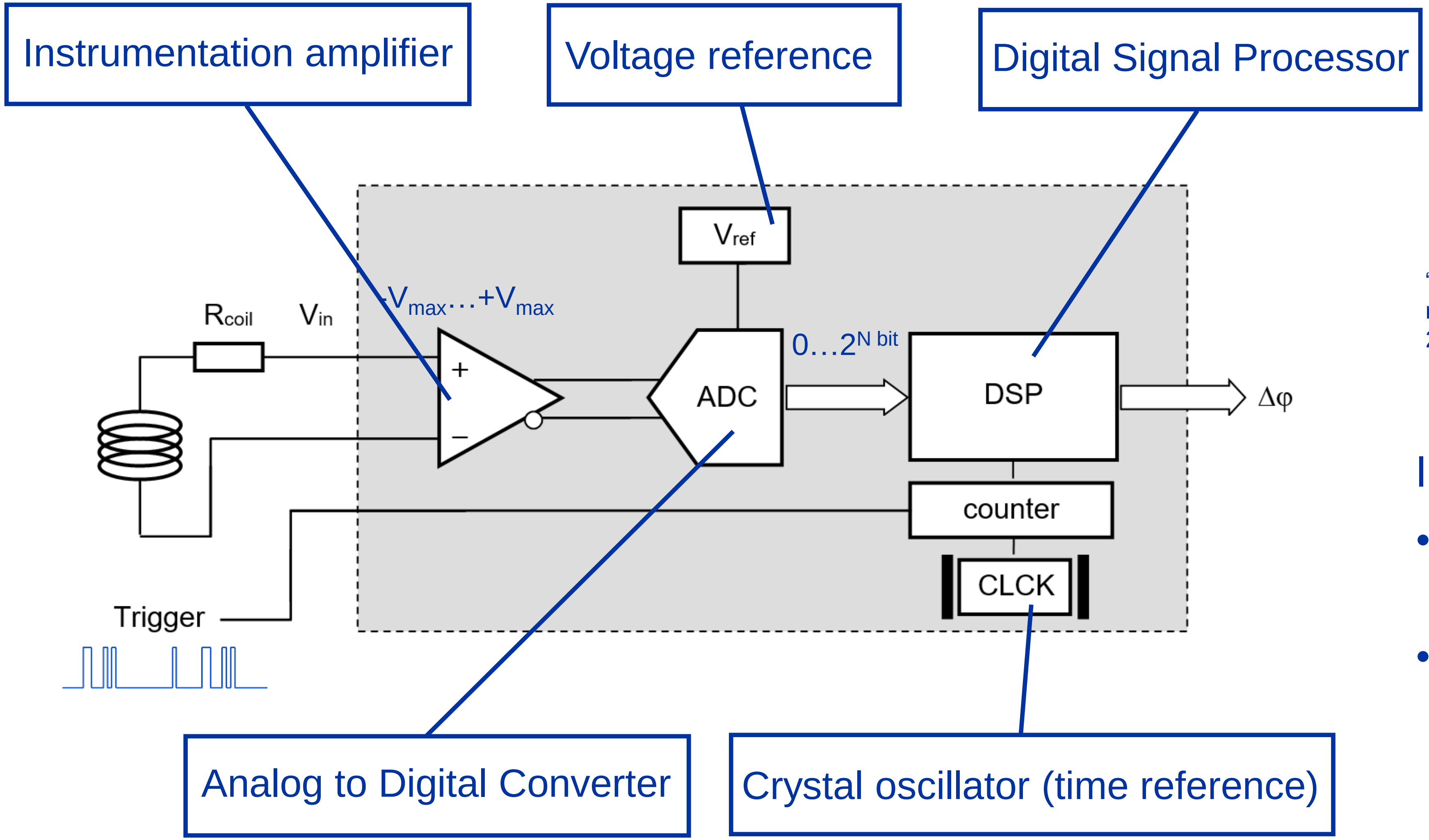
Induction law $$V = -\frac{d\varphi}{dt}$$



Need of an *integrator* and a *flux change* …

… and a coil sensor with *known geometry*

Digital integrator



Instrumentation amplifier

Voltage reference

Digital Signal Processor

Analog to Digital Converter

Crystal oscillator (time reference)

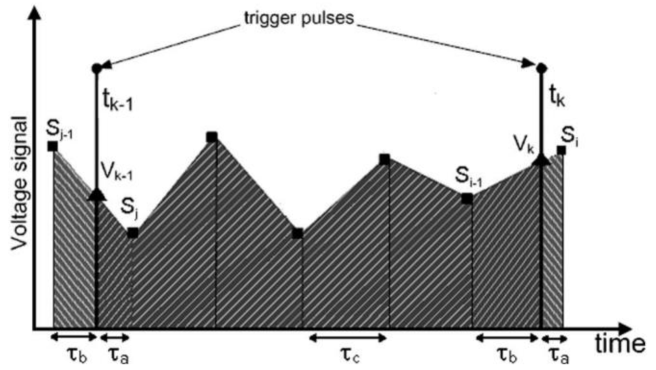


FIG. 2. Integration algorithm: V_k (▲) are computed by means of a linear interpolation between the previous S_{i-1} and the next S_i ADC sample (■).τ_a and τ_{ba} are known by the on board UTC.

“Performance of a fast digital integrator in on-field magnetic measurements for particle accelerators.” Rev. Sci. Instrum. 2012; 83 (2): 024702. https://doi.org/10.1063/1.3673000

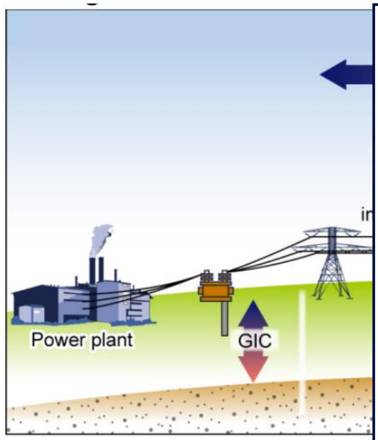
Integration is affected by drift:

- find a way to estimate and correct the drift
- reduce as much as possible the noise at very low frequencies

Search coils

- Are simple, passive, linear, drift-free devices.
- Require change of flux:
  - ramp field with static coil;
  - move coil in a static field;
  - ramp or displacement must be accurate.
- Measure flux, not field.
- Must be well-built and calibrated (known geometry).

The biggest and the smallest coil



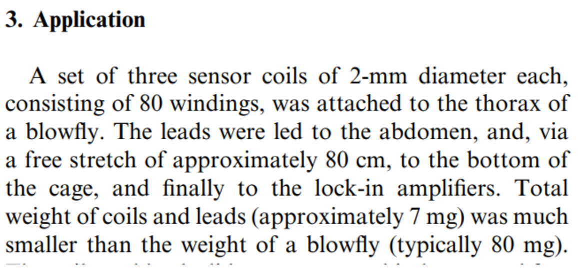
Sources: GAO (presentation); Art Explosion (imag

**“Geomagnetic distur
weather, pose a risk
is not clear how seve
can cause geomagne
electric transmission
disruption or damage**

https://www.gao.gov/assets/gao-19-98.pdf

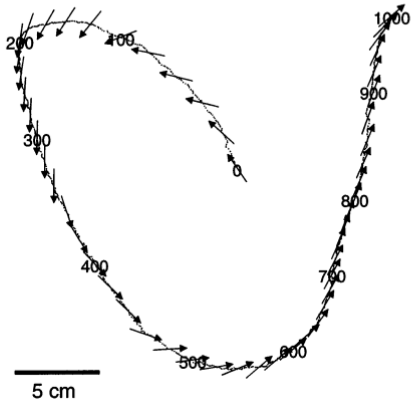
The Karate Kid (1984)

“Man who catch fly with chopstick, accomplish anything.”



3. Application

A set of three sensor coils of 2-mm diameter each, consisting of 80 windings, was attached to the thorax of a blowfly. The leads were led to the abdomen, and, via a free stretch of approximately 80 cm, to the bottom of the cage, and finally to the lock-in amplifiers. Total weight of coils and leads (approximately 7 mg) was much smaller than the weight of a blowfly (typically 80 mg).



Example of a flight ath, recorded from the thorax of a flying blowfly. The three-dimensional path (in this case almost confined to a horizontal plane) was projected on a horizontal plane. Dots show positions at consecutive ms (starting at ms 0, ending at ms 1000), the arrows the orientation of the thorax at 20-ms intervals.

“Using miniature sensor coils for simultaneous measurement of orientation and position of small, fast-moving animals”, Neurosci. Meth. 83, 125-131.

Common geometries for coils

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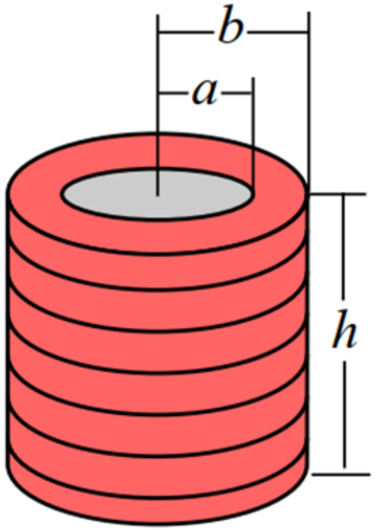


Point Coil

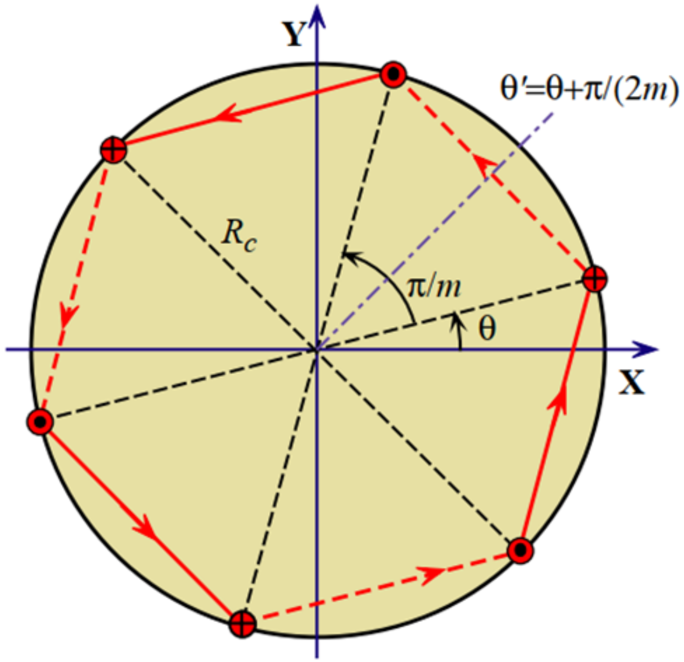
Insensitive up to 4th order spatial harmonic with proper choice of height and radii.

Flat Coil (Line or Area Coil)

-Fixed coil; Varying field

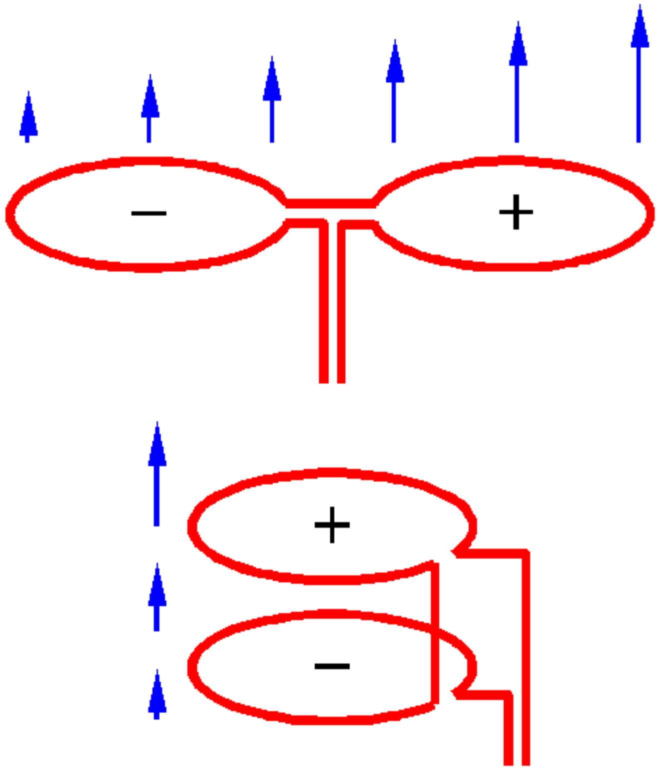
-Flip Coil/Moving Coil; Static field

-Rotating Tangential/Radial



Multipole Coil

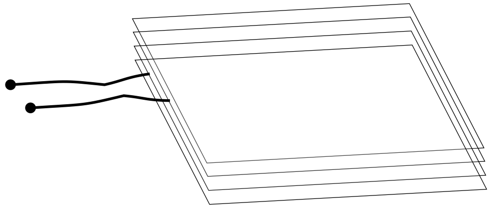
Sensitive to only odd multiples of a specified harmonic (Morgan Coils)



Gradient Coil

Sensitive to field gradients

Coil design



Ideal rectangular coil

- 4 geometrical parameters: N_T turns, length ℓ_C, width w_C, wire diameter $\varnothing_W$

$$A_c = N_T \ell_c w_c$$

$$R_c = \frac{8}{\pi} N_T \rho \frac{\ell_c + w_c}{\varnothing_w^2}$$

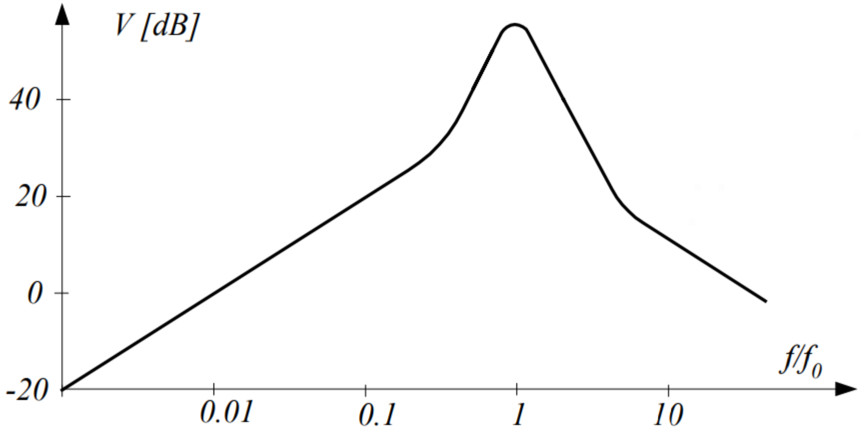
$$L_c = \frac{\mu_0}{\pi} N_T^2 \left(\ell_c \ln \frac{\ell_c}{\varnothing_w} + w_c \ln \frac{w_c}{\varnothing_w} + 2\sqrt{\ell_c^2 + w_c^2} - \ell_c \sinh^{-1} \frac{\ell_c}{w_c} - w_c \sinh^{-1} \frac{w_c}{\ell_c} - \frac{7}{4}(\ell_c + w_c) \right)$$

- Capacitance is more difficult to evaluate (can be neglected at low frequency)
- The total $\boldsymbol{A_c}$ determines the peak induced voltage (maximum voltage dictated by electronics, typically ±5 or ±10 V)

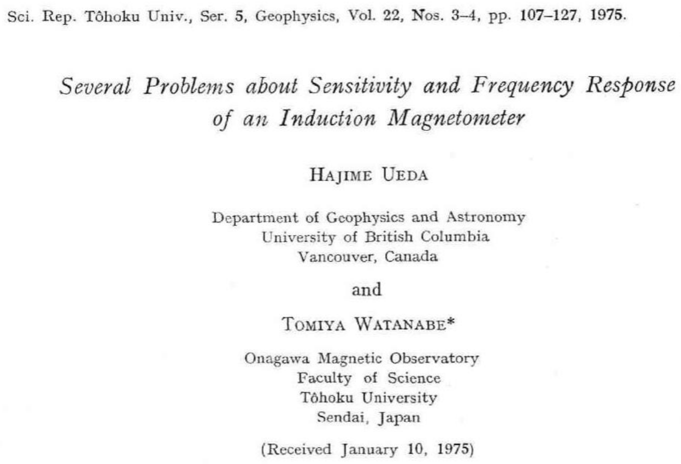
M. Buzio, “Fabrication and calibration of search coils” CAS 2009

Equivalent circuit

- A search coil is characterized primarily by its own resistance and the mutual inductance corresponding to the linked flux to be measured
- Coil self-inductance and capacitance become important only at high frequencies (10~100 kHz or more, to be compared to $(LC)^{-1/2}$).



Typical frequency characteristic of an induction coil sensor



Sci. Rep. Tôhoku Univ., Ser. 5, Geophysics, Vol. 22, Nos. 3–4, pp. 107–127, 1975.

Several Problems about Sensitivity and Frequency Response of an Induction Magnetometer

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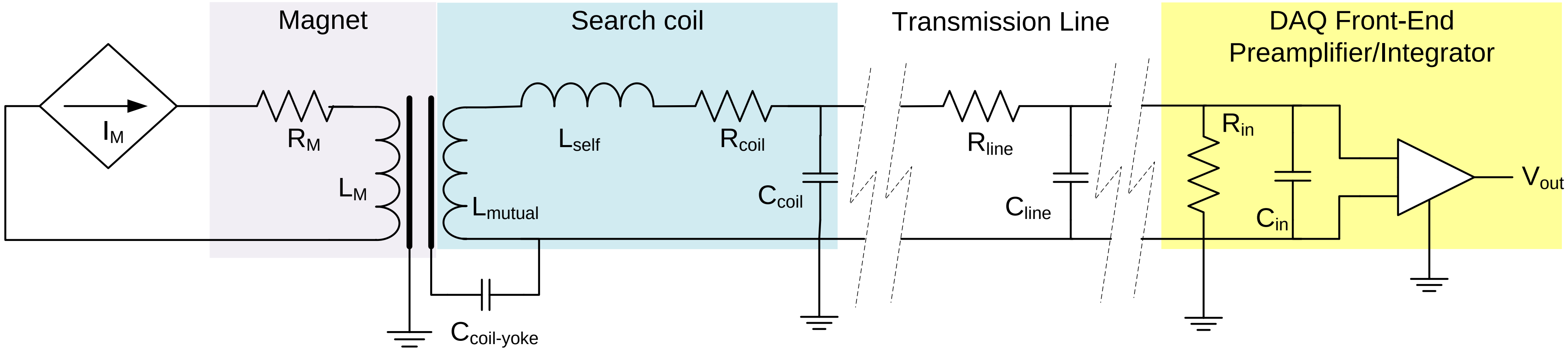
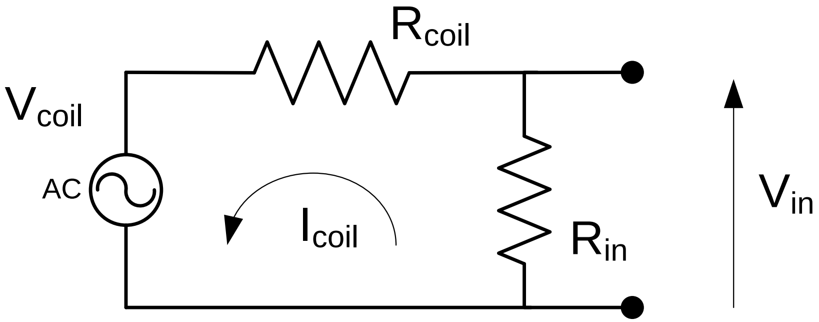


M. Buzio, “Fabrication and calibration of search coils” CAS 2009

Low frequency approximation

- The mutual inductance to the magnet is replaced by an e.m.f. source
- The only relevant coil parameter is its resistance, which should be kept small
- The voltage at the input of the acquisition system will be equal to the coil e.m.f. only if $R_{coil} << R_{in}$ (R_{in} ranges from 1 MΩ to 1 GΩ)
- In the general case, an appropriate correction factor k_R must be measured and applied
- Coil current I_{coil} typically in the µA range can be safely ignored (actual value dominated by R_{in}).
- Potential issues:
  - perturbation of V_{in} (consider behavior full coil circuit)
  - wire heating (with diminution of R_c): e.g. a Ø32 µm wire can carry adiabatically ~5 mA.



$$V_{in} = \underbrace{\frac{1}{1+\frac{R_{coil}}{R_{in}}}}_{k_R} V_{coil}$$

$$I_{coil} = \frac{V_{coil}}{R_{coil} + R_{in}}$$

M. Buzio, “Fabrication and calibration of search coils” CAS 2009

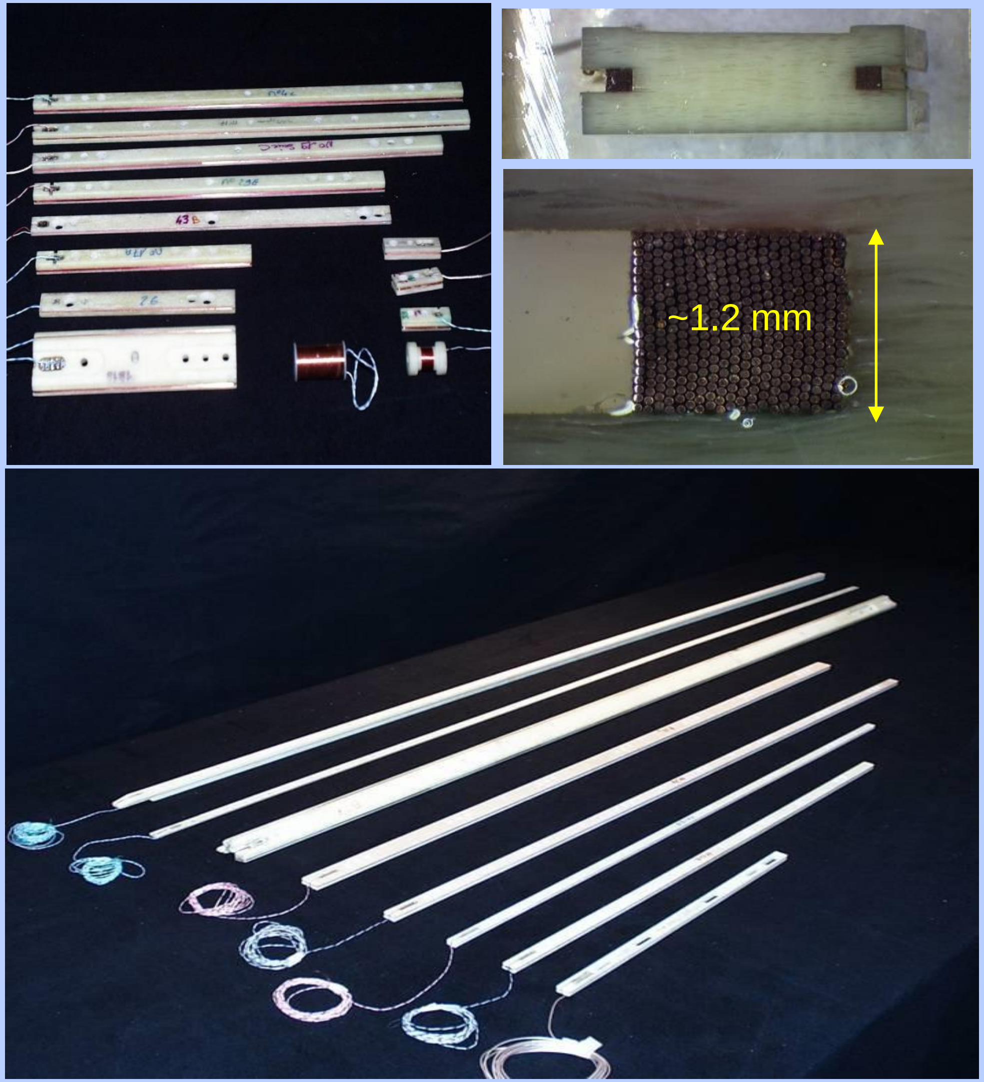
Criteria for coil design

N_T	• Increase for high sensitivity • Balance with R_C
ℓ_C	• Dictated by the geometry of the magnet to be measured (local or integral measurement)
w_C	• Dictated by the geometry of the magnet to be measured (aperture size): coil must rotate, or translate, or stay fixed • Case of tangential coils: choose appropriately the blind harmonic (n: $\sin\frac{1}{2}n\alpha=0$)
$Ø_w$	• Reduce to wind more turns, get small cross-section (improve harmonic accuracy) • Increase to improve mechanical strength, reduce R_C
A_C	• Aim at having $\lvert V_C\rvert_{max} \leq 5$ or 10 V in normal use (depending on electronics)
R_C	• Lower for higher measurement accuracy (also reduces thermal voltage noise)
C_C, L_C	• In case of high-frequency measurements: resonant frequency >> bandwidth

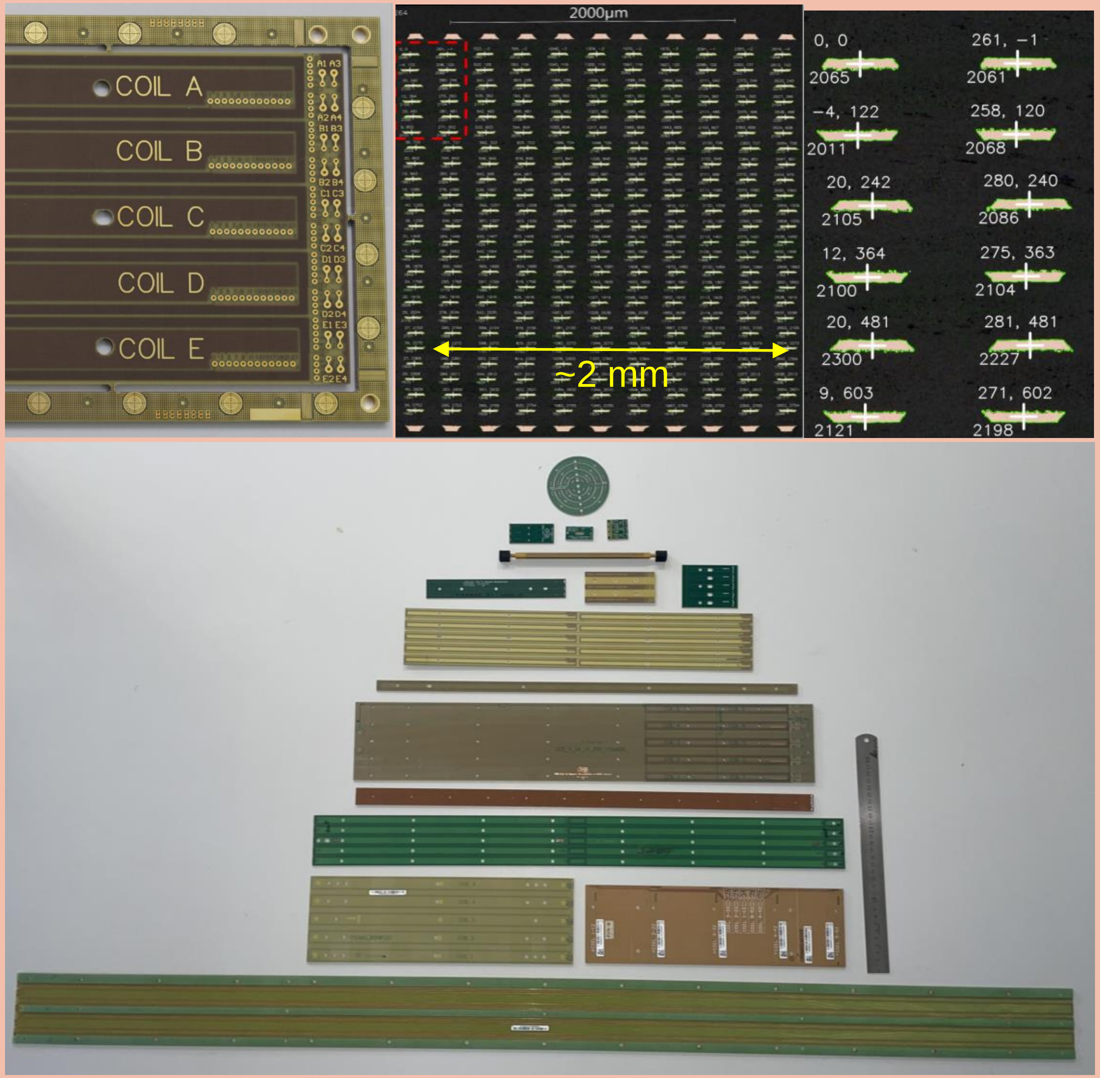
M. Buzio, "Fabrication and calibration of search coils" CAS 2009

Coil fabrication: two main options

Wound coils



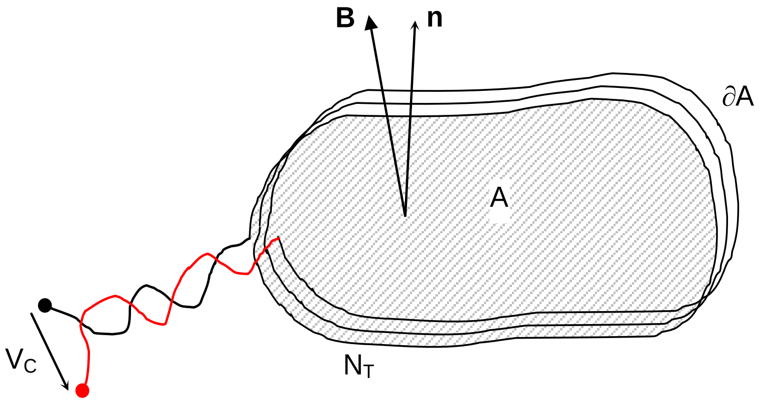
Printed circuits



Wound coils vs printed circuit boards

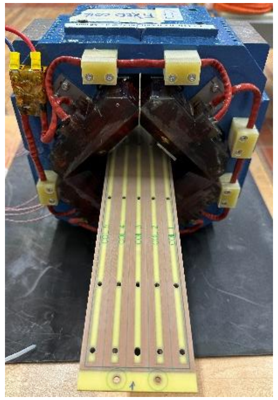
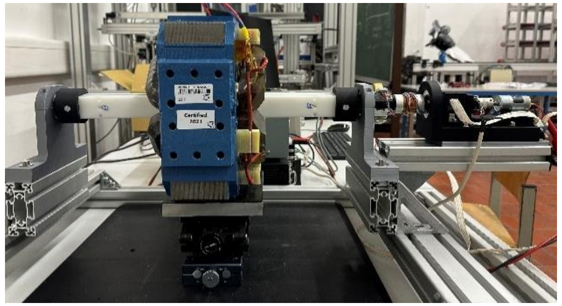
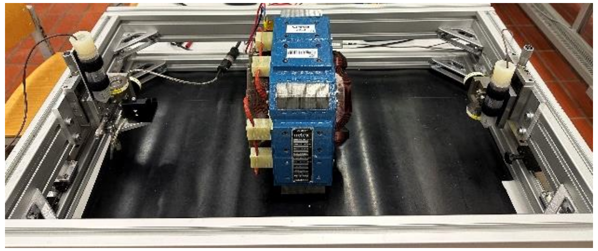
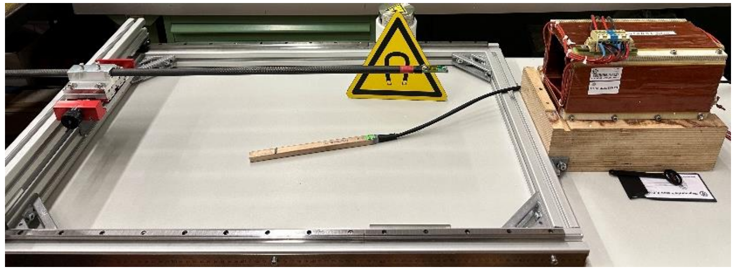
 	
• High winding density (high sensitivity) • Precise wire positioning is challenging • Manufacturing is laborious, requires specialized tools and operators (expensive) • Microscopic soldering required when multifilament wire is used • Calibration and sorting required to achieve good compensation (produce more coils than strictly required, even more expensive) • Coil length above ~1 m feasible • Coil resistance can be kept low • Geometries other than rectangular and round are difficult to produce (wires in a groove)	• Precise trace positioning (<10 μm) • High sensitivity when multiple layers (32 layers feasible on standard size < 600 mm) • High coil resistance (in the kΩ range), must use high Z_{in} electronics • High aspect ratio winding cross-section (winding dimensions must be considered) • Manufacture large series quickly, reproducibly, cheaply • Makes practical high-order compensation schemes (B1=B2=B3=B4=B5=0) • Multiple coils on the same board (good geometrical relation among them) • Many geometries are possible without loosing accuracy (rectangular, sector, curved) • Flexible substrate possible (the coil take the shape of the support structure) • Coil length above ~1 m not easy feasible (but possible)

Flux-metric methods



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

- Static coil in a time-changing field
- Coil moving in a static field
  - Rotating (or flipping) coil
  - Translating wire
  - Translating coil

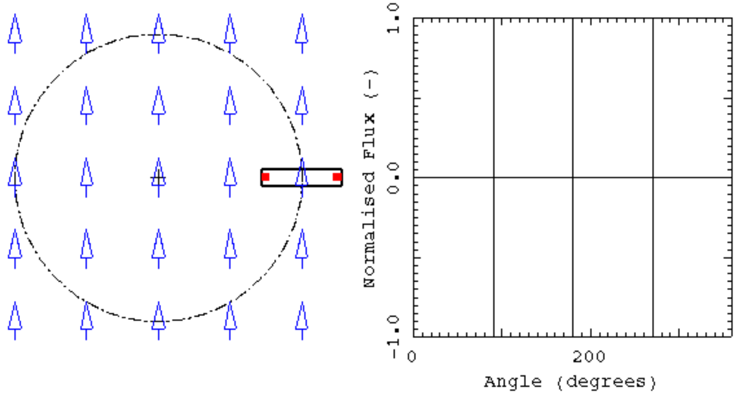





Hands-on exercises

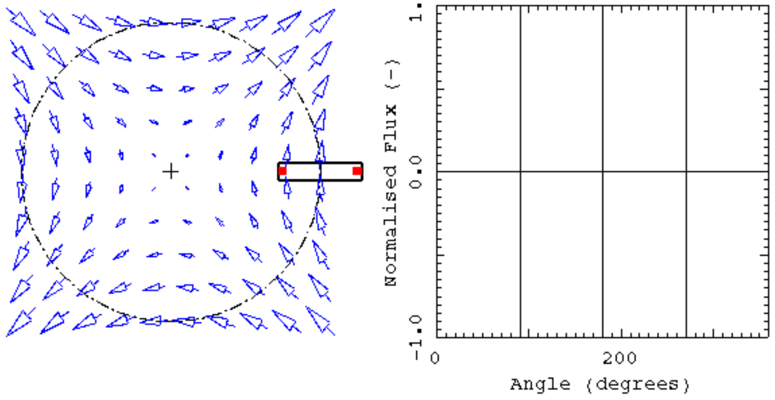
M. Buzio, “Fabrication and calibration of search coils” CAS 2009

Rotating coils

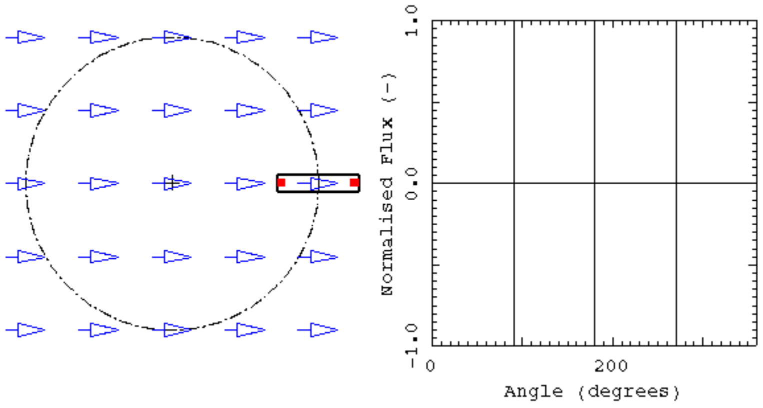
Radial coil in a normal dipole (B_1)



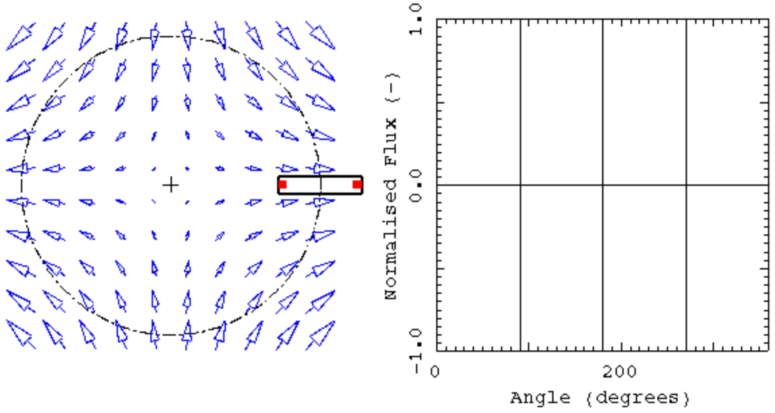
Radial coil in a normal quadrupole (B_2)



Radial coil in a skew dipole (A_1)



Radial coil in a skew quadrupole (A_2)



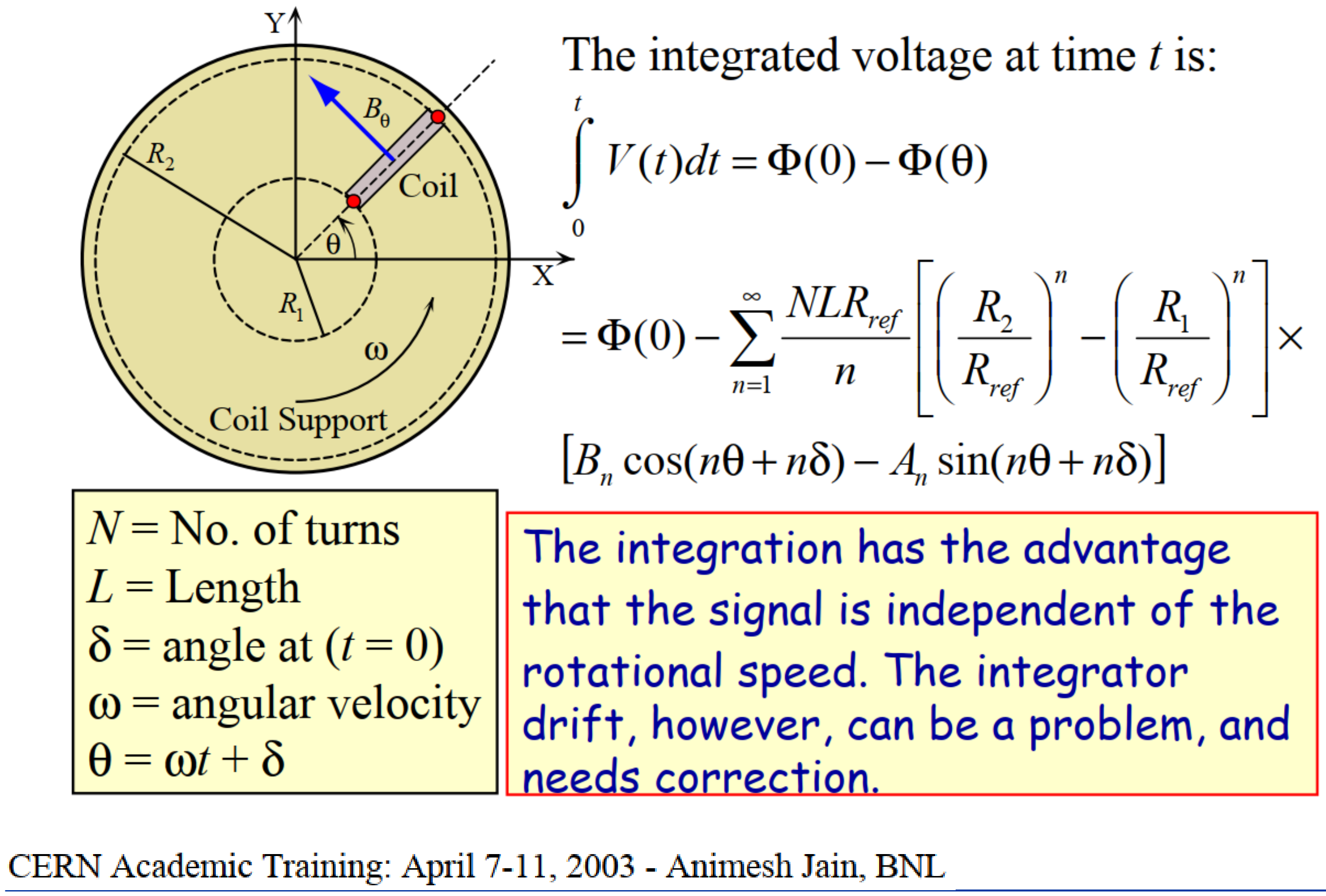
L. Bottura, “Field Measurement Methods” CAS 2009

The flux, as function of the angle, seen by a coil in a magnetic field, is a 2π periodic function on a full turn.

- The periodicity tells us the harmonic order.
- The phase tells us the orientation (normal / skew).

Rotating coils

The **field harmonics** can be retrieved from the **flux** intercepted by a **coil**, with known **geometry**, **rotating** in the magnet aperture.



The integrated voltage at time *t* is:

$$\int_0^t V(t)dt = \Phi(0) - \Phi(\theta)$$

$$= \Phi(0) - \sum_{n=1}^{\infty} \frac{NLR_{ref}}{n}\left[\left(\frac{R_2}{R_{ref}}\right)^n - \left(\frac{R_1}{R_{ref}}\right)^n\right] \times [B_n \cos(n\theta + n\delta) - A_n \sin(n\theta + n\delta)]$$

N = No. of turns
L = Length
δ = angle at $(t = 0)$
ω = angular velocity
$\theta = \omega t + \delta$

The integration has the advantage that the signal is independent of the rotational speed. The integrator drift, however, can be a problem, and needs correction.

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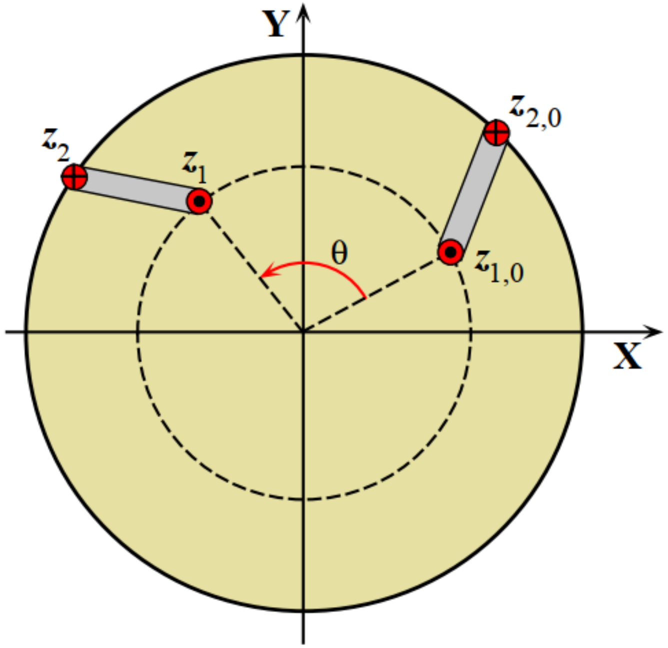
Signal processing of rotating-coil signals:

- The induced voltage is integrated over time to get the flux φ
- The integration is triggered by an angular encoder to get $\varphi(\theta)$
- The Fourier transform of the flux $\varphi(\theta)$ from one full rotation to the get $\mathbf{\Phi}_n$
- Coil sensitivity factors (coil geometry) are applied to get B_n and A_n

$$\mathbf{C}_n = \frac{\mathbf{\Psi}_n}{\boldsymbol{\kappa}_n}$$

Sensitivity of a coil



After a rotation of the coil by θ:

$$z_1 = z_{1,0}\exp(i\theta); \quad z_2 = z_{2,0}\exp(i\theta)$$

$$\Phi(\theta) = \mathrm{Re}\left[\sum_{n=1}^{\infty} \boldsymbol{K}_n \exp(in\theta)\left(B_n + iA_n\right)\right]$$

where $\boldsymbol{K}_n$ is the sensitivity factor:

$$\boldsymbol{K}_n = \left(\frac{NLR_{ref}}{n}\right)\left\{\left(\frac{z_{2,0}}{R_{ref}}\right)^n - \left(\frac{z_{1,0}}{R_{ref}}\right)^n\right\}$$

The complex sensitivity factor gives both the amplitude and phase of the n-th harmonic term in the flux seen by the coil.

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Correction for finite winding size

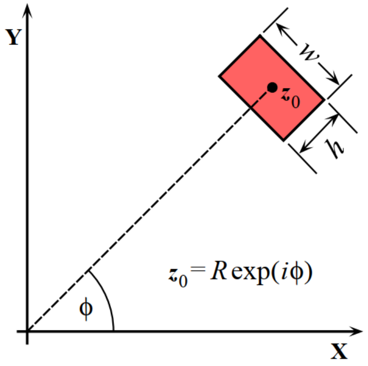
If

- **Square cross-section ≤ 1 mm^2**
- **$R_0 \geq$ 10 mm**
- **n≤6**

then

- **no error for a dipole**
- **error << 10^{-4} for a quadrupole**
- **error << 10^{-3} for n>2**

else



Finite Winding Size

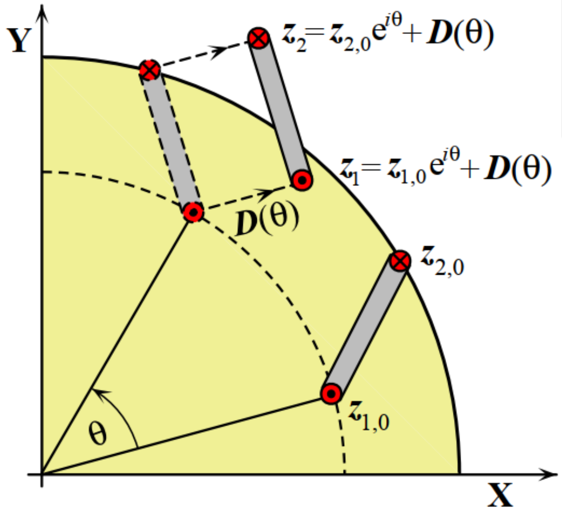
$$\xi_{1,2} = \sqrt{\left(1 \pm \frac{h}{2R}\right)^2 + \left(\frac{w}{2R}\right)^2}$$

$$\lambda_{1,2} = \tan^{-1}\left[\frac{(w/2R)}{1 \pm (h/2R)}\right]$$

$$(z^n)_{avg.} = z_0^n \cdot \left[\frac{\xi_1^{n+2}\sin\{(n+2)\lambda_1\} - \xi_2^{n+2}\sin\{(n+2)\lambda_2\}}{2(h/2R)(w/2R)(n+1)(n+2)}\right]$$

Errors from transverse and torsional vibrations

Transverse Vibrations

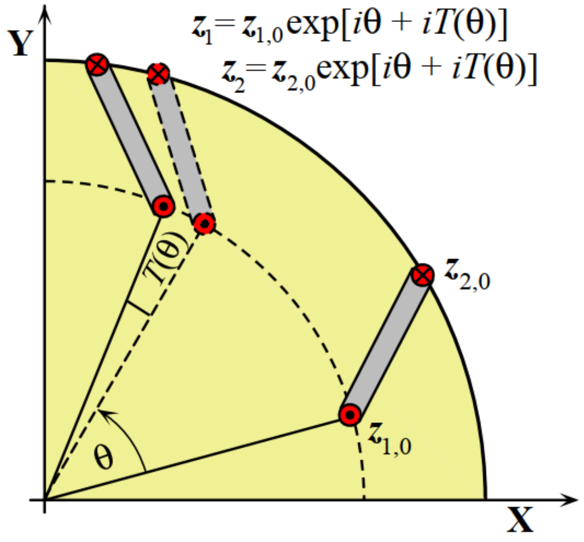


The coil is displaced from the ideal position by a vector $D(\theta)$ when the coil rotates through θ.

In a pure $2n$-pole field, the amount of spurious harmonics in the coil signal is roughly proportional to the sensitivity of the coil to the $(n-1)$th harmonic.

The effect of transverse vibrations in a $2n$-pole magnet can be minimized by using a coil system whose sensitivity to the $(n-1)$th harmonic is zero.

Torsional Errors



The coil angular position is $\theta + T(\theta)$ when it should have been θ.

In a pure $2n$-pole field, the amount of spurious harmonics in the coil signal is roughly proportional to the sensitivity of the coil to the n-th harmonic.

The effect of torsional errors in measuring a $2n$-pole magnet can be minimized by using a coil system whose sensitivity to the n-th harmonic is zero.

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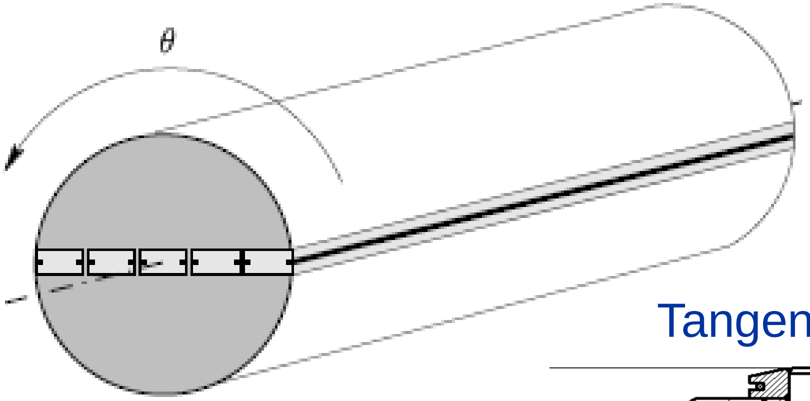
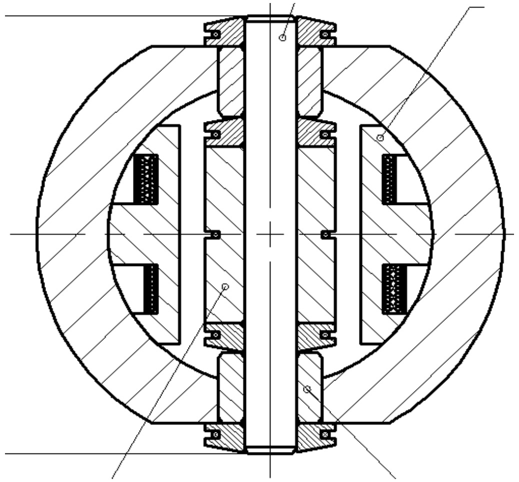
Compensation (or bucking)

- The rotation axis may move (wobble) by small amounts as the coil rotates.
- Because of torsional vibrations, the coil angular position may not precisely match the expected angular position for a particular trigger.
- These imperfections produce spurious harmonics in the coil signal.
- These spurious harmonics can be minimized by employing “compensation” (or “bucking”).
- In general, in a n-pole magnet, two signals are measured: one containing all harmonics, and a second one not sensitive to the n and n-1 components.



Radial coils

Tangential coils



3 or 5 parallel coils can be present on the same rotating shaft. There are combinations of signals from different coils that are not sensitive to the n and n-1 components. Other configurations are possible.

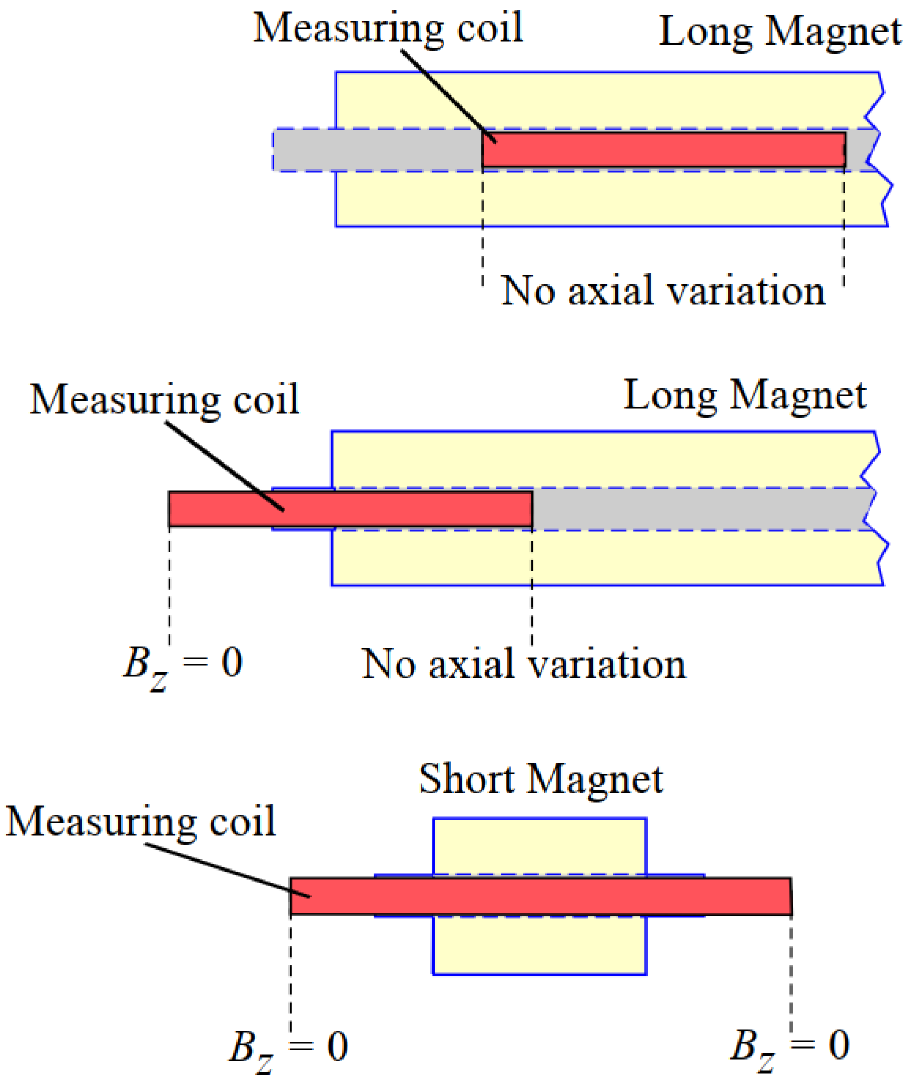
Validity of the 2-D field expansion

The magnetic field has all three components (it is not 2-D):

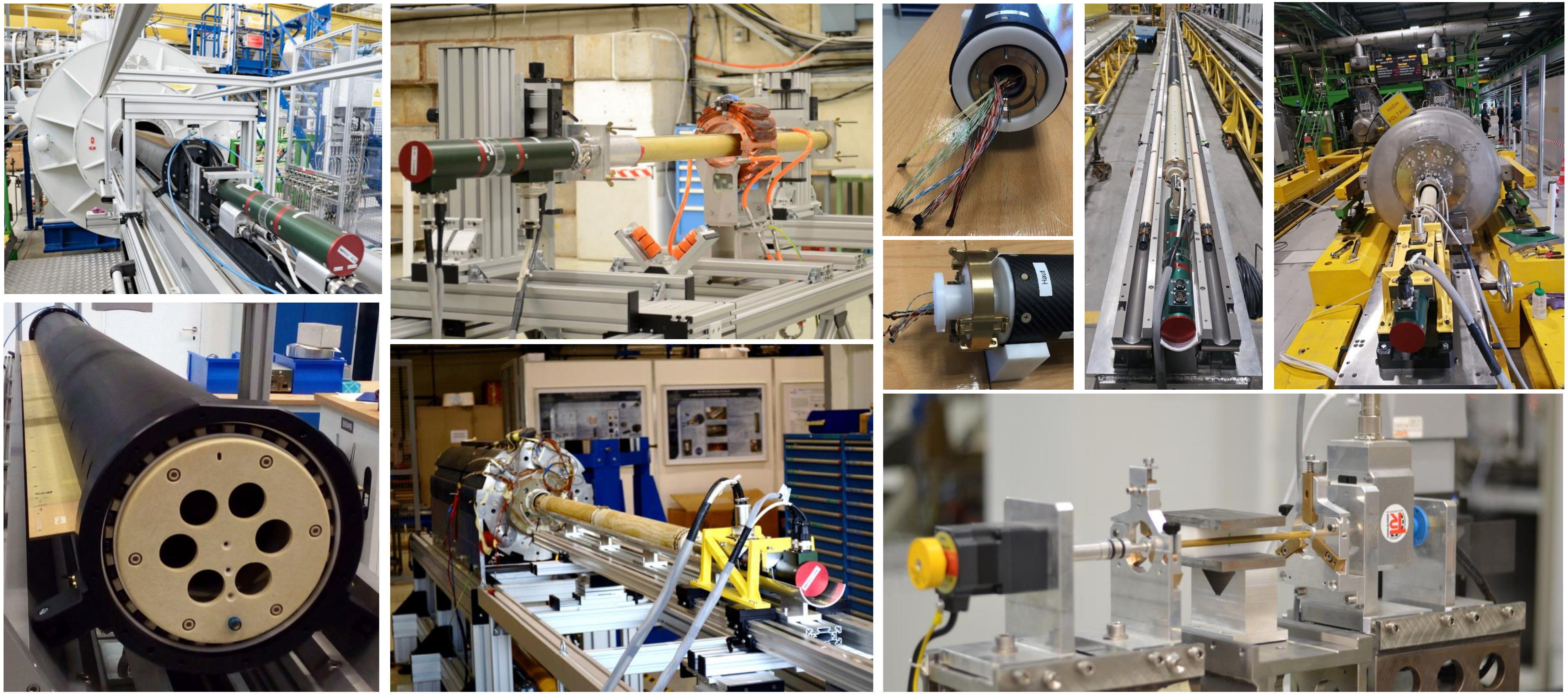
- near the ends of a long magnet
- everywhere in a short magnet

In these cases, the simple 2-D expansion is not valid locally!

However, if we consider the integral of the field components from/to a region where B_z is zero, the 2-D expansion is valid.



Rotating-coil systems in reality



The rotating probe is designed to fit the dimensions of magnet aperture.

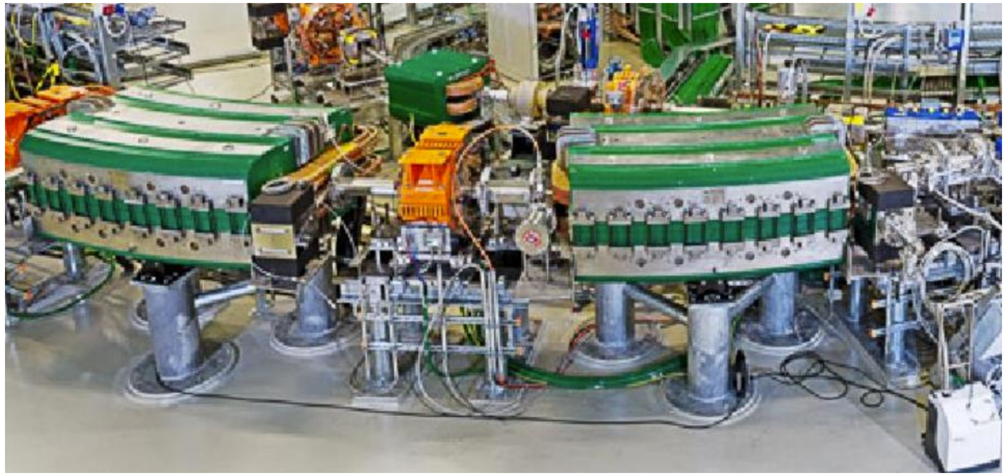
Static coils

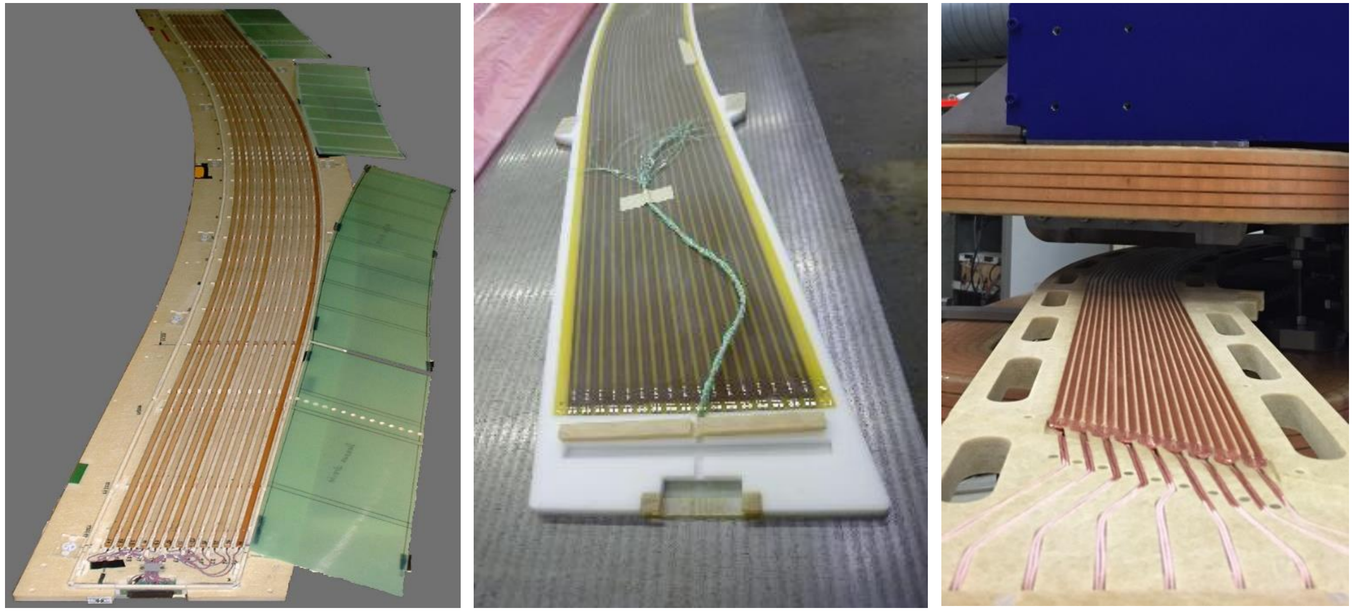
The rotating coils cannot be directly used on fast-ramped or curved magnets. In these cases, array of static coils are often employed.

The array of coils can be:
- full length or segmented
- made of wound coils or PCB

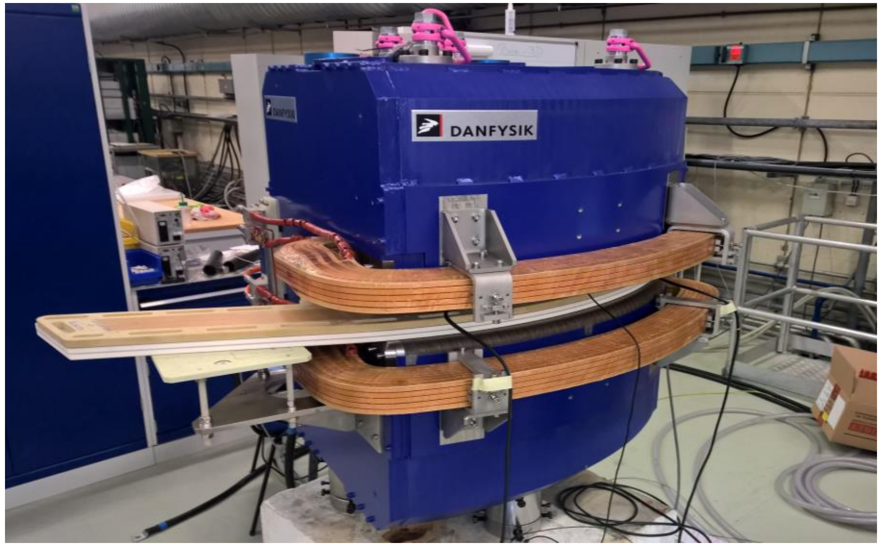
The design depends on required: length, surface, bending radius, cost.

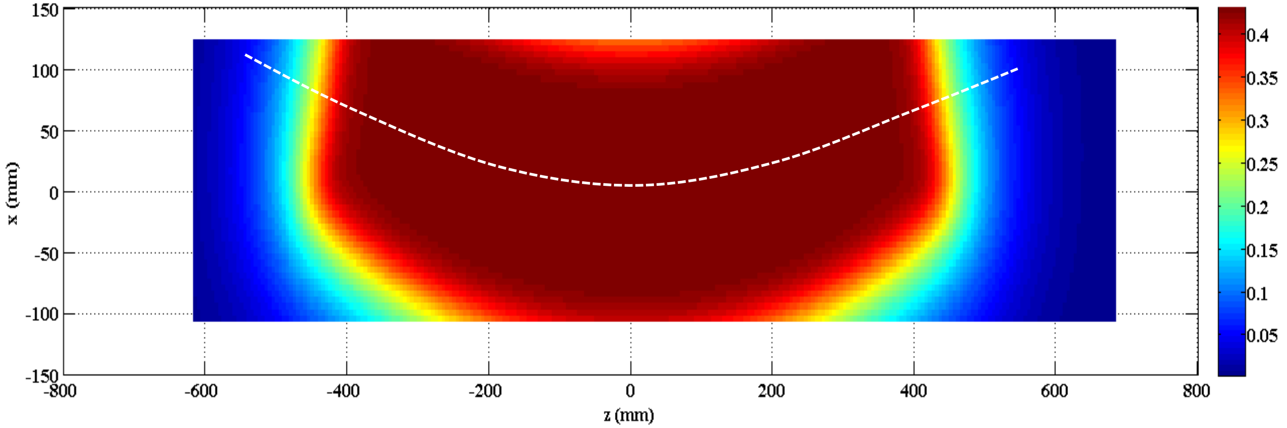
The main challenges are:
- remanent field and integration drift
- **calibration**
- handling and positioning

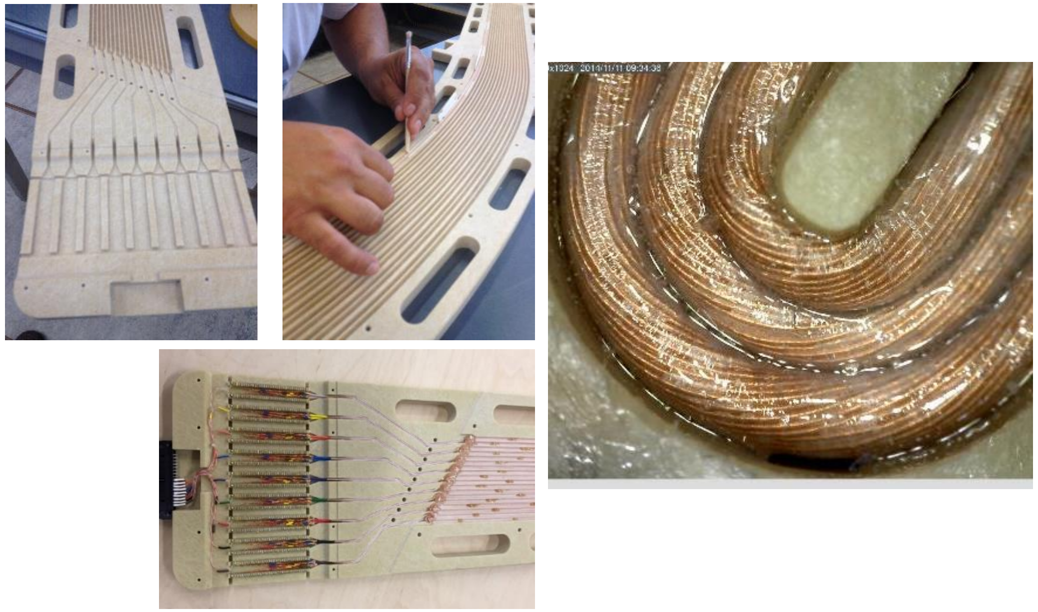




Curved array for the ELENA dipole





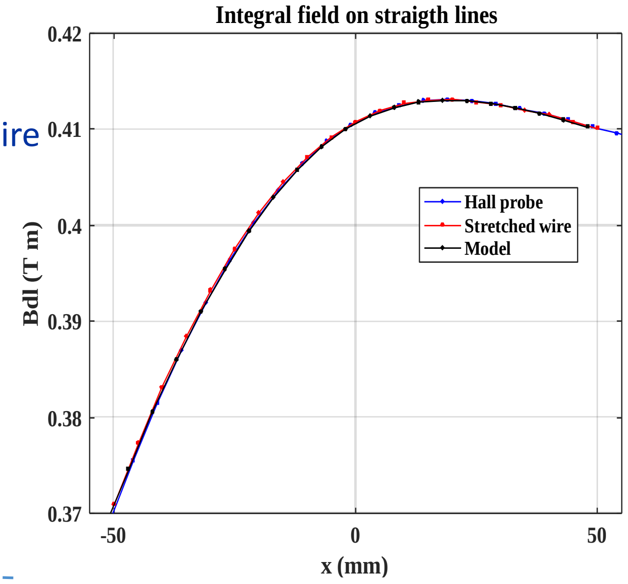


- 60° bending, low-energy pbar ring therefore low field (50 to 420 mT), accelerating and decelerating cycles, 2 min-long e-cooling plateaux
- Measured with Litz-wire fluxmeter, with 2% coil area uncertainty originally intended as a backup for higher quality PCB unit

Calibration of the curved array

(2) Central NMR for high-field calibration

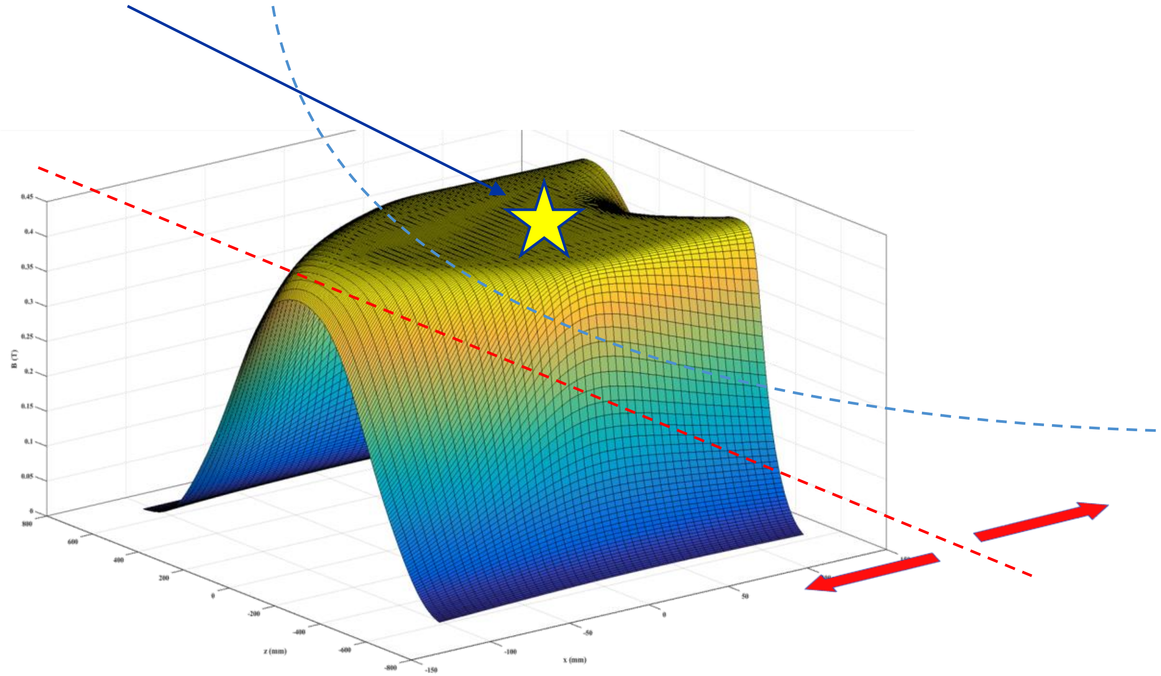
(3) Integral calculated along straight lines matched to stretched wire



Independent remanent field measurement

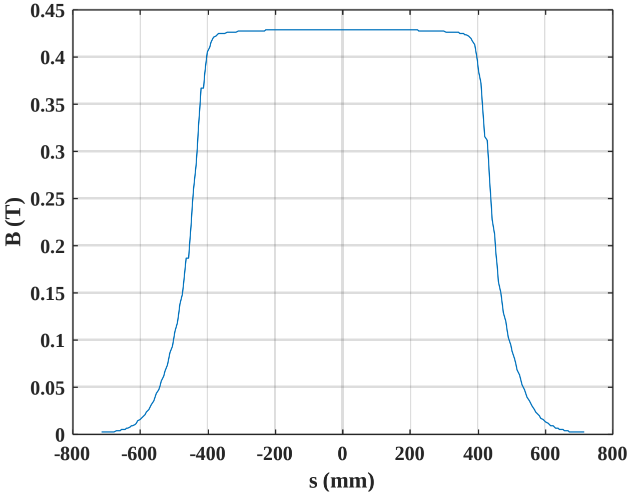
Pulsed-mode fluxmeter coil measurement

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



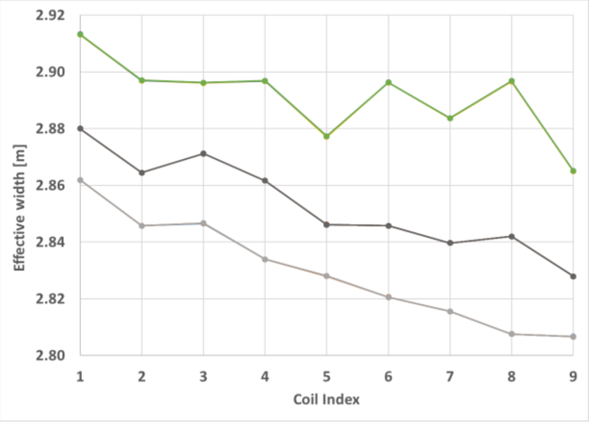
(1) 2D Hall probe map on the mid-plane

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



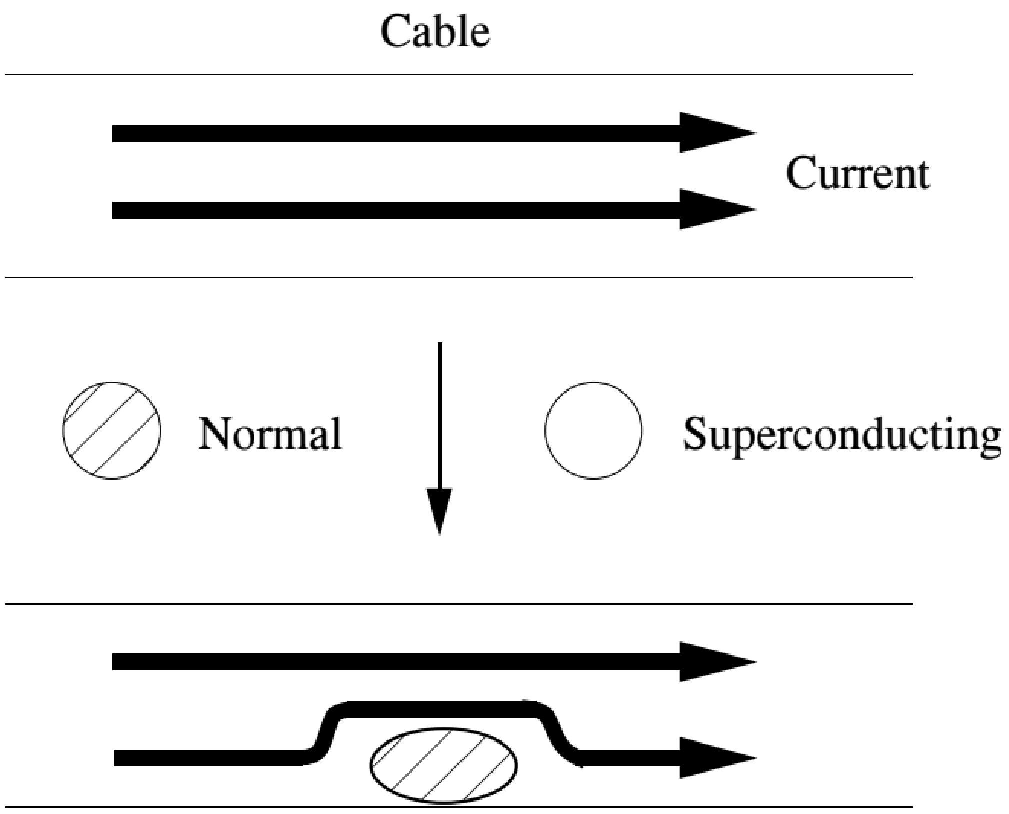
(4) Hall probe gain and offset calibration

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



Final calibrated surfaces
(3 fluxmeters with 9 coils each)

Static coils for quench localization



T. Ogitsu, Review of Magnetic Quench Antenna for Accelerator Magnets, IDSM01 2019

- At the quench onset, the current tries to bypass the forming resistive region.
- Considering only the change, it is equivalent to a $-\Delta$ current flowing in the resistive region, and a $+\Delta$ current flowing at a certain distance.
- It is a **magnetic moment**

Field generated by a magnetic moment

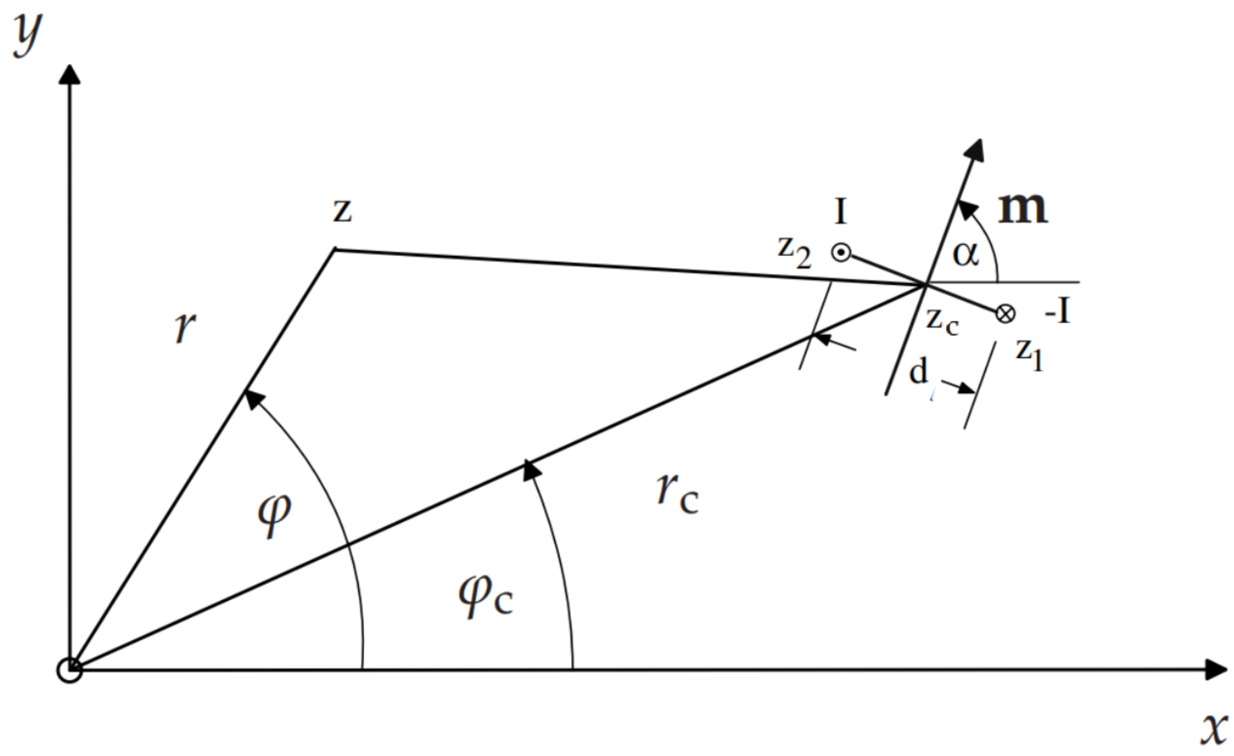
- In 2D, the field generated by a magnetic moment can be written in terms of multipoles:

$$C_n = m\frac{i\mu_0 n}{2\pi}\frac{e^{i\alpha}}{z_c^2}\left(\frac{r}{z_c}\right)^{n-1}$$

- Knowing two multipoles of different order, for example C3 and C4, we can retrieve z_c

$$z_c = \frac{4}{3}\frac{C_3}{C_4}\,\mathrm{r}$$

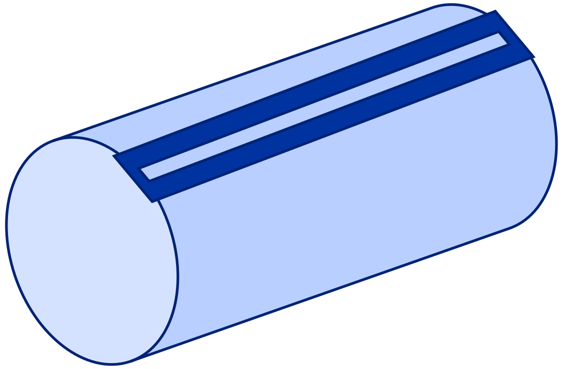
$$C_n = B_n + i\,A_n$$

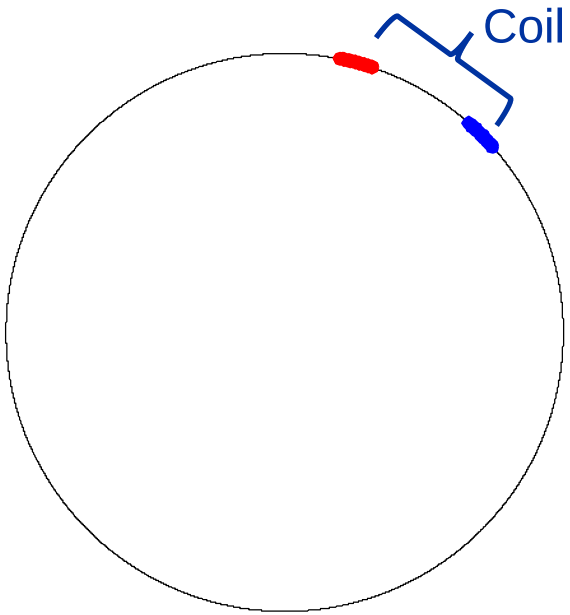


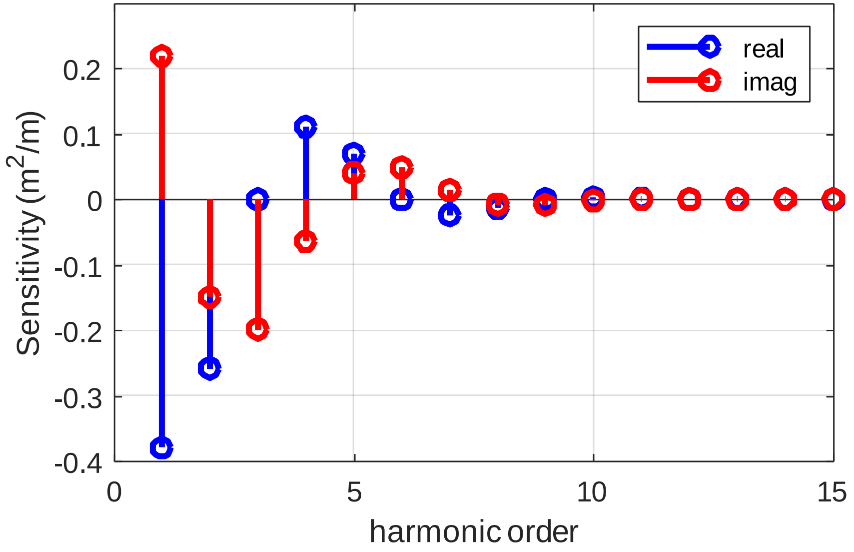
S. Russenschuck, Field Computation for Accelerator Magnets, WILEY 2010

Sensitivity of a coil

- A coil at a radius R>0 is sensitive to several multipoles.
- A combination of coils can be used to tune the sensitivity (the so-called “Morgan coil”).
- We are looking for a combination sensitive to one multipole (this as well guaranties compensation i.e. no sensitivity to main field and lower order multipoles).







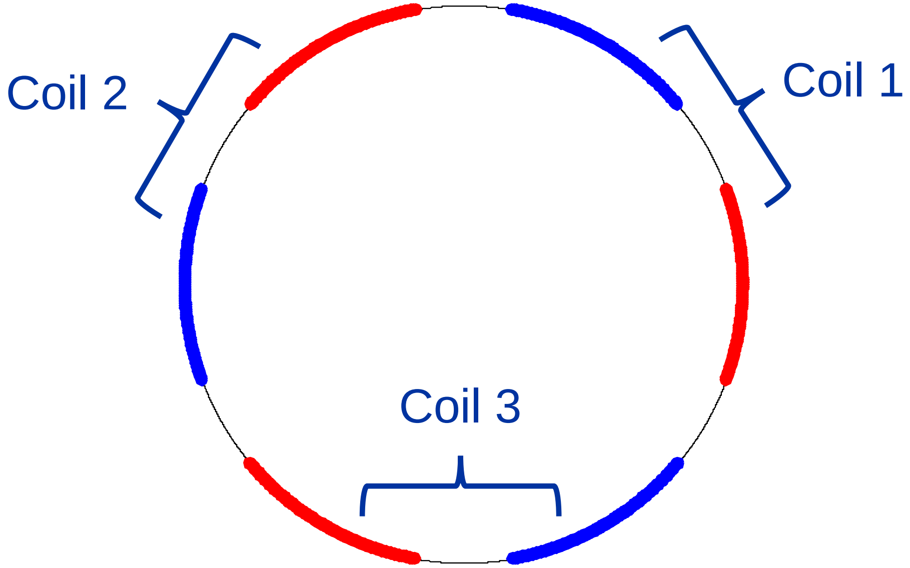
Coils sensitive to one multipole

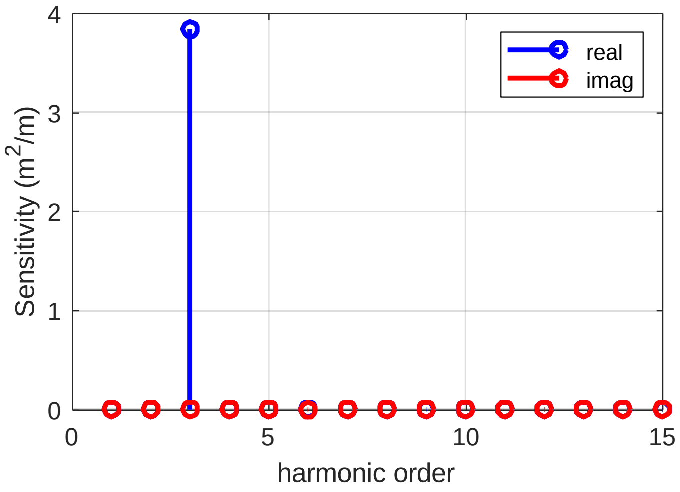
By choosing the appropriate

- number of coils
- winding size
- angle

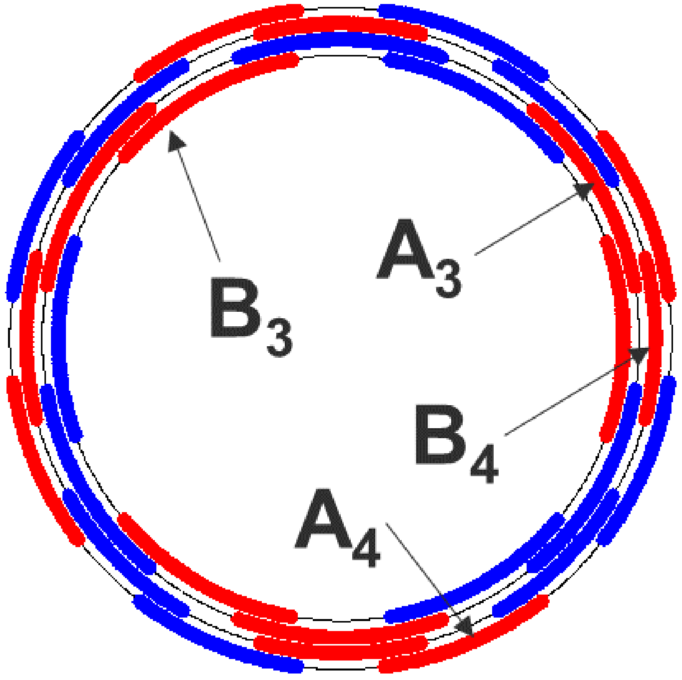
we can build a sensor sensitive almost only to one specific multipole

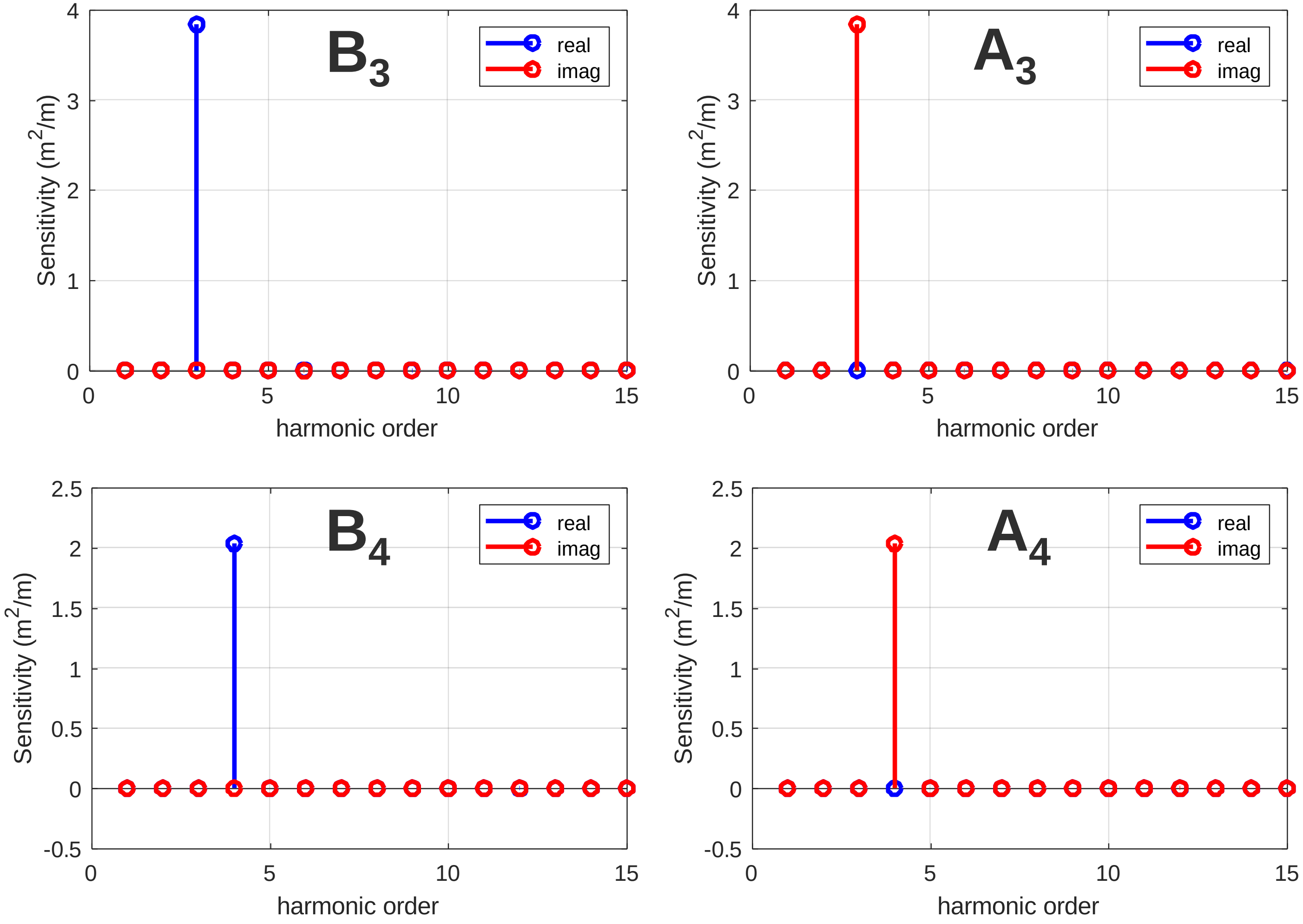
- Example for B3





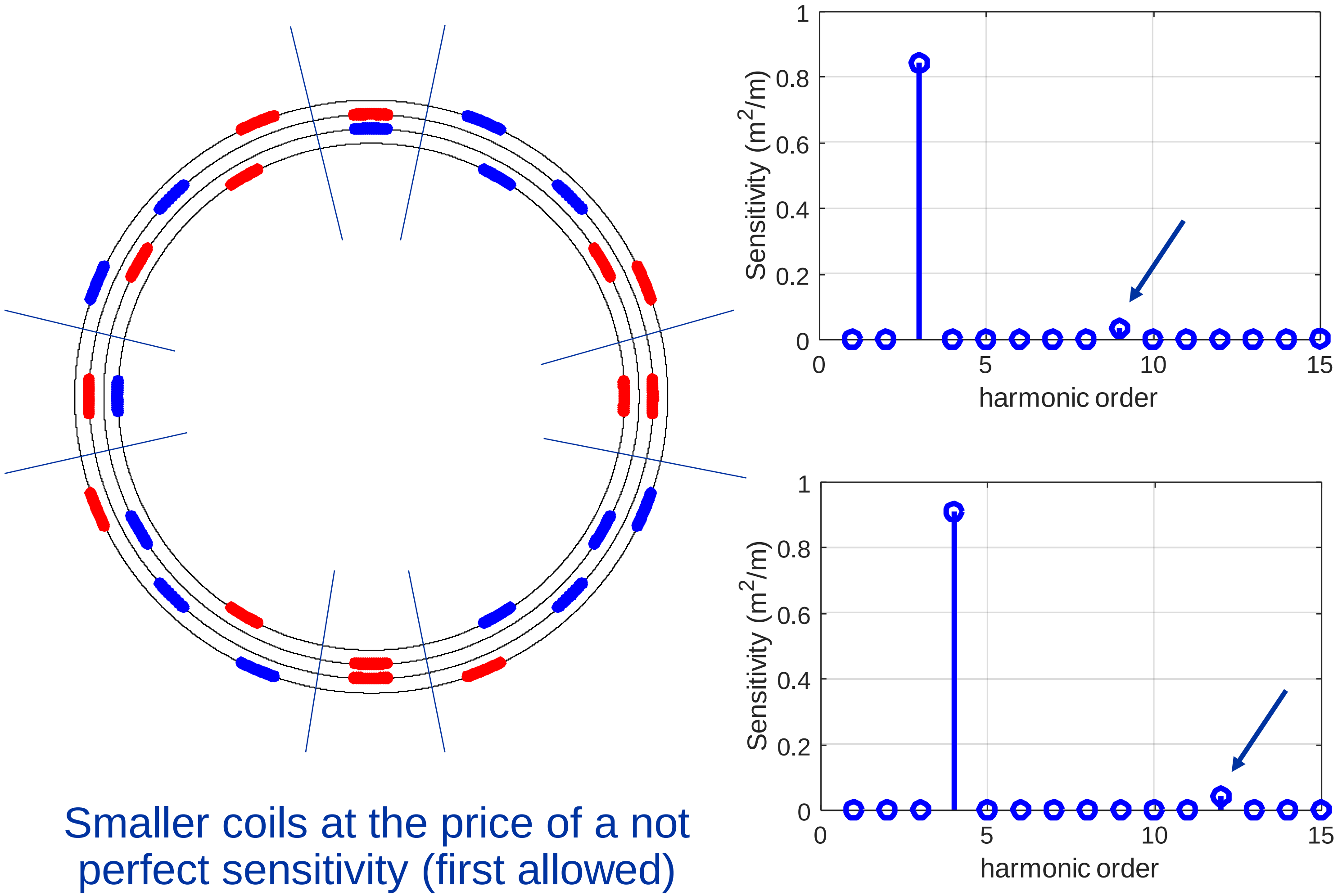
Ideal configuration





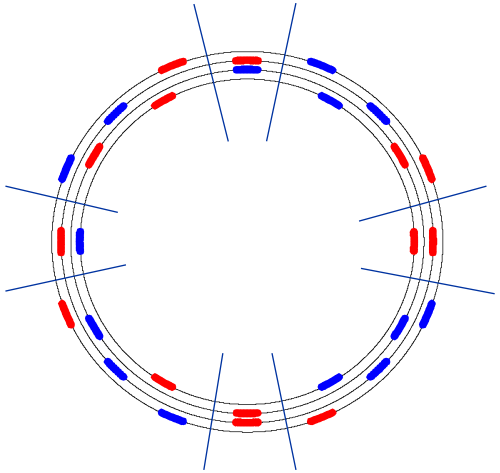
More practical configuration

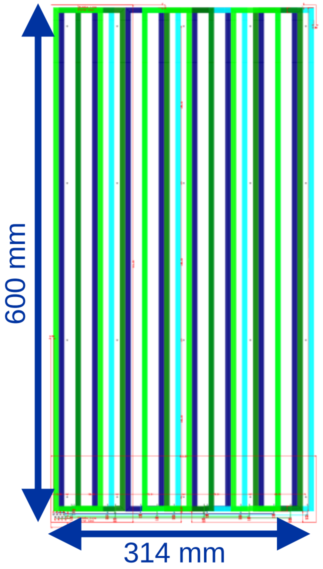
- The 4 sets of coils can be “easily” realized on different layers of a flexible PCB, then wrapped around a support tube.
- The multilayer PCB guarantees the alinement among coils.
- Need of areas free of traces for:
  - making a cut along the PCB
  - placing alignment holes

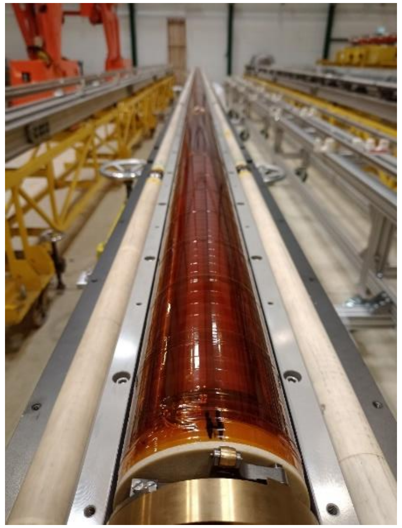


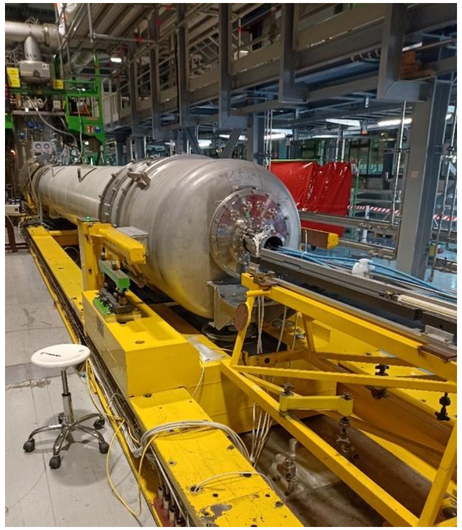
Smaller coils at the price of a not perfect sensitivity (first allowed)

Fabrication and assembly

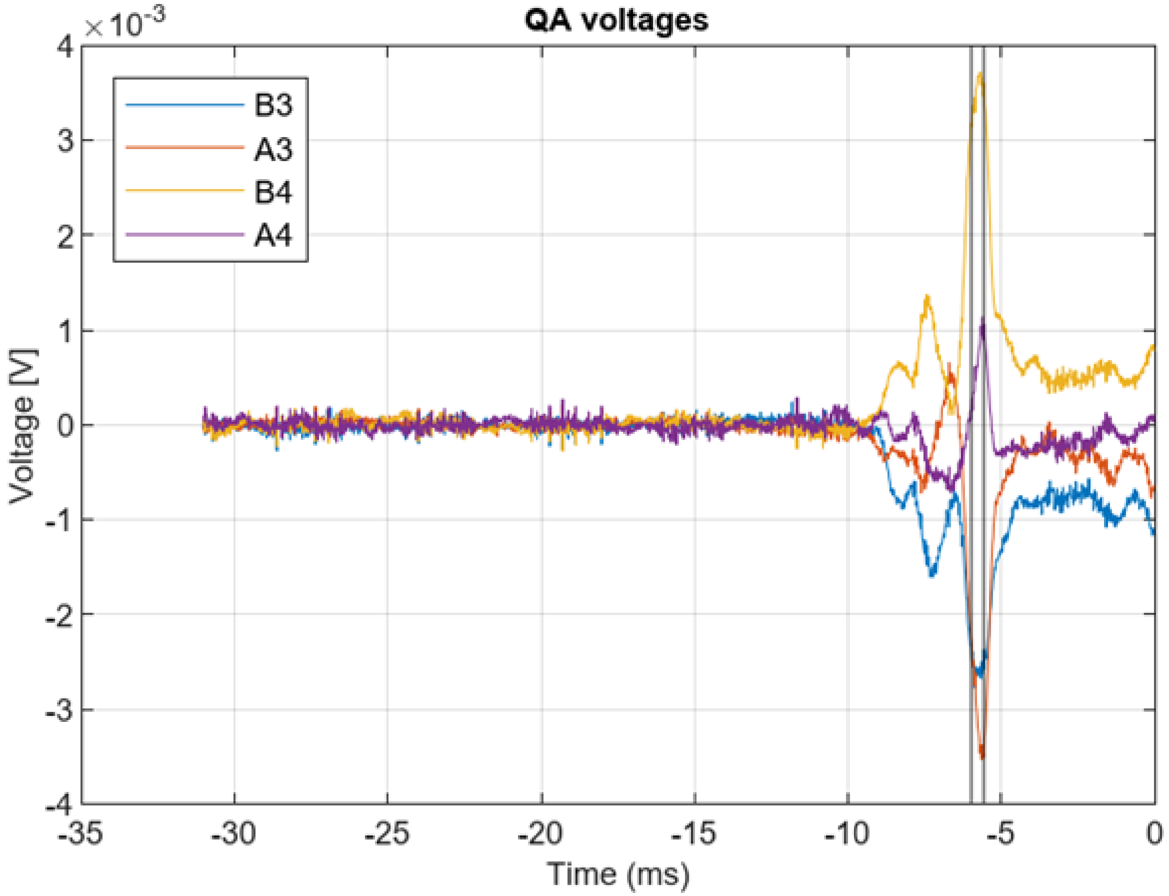


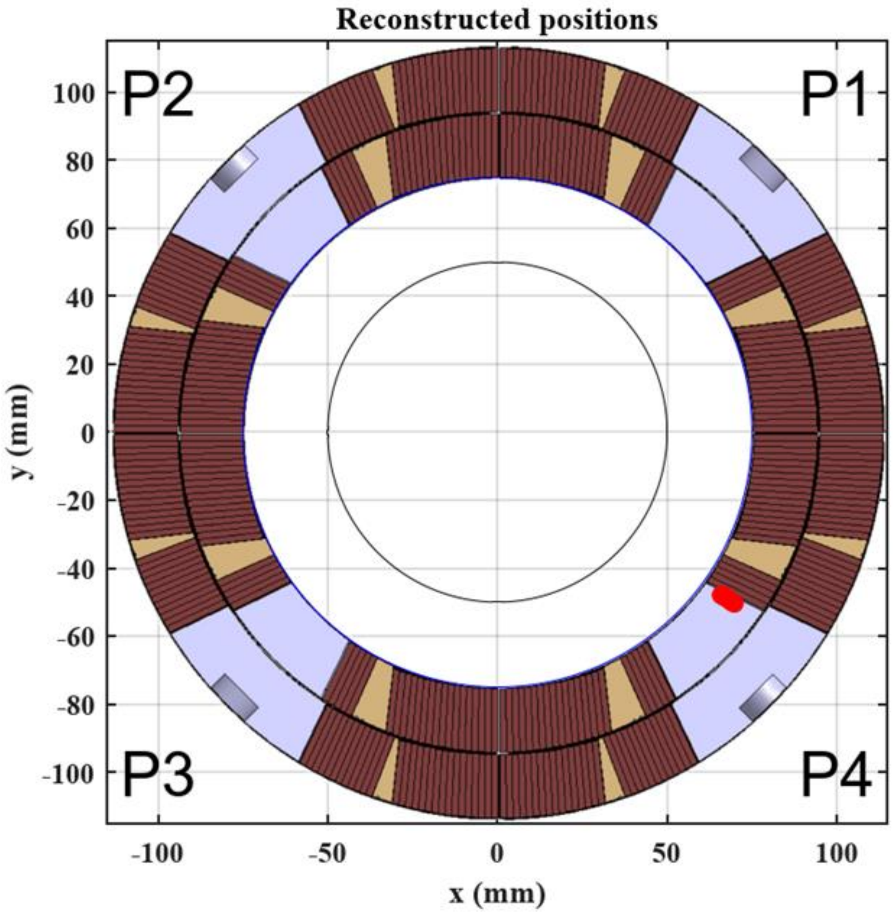




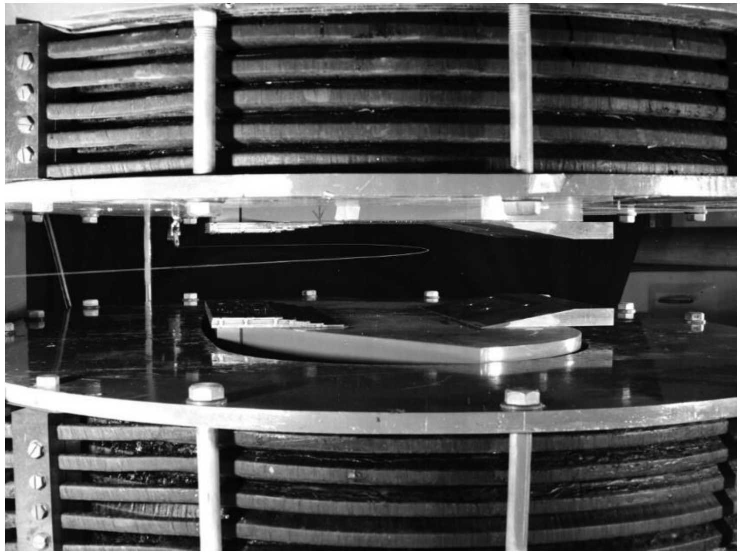


Example of a real quench event





Wires: floating, vibrating, or stretched



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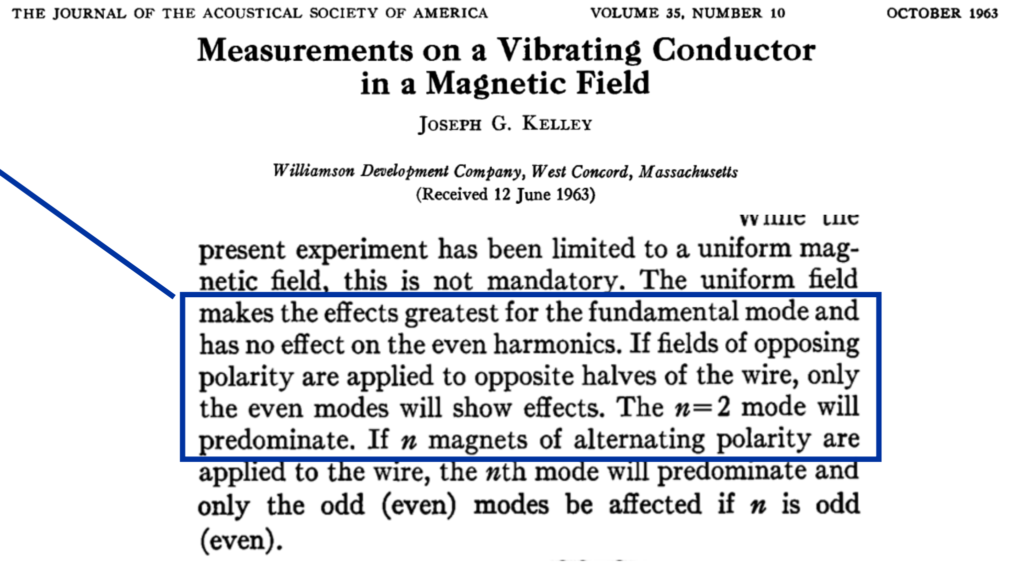
"Floating wire measurements in a bending magnet. A stretched, current-carrying wire simulated the particle trajectory in this analogue technique of the epoch."

Vibrating wire modes (1963)

Stretched wire not accurate enough on a 7-m dipole (1979)

A kind of loose oscillating wire (1959)



THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA VOLUME 35, NUMBER 10 OCTOBER 1963

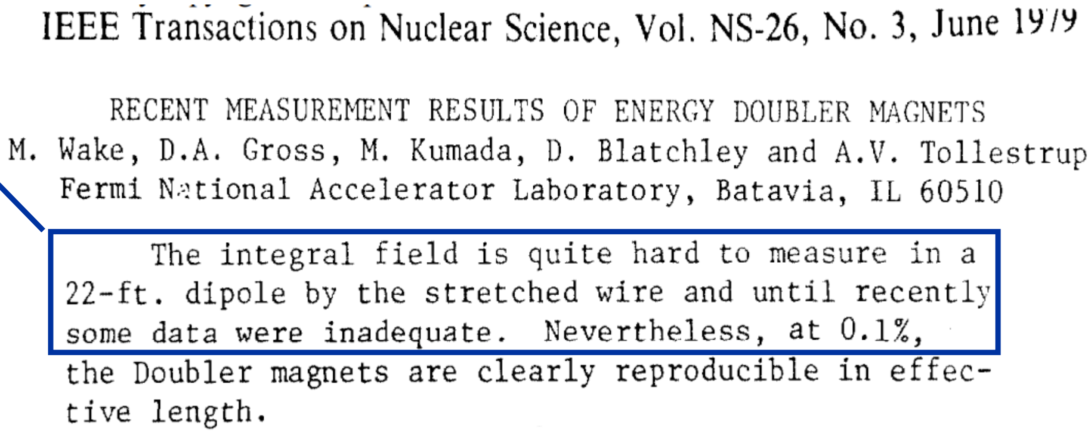
Measurements on a Vibrating Conductor in a Magnetic Field

JOSEPH G. KELLEY

Williamson Development Company, West Concord, Massachusetts

(Received 12 June 1963)

present experiment has been limited to a uniform magnetic field, this is not mandatory. The uniform field makes the effects greatest for the fundamental mode and has no effect on the even harmonics. If fields of opposing polarity are applied to opposite halves of the wire, only the even modes will show effects. The $n=2$ mode will predominate. If n magnets of alternating polarity are applied to the wire, the nth mode will predominate and only the odd (even) modes be affected if n is odd (even).



IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

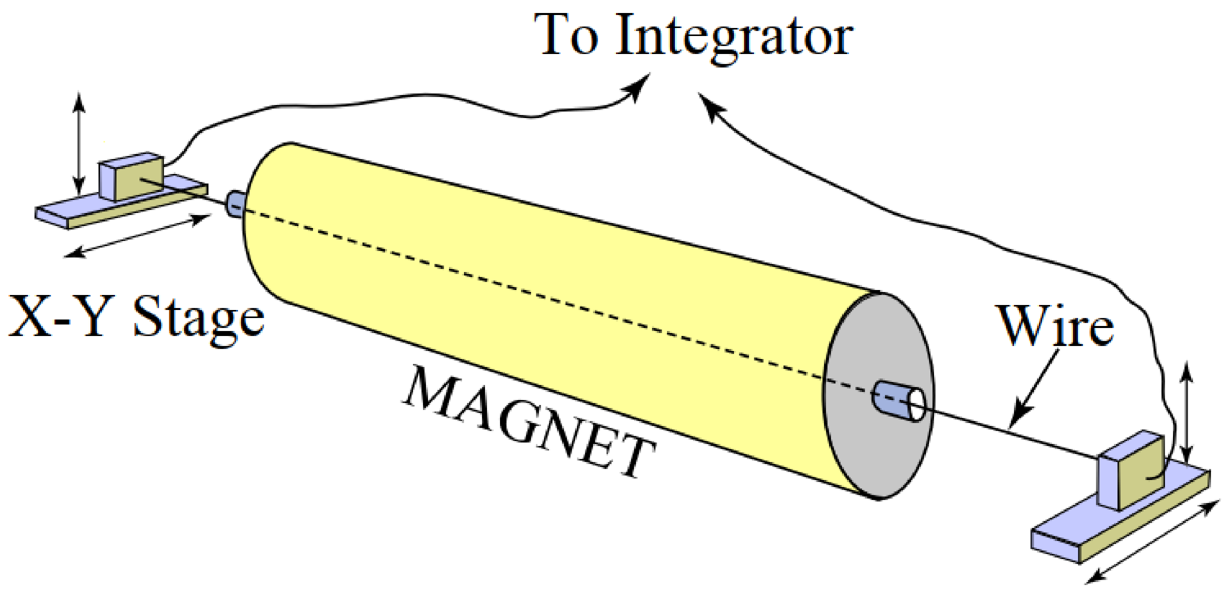
RECENT MEASUREMENT RESULTS OF ENERGY DOUBLER MAGNETS

M. Wake, D.A. Gross, M. Kumada, D. Blatchley and A.V. Tollestrup
Fermi National Accelerator Laboratory, Batavia, IL 60510

The integral field is quite hard to measure in a 22-ft. dipole by the stretched wire and until recently some data were inadequate. Nevertheless, at 0.1%, the Doubler magnets are clearly reproducible in effective length.

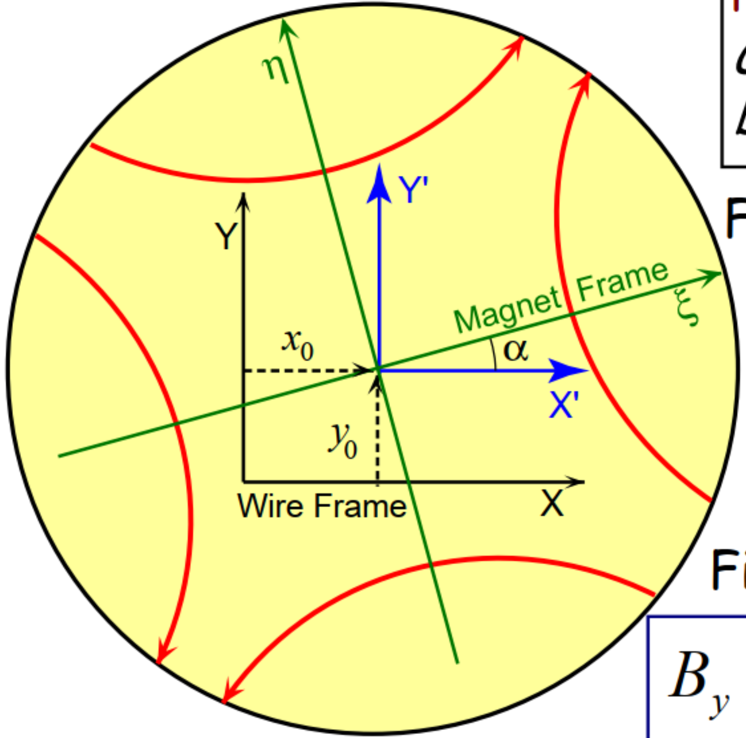
Single stretched wire

- Measurements of the flux change as the wire is moved by known distance in different directions are used to calculate the **magnetic axis**.
- This method gives the axis in an integral sense.
- One can also derive other quantities of interest, such as the **integrated quadrupole gradient** and the **roll angle**.



CERN Academic Training: April 7-11, 2003 - Animesh Jain, BNL

Single stretched wire in a quadrupole



Pure Quadrupole field assumed

G = Gradient

$b_2 = \cos(2\alpha)$; $a_2 = -\sin(2\alpha)$

Field components in X'-Y' frame:

$$B_{y'} = G(b_2 x' - a_2 y')$$
$$B_{x'} = G(b_2 y' + a_2 x')$$

Field components in Wire frame:

$$B_y = G[b_2(x - x_0) - a_2(y - y_0)]$$
$$B_x = G[b_2(y - y_0) + a_2(x - x_0)]$$

Wire misaligned with respect to the magnet

Rotation

Offset

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Single stretched wire in a quadrupole

Change in flux for a horizontal wire motion from X =0 to ±D :

$$\Phi_H^{\pm} = L_m \int_0^{\pm D} B_y \cdot dx = L_m G \left[b_2 \frac{D^2}{2} \underline{\mp (b_2 x_0 + a_2 y - a_2 y_0) D} \right]$$

L_m = Magnetic Length

Similarly, for a vertical wire motion from $Y = 0$ to $Y = \pm D$:

$$\Phi_V^{\pm} = L_m \int_0^{\pm D} B_x \cdot dy = L_m G \left[b_2 \frac{D^2}{2} \underline{\mp (b_2 y_0 - a_2 x + a_2 x_0) D} \right]$$

The integrated gradient, $L_m G$, can be obtained from:

$$L_m G = \left(\frac{\Phi_H^+ + \Phi_H^-}{b_2 D^2} \right) = \left(\frac{\Phi_V^+ + \Phi_V^-}{b_2 D^2} \right)$$

For roll angles, α, less than 7 mrad, $b_2 \approx 1$ may be used with < 0.01% error.

Terms due to misalignment change sign when the displacement change direction

Due to misalignment

The combination of two movements in opposite directions is not sensitive to the offset, and robust versus small rotations

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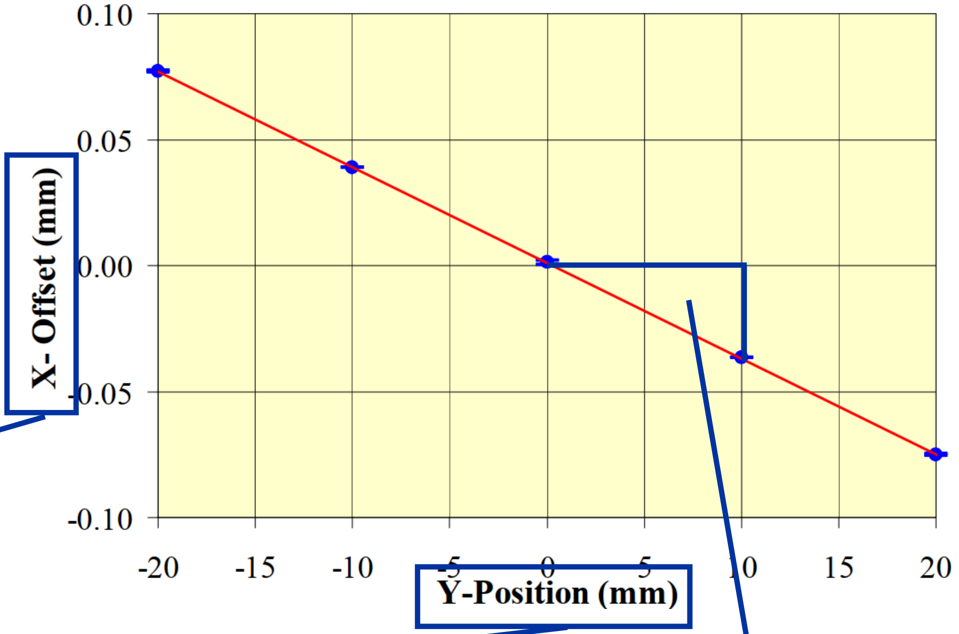
Single stretched wire in a quadrupole

And the offset of the magnetic center:

$$x_0' = -\left(\frac{D}{2}\right)\left(\frac{\Phi_H^+ - \Phi_H^-}{\Phi_H^+ + \Phi_H^-}\right); \quad y_0' = -\left(\frac{D}{2}\right)\left(\frac{\Phi_V^+ - \Phi_V^-}{\Phi_V^+ + \Phi_V^-}\right)$$



The roll angle, α, can be obtained by measuring the quantity x_0' as a function of Y (or y_0' as a function of X) and then fitting a straight line to the data.

-0.035 / 10 mm
=
-3.5 mrad

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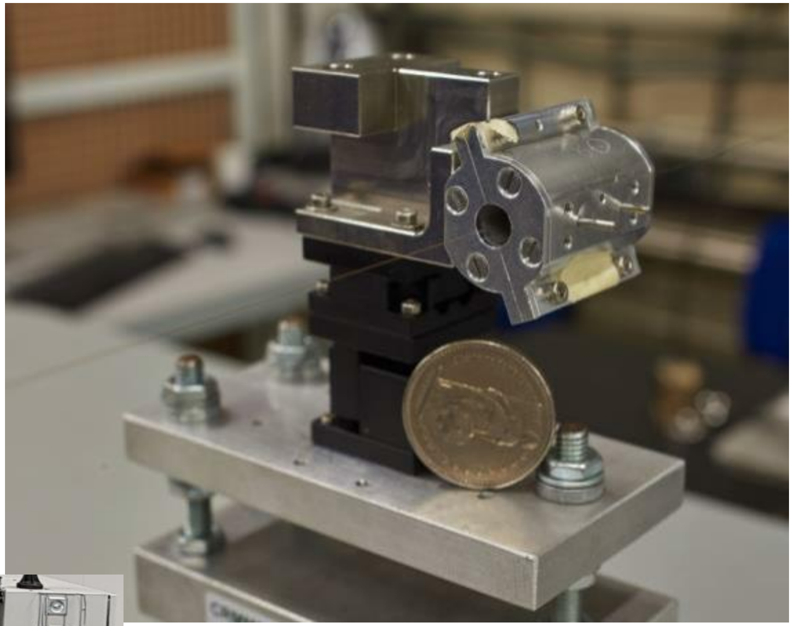
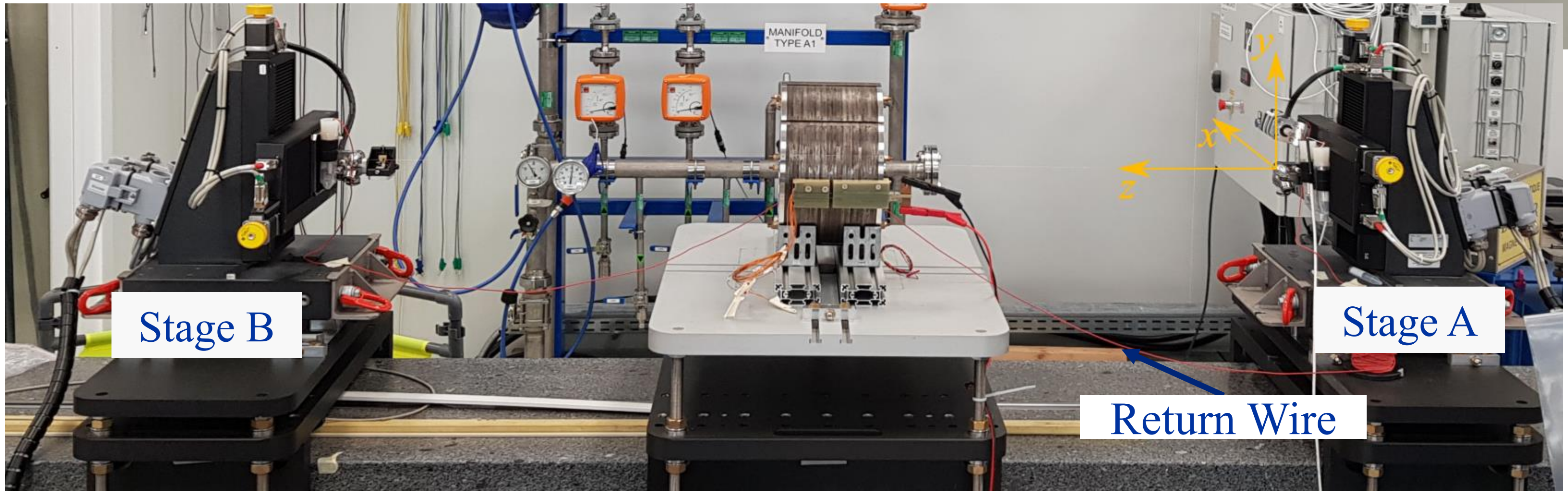
Single stretched wire in reality

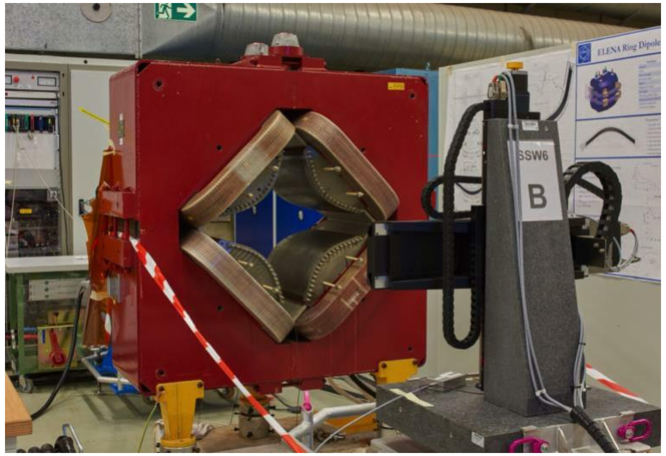
- Positioning stages accuracy <1 μm
- Copper-Beryllium wire 0.125 mm
- Integrator with gain 0.1 to 100

Same hardware for measuring magnets with much different geometry:

- aperture ~10 mm to ~300 mm
- length ~1 cm to ~20 m







Overview of magnetic instruments

Credit M.Buzio

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
Static-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 ($\lambda>0.1$ 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

Conclusions I

Many methods exist for the measurement of magnetic fields. Only some of them are commonly used for measuring accelerator magnets.

- Rotating coils are the most often used tools for characterizing field quality in accelerator magnets.
- Methods based on wires are the reference for integral quantities.
- NMR technique is the standard for absolute accuracy but cannot be used in all situations.
- Hall probes are very popular for point measurements, such as for field mapping on fine meshes.

Conclusions II

The classical techniques and methods for magnetic measurements are very refined. Always start from them!

There is margin for improvement:

- Technology is advancing (better acquisition systems, better motion controllers, more powerful processors, new materials…)
- Numerical calculations are more and more detailed and accurate. Ask yourself what can be computed and what must be measured. Remember: measurements are expensive!

Conclusions III

All measurements are wrong… if uncertainty is not specified.

Once the uncertainty is well determined… all measurements are correct.

- Don’t read a display and provide a result. Always ask yourself “up to which level this measurement is valid?”
- The evaluation of the measurement uncertainty tells more than the measurement itself. It gives hints on how to improve the measurement setup/method.
- A measurement result is always associated to the person who has provided it. Build trust!

… and don’t eat magnets!

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