Gianni Caiafa

Tutor: Pasquale Arpaia

XXXI Cycle - III year presentation

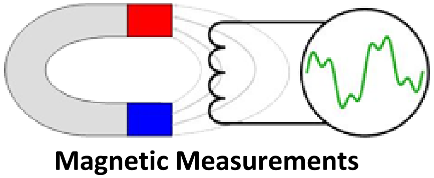
Induction-coil transducers for measuring transversal field harmonics in accelerator magnets

Background

Master's Degree in Electrical Engineer (cum laude)
LM-28 - University of Naples "Federico II"

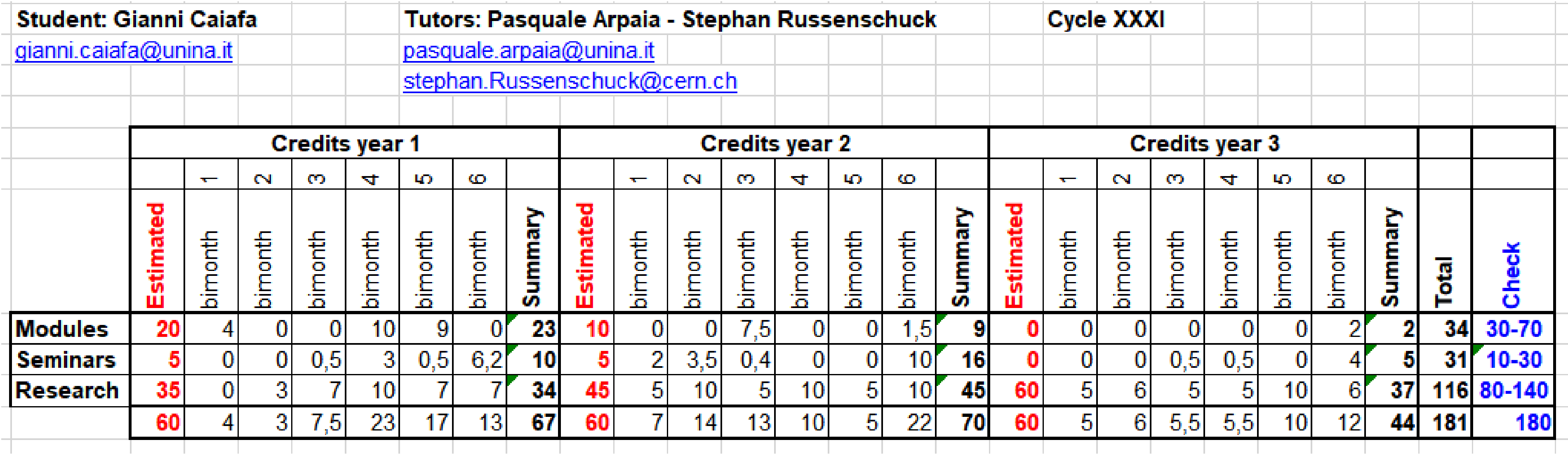
Ph.D. student XXXI Cycle Information Technology and Electrical Engineering, DIETI

Member of Instrumentation & Measurement for Particle Accelerator Lab IMPALAB



Member of Doctoral Student Program at CERN (European Organization for Nuclear Research) Magnetic Measurement (MM) section of the Magnets, Superconductors and Cryostats (MSC) group in the Technology Department (TE)

Credits Summary



Student: Gianni Caiafa **Tutors: Pasquale Arpaia - Stephan Russenschuck** **Cycle XXXI**
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	Credits year 1								Credits year 2								Credits year 3									
	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Estimated	bimonth 1	bimonth 2	bimonth 3	bimonth 4	bimonth 5	bimonth 6	Summary	Total	Check
Modules	20	4	0	0	10	9	0	23	10	0	0	7,5	0	0	1,5	9	0	0	0	0	0	0	2	2	34	30-70
Seminars	5	0	0	0,5	3	0,5	6,2	10	5	2	3,5	0,4	0	0	10	16	0	0	0	0,5	0,5	0	4	5	31	10-30
Research	35	0	3	7	10	7	7	34	45	5	10	5	10	5	10	45	60	5	6	5	5	10	6	37	116	80-140
	60	4	3	7,5	23	17	13	67	60	7	14	13	10	5	22	70	60	5	6	5,5	5,5	10	12	44	181	180

All the established objects have been reached. The all three years have been spent abroad (CERN - Switzerland).

Table of Courses/Seminars (I)

Year	Lecture/Activity	Type	Credits	Certification
1	Field Computation and Magnetic Measurements for Accelerator Magnets	Ad hoc module	4	x
1	Language course- French A1	External Module	7.5	x
1	Electrical Approval Certificate	External Module	2.5	x
1	Misure per l'Automazione e Produzione Industriale	MS Module	9	x
1	The Magnetic Model of the LHC at 6.5 TeV	Seminar	0.5	x
1	Magnetic system and magnetic measurements in EFFL's TCV tokamak	Seminar	0.5	x
1	PACMAN Project: a Study on New Solutions for the High-accuracy Alignment of Accelerator Components	Seminar	0.5	x
1	The translating fluxmeter prototype: early results, Research and development on stretched –wire systems for magnetic measurements	Seminar	2	x
1	Stray Field Measurements	Seminar	0.5	x
1	Seminario di Eccellenza Italo Gorini 2016	Doctoral School	3.7	x
1	Scientific writing	External Seminar	2	x
1	3D computation of magnetic fields and induced currents in hysteretic media with time-periodic sources	External Seminar	0.5	x

Table of Courses/Seminars (II)

2	AWAKE Beam Commissioning	Seminar	0.5	x
2	Identification of Complex Dynamical Systems with Neural Networks	Seminar	1	x
2	GaN for power applications: devices and switching performances	Seminar	0.5	x
2	ADS Workshop	External Seminar	3	x
2	Tokamak Energy - A Faster Way to Fusion	Seminar	0.5	x
2	How to Organise and Write a Scientific Rebuttal	Seminar	0.4	x
2	Language course- English B2	External Module	7.5	x
2	Seminario di Eccellenza Italo Gorini 2016	Doctoral School	3.7	x
2	EUCAS 2017 European Conference on Applied Superconductivity	External Seminar	5	x
2	High temperature superconductors: How to build powerful magnets using these imperfect conductors?	Seminar	1	x
2	Lesson learned the 2-m Nb3Sn 11 T Model Dipole Magnets - From coil fabrication to magnet tests	Seminar	0.5	x
2	First Aider Course	External Module	1.5	x

Table of Courses/Seminars (III)

3	HiLumi-FCC Innovation Course	Seminar	0.5	x
3	Accelerators for Medicine	Seminar	0.5	x
3	Seminario di Eccellenza Italo Gorini 2018	Doctoral School	4	x
3	PMI Project Management	External Module	2	x

Content

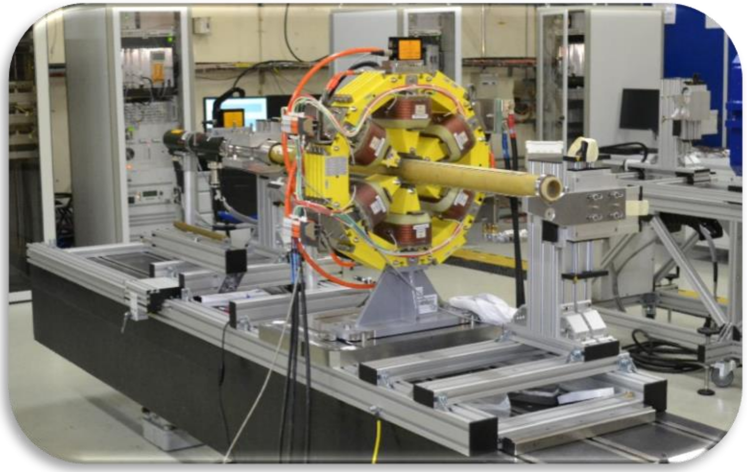
Magnetic Measurements for Accelerator Magnets

Magnetic Measurements for Accelerator Magnets

Why magnetic measurements at CERN?

- To verify the field quality of magnets [1]
- Feedback to steer manufacturing
- Beam optics tracking [2]

Rotating Coil



Stretched/Vibrating Wire

[1] DAVIES, W. G., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1992.

[2] ZANGRANDO, D., et al., Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1996.

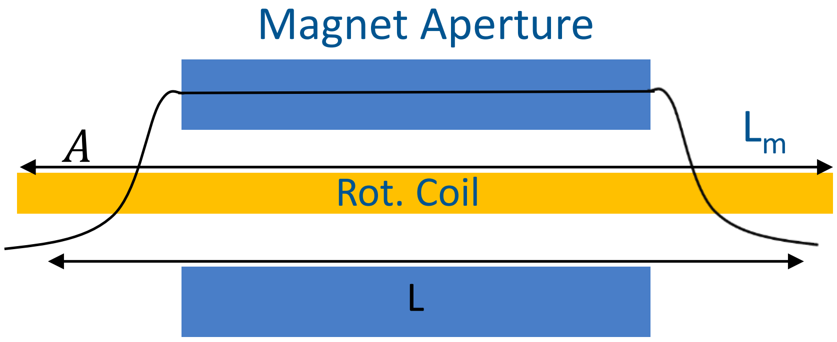
Magnetic Measurements for Accelerator Magnets

Rotating coil-based measurement technology

$$\Phi = N \int_A B \cdot da$$

$$U = -\frac{d\Phi}{dt}$$

Faraday/Lenz Law

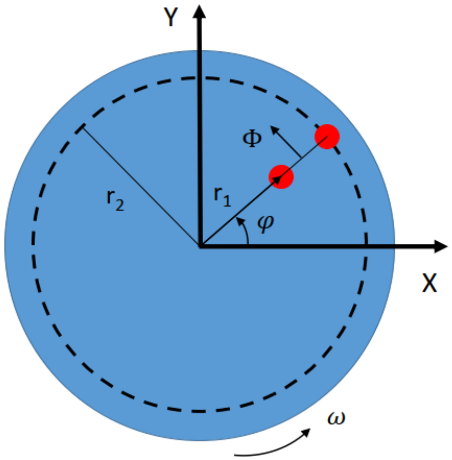


Coil length L_m > Magnet length L

Coil sensitivity factors

$$K_n = K_n^{rad} + iK_n^{tan} = \frac{Nl}{n}\left(r_2^n e^{in(\varphi_2-\varphi)} - r_1^n e^{in(\varphi_1-\varphi)}\right)$$

computed using the tracks average position



Magnetic Measurements for Accelerator Magnets

Rotating coil-based measurement technology

Solving the Laplace equation in 2D $\nabla^2 A_z = 0$, the eingensolutions are

$$A_z(r,\varphi) = \sum_{n=1}^{\infty} r^n (A_n \sin n\varphi + B_n \cos n\varphi)$$

The radial field component is $$B_r(r,\varphi) = \frac{1}{r}\frac{\delta A_z}{\delta\varphi} = \sum_{n=1}^{\infty} n r^{n-1} (A_n \cos n\varphi - B_n \sin n\varphi)$$

Where the coefficients A_n and B_n are called **multipole** or field harmonics

The measured flux is correlated to the fiscal dimension of the coil through the sensitivity factors [3] K_n

$$\Phi(\varphi) = \sum_{n=1}^{\infty} \frac{1}{r_0^{n-1}} \left[K_n^{rad}(B_n(r_0)\cos n\varphi - A_n(r_0)\sin n\varphi) + \right.$$
$$\left. + K_n^{tan}(B_n(r_0)\cos n\varphi - A_n(r_0)\sin n\varphi)\right],$$

[3] Walckiers L., CERN CdS, 1992.

Local Field Distribution Measurements

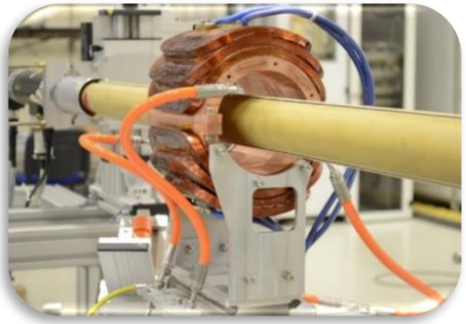
Applications

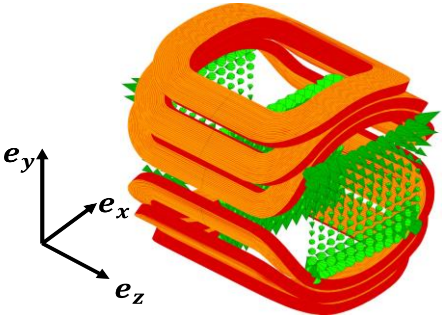
Local Field Distribution Measurements

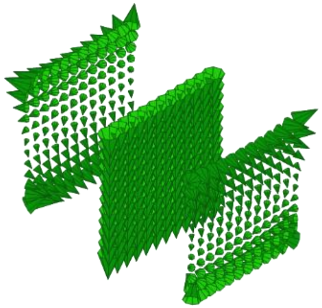
State of Art

Local field distribution measurements are required

- for fringe-field dominated magnets [4]
- when the measurements are to be used for track reconstruction in spectrometers
- for the study of the beam dynamics





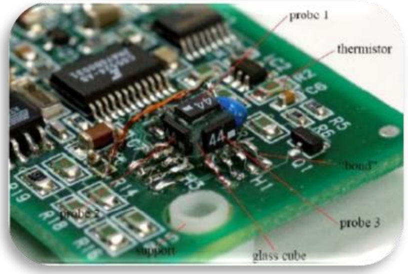


The classical multipole description is no more appropriate for the high non-linear field distribution on the magnet extremities [5]

Fringe field-dominated magnets are short magnets [6] with relatively wide apertures, where the effect of the magnet ends are not negligible

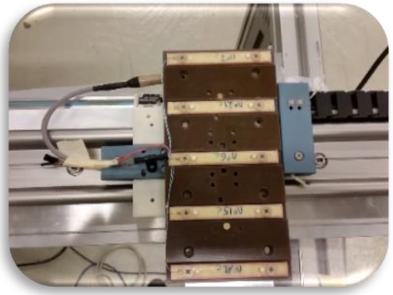
[4] BERZ, Martin, et al., Physical Review Special Topics-Accelerators and Beams, 2000.
[5] RUSSENSCHUCK, Stephan, Book John Wiley & Sons, 2011.
[6] Zhu, Y., et al., Radiation Detection Technology and Methods, 2018.

Local Field Distribution Measurements

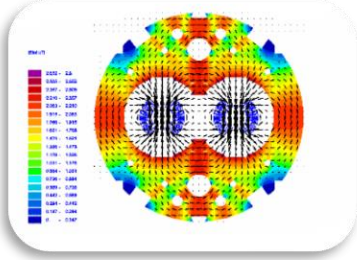


State of Art

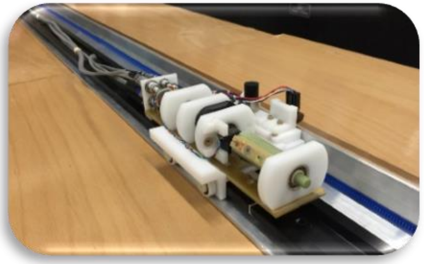
- Full mapping using Hall sensors [7]
  - Not always suitable to measure harmonics



- Translating-coil scanner on the magnet’s mid-plane [8]
  - Harmonics number limited by the transversal resolution (number of induction coils)



- FEM/BEM analysis validated by integral measurements [5]
  - Manufacturing errors and dynamic effects are not evaluated



- Measuring on the boundary surface by using short rotating coils [9] applying the concept of **pseudo-multipoles**
  - Fringe field region effects [10] and convolution

[7] S. Sanfilippo, IMMW20, 2017.
[8] I. Bolshakova, et al., IEEE transactions on applied superconductivity, 2004.
[9] E. De Matteis, Doctoral dissertation, CERN, 2016.
[10] P. Arpaia, et al., Journal of Instrumentation, 2015.

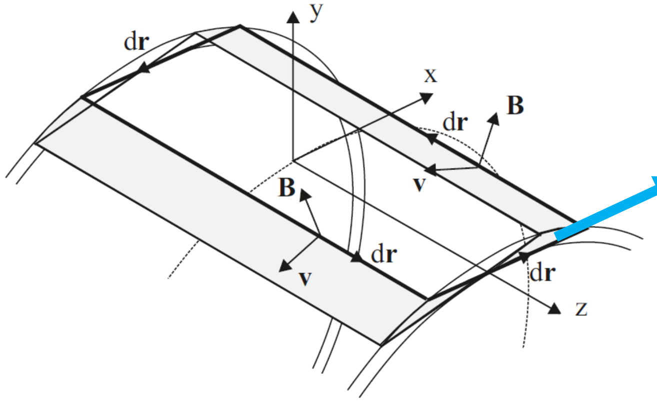
Local Field Distribution Measurements

Proposal: Short Iso-Perimetric Rotating Coil

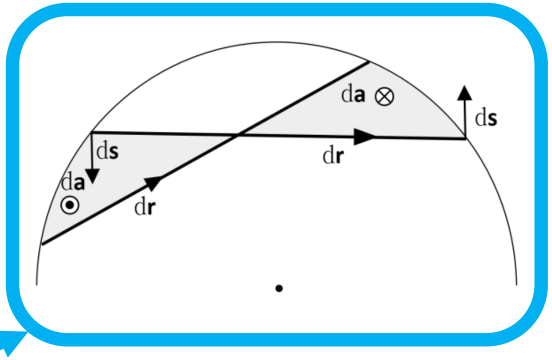
Local Field Distribution Measurements

Proposal: Short Iso-Perimetric Rotating Coil

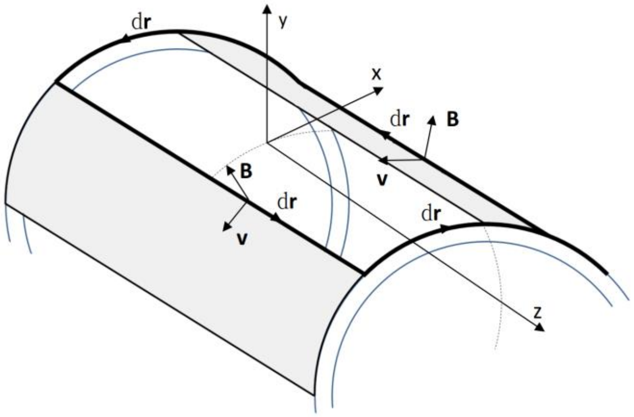
To perform this measurement, the coil magnetometer must be non-sensitive to the longitudinal ($\mathbf{B}_z$) field component. This requires an **Iso-Perimetric coil** [11]. The total field distribution is computed using the **pseudo-multipole** mathematical model



Tangential coil geometry



$$\begin{aligned}\int_{t_1(s_1)}^{t_2(s_2)} U(\partial A)\cdot dt &= \int_{t_1(s_1)}^{t_2(s_2)}\int_{\partial A}(\mathbf{v}\times\mathbf{B})\cdot d\mathbf{r}\,dt\\ &= \int_{t_1(s_1)}^{t_2(s_2)}\int_{\partial A}-\mathbf{B}\cdot(\mathbf{v}\times d\mathbf{r})dt\\ &= \int_{t_1(s_1)}^{t_2(s_2)}\int_{\partial A}-\mathbf{B}\cdot(\mathbf{v}dt)\times d\mathbf{r}\\ &= \int_{\partial A}\int_{s_1}^{s_2}-\mathbf{B}\cdot(d\mathbf{s}\times d\mathbf{r})\\ &= \int_{A_s}-\mathbf{B}\cdot d\mathbf{a}\,,\end{aligned}$$



Iso-Perimetric coil geometry

[11] P. Arpaia, **G. Caiafa**, submitted to Scientific Reports- Nature, September 2018.

Technical Details

Pseudo-Multipoles Mathematical Model

Technical Details

Pseudo-Multipoles Mathematical Model

The field components can be calculated from a magnetic scalar potential obeying the Laplace equation

$$\nabla^2 \phi_m = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \phi_m}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 \phi_m}{\partial \varphi^2} + \frac{\partial^2 \phi_m}{\partial z^2} = 0$$

Eingensolutions are given by a Fourier-Bessel series that can be approximated by

$$\phi_m(r,\varphi,z) = \sum_{n=1}^{\infty} r^n (\widetilde{C}_n(r,z)\sin(n\varphi) + \widetilde{D}_n(r,z)\cos(n\varphi))$$

Field components at any radius within the bore of the magnet

$$B_r(r,\varphi,z) = -\mu_0 \sum_{n=1}^{\infty} r^{n-1} (\bar{C}_n(r,z)\sin(n\varphi) + \bar{D}_n(r,z)\cos(n\varphi)) \ ,$$

$$B_\varphi(r,\varphi,z) = -\mu_0 \sum_{n=1}^{\infty} n r^{n-1} (\widetilde{C}_n(r,z)\cos(n\varphi) + \widetilde{D}_n(r,z)\sin(n\varphi))$$

$$B_z(r,\varphi,z) = -\mu_0 \sum_{n=1}^{\infty} r^n (\frac{\partial \widetilde{C}_n(r,z)}{\partial z}\sin(n\varphi) + \frac{\partial \widetilde{D}_n(r,z)}{\partial z}\cos(n\varphi))$$

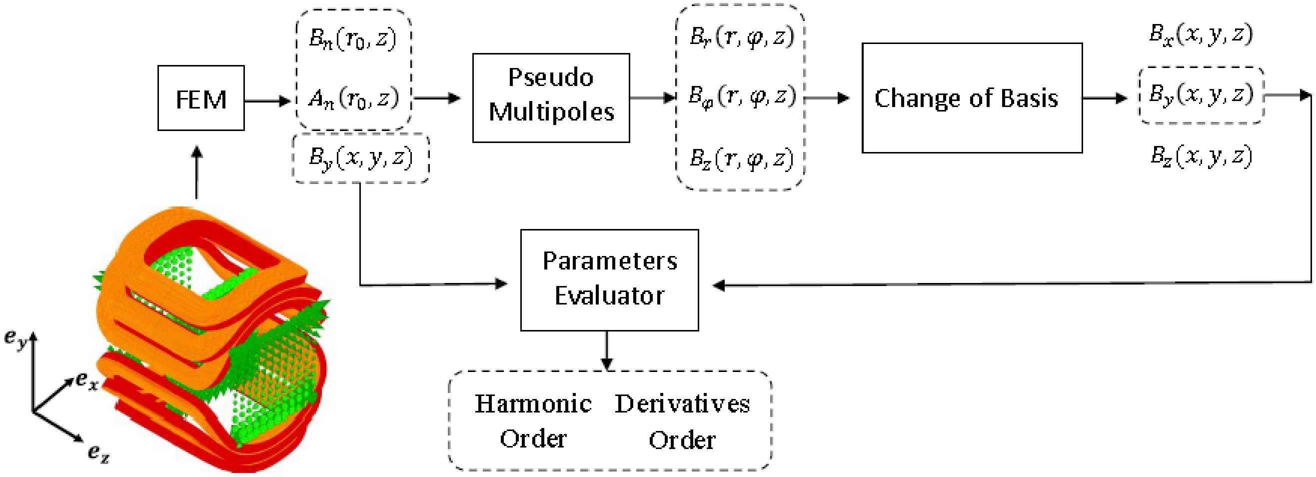
Technical Details

Pseudo-Multipoles Mathematical Model

The challenge is to find a suitable order *n* of the pseudo-multipoles $C_{n,n}$ and the highest order derivatives $C_{n,n}^{(m)}$ in Eq.

$$\bar{C}_n(r,z) = n\,C_{n,n}(z) - \frac{(n+2)C_{n,n}^{(2)}(z)}{4(n+1)}r^2 + \frac{(n+4)C_{n,n}^{(4)}(z)}{32(n+1)(n+2)}r^4 + \ldots$$

to minimize the reconstruction uncertainty of the local magnetic field distribution [11]



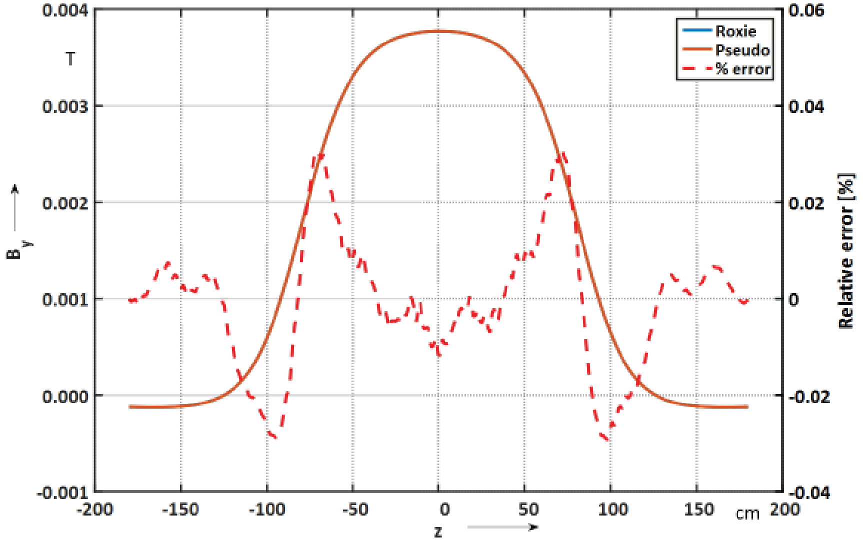
Method for assessing the design parameters: harmonic order *n* and derivative order *m*

Technical Details

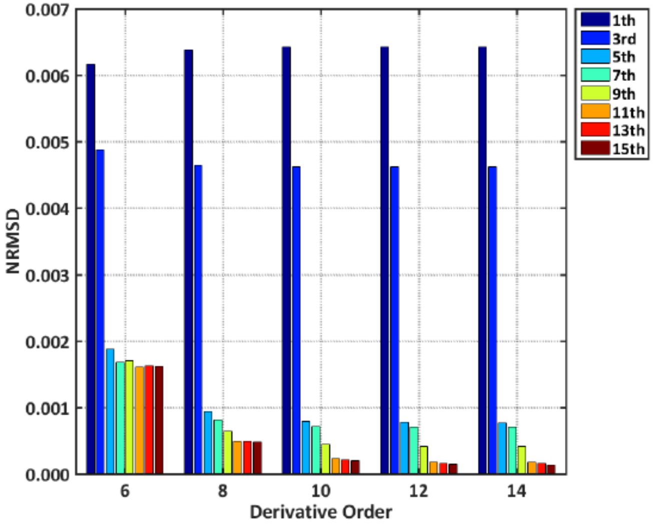
Pseudo-Multipoles Mathematical Model

Using computed field distributions and boundary values, a metric for the reconstruction uncertainty can be given by the residual R_B expressed as the normalized root-mean-square error [16]

$$R_B = \frac{1}{B_y(K/2)} \sqrt{\frac{\sum_{k=1}^{K} [B_y(k) - B_y^p(k)]^2}{K}},$$



B_y field component and reconstruction error (in percent) along z using *n*=15 and *m*=14



Numerical results of the field reconstruction residual R_B versus derivative *m* and harmonic order *n*. *n*=[1,...,15] and *m*=[6,...,14]

[16] P. Arpaia, **G. Caiafa**, 2nd PACMAN workshop, 2016.

Technical Details

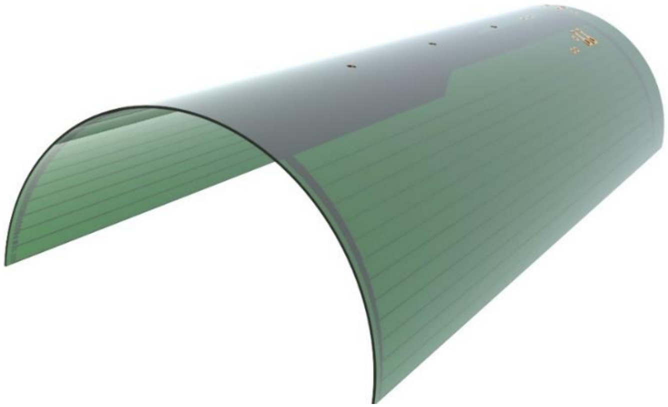
Iso-Perimetric Sensor Design

Technical Details

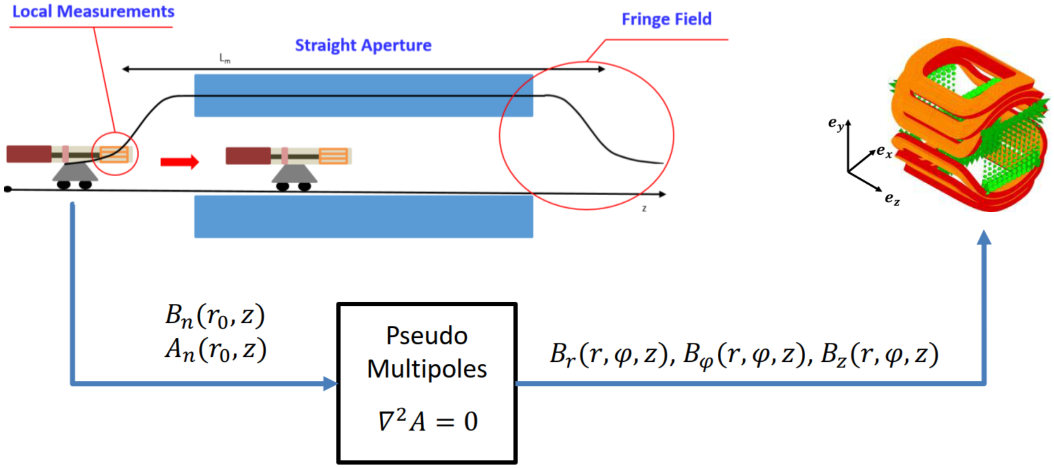
Iso-Perimetric Sensor Design

Magnetic measurements in the fringe-field regions require a ***short iso-perimetric*** coil [11]

Measuring on the boundary surface and applying the concept of pseudo-multipoles, we obtain the entire field description [14]



Layout iso-perimetric coil



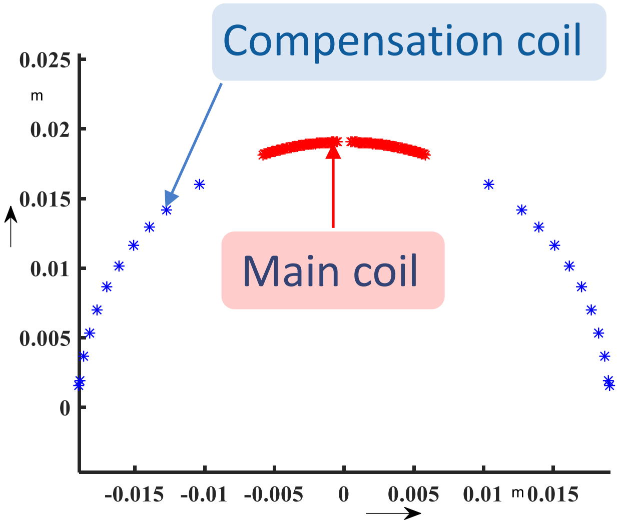
Sketch of the measurement process

[14] P. Arpaia, **G. Caiafa**, International Magnetic Measurement Workshop (IMMW20), 2017.

Technical Details

Ref. [1]

Iso-Perimetric Sensor Design [11]


Compensation coil

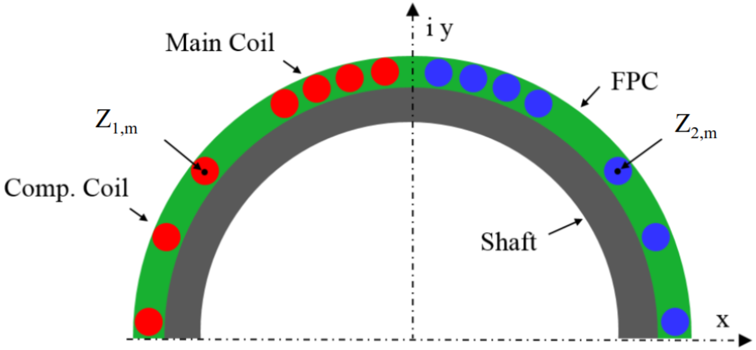
Main coil

Central coil (**Main Coil**) sensitive to higher-order field harmonics

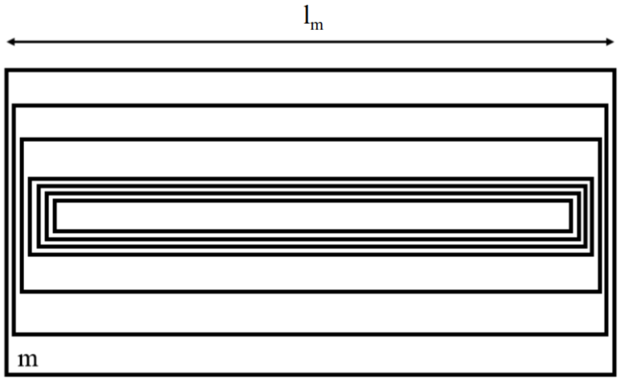
Compensation coil designed to be sensitive only to the main dipole field component

Coils are combined on a common shaft

Design optimized by ROXIE



2D section view



Top view

FPC: Flexible Printed Circuit

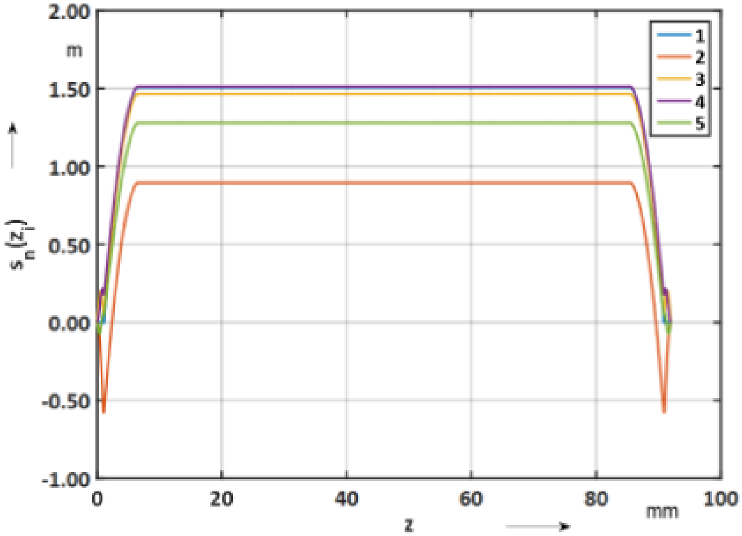
Technical Details

Ref. [1] [2]

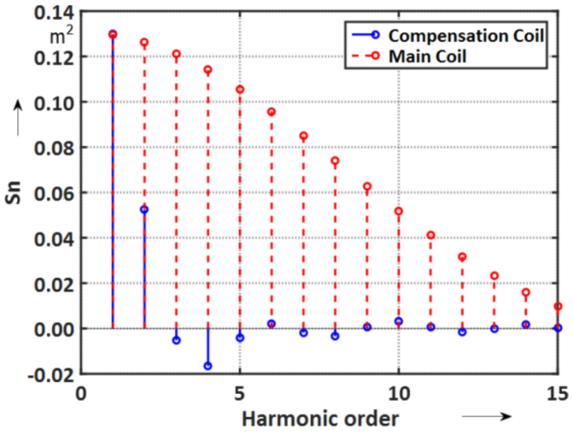
Iso-Perimetric Sensor Design [11]

$$K_n = \sum_{m=1}^{M} \frac{N l_m}{n} \left(z_{2,m}^n - z_{1,m}^n \right) \qquad S_n := \frac{K_n}{R_{\mathrm{ref}}^{n-1}}$$

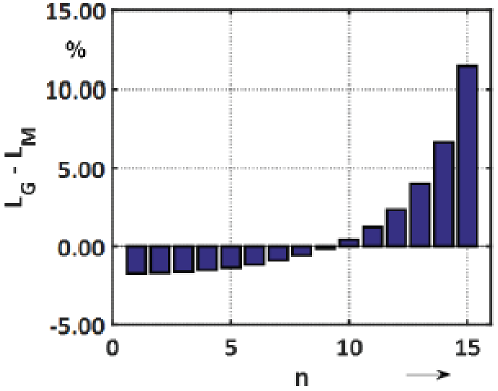
K_n factors for PCB coils **computed using the position of each track**



Compensated coil **sensitivity functions** along the induction coil (R_{ref} = 19 mm)



Sensitivity factors Sn at R_{ref} = 19 mm for the main and compensation coils



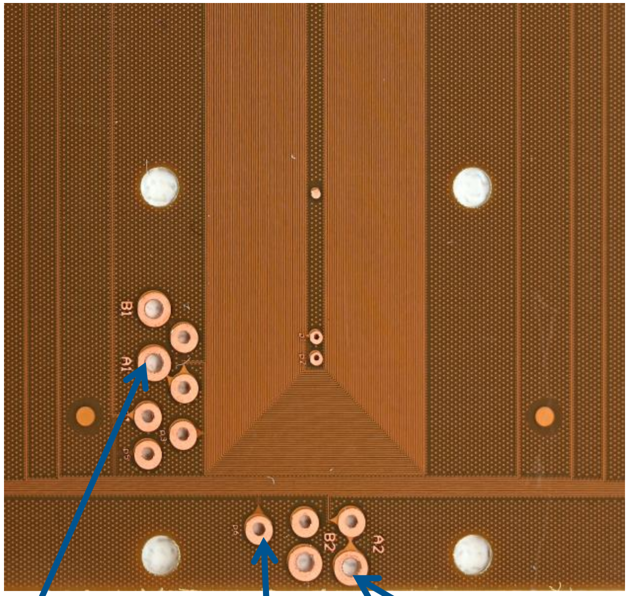
Differences between the geometric mean and magnetic lengths as a function of the multipole order n

Technical Details

Iso-Perimetric Sensor/Transducer Production

Technical details

Iso-Perimetric Sensor Production [12]



In-out pins
main coil

Layer jump
“via”

In-out pins
compensation coil

Sensor dimension:

total length	98.2 mm
diameter	38.1 mm
thickness	240 µm

Main coil dimension:

turns	59
surface	0.13 m^2
measuring length	84.3 mm

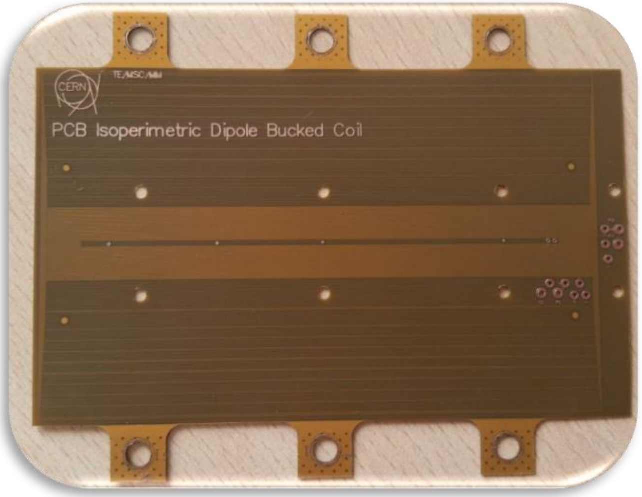
Compensation coil dimension:

turns	11
surface	0.13 m^2
measuring length	90.9 mm

[12] P. Arpaia, **G. Caiafa**, to be submitted to Sensor and Actuators A: Physical, 2018.

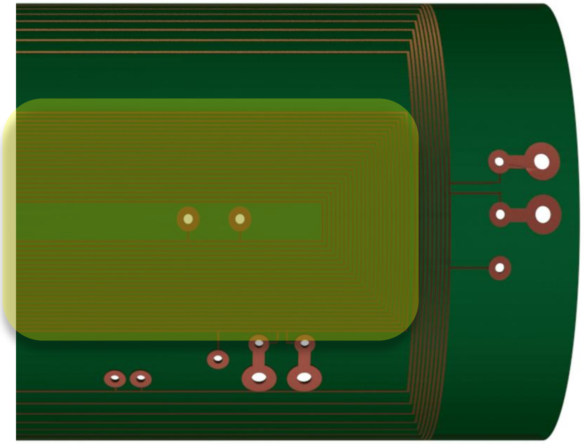
Technical Details

Iso-Perimetric Sensor Production

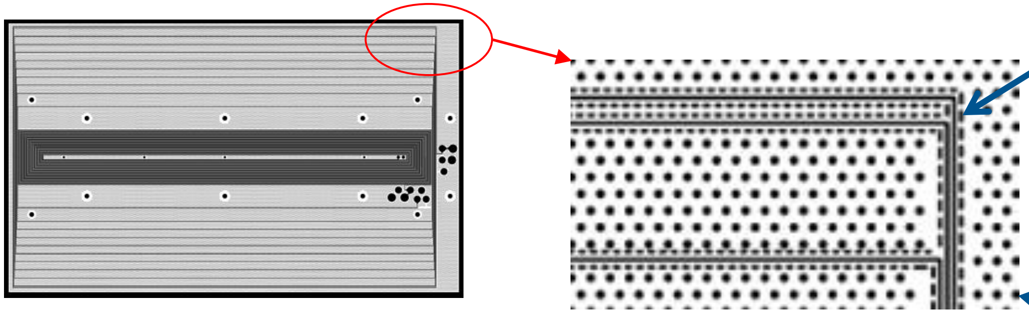


Produced FPC

Main coil



Additional tracks (dashed) around the compensation coil's tracks to avoid a concentration of acid during the edging process [15]



Copper points on the substrate to increase the rigidity

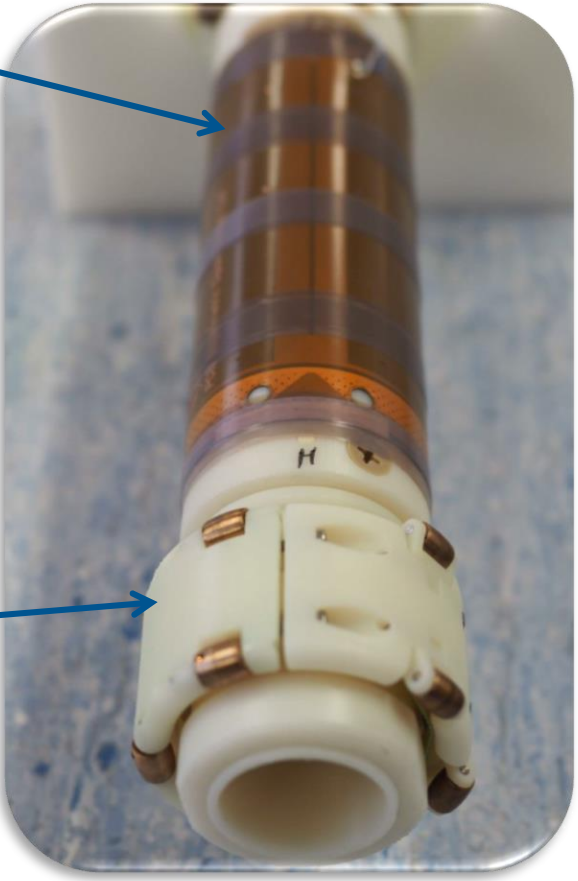
Production solution

[15] P. Arpaia, **G. Caiafa**, IEEE SENSORS 2018, 2018.

Technical Details

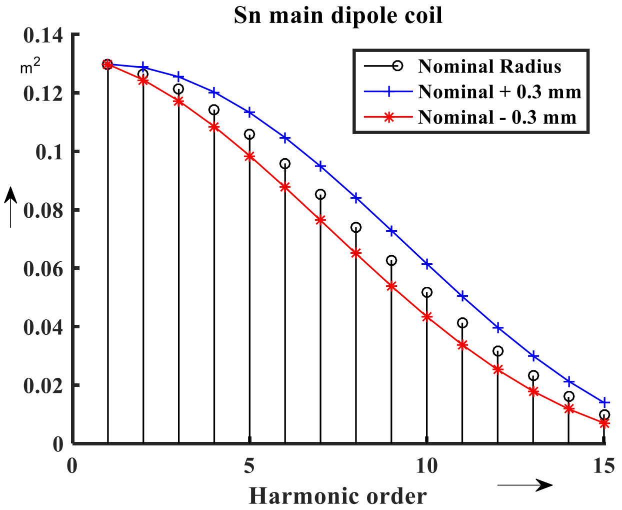
Iso-Perimetric Transducer Production (1st prototype)

FPC



Roller

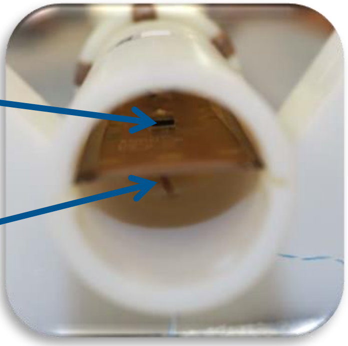
Uncertainty analysis on the production tolerances



S_n computed in the radius tolerance range (-0.3 mm; +0.3 mm)

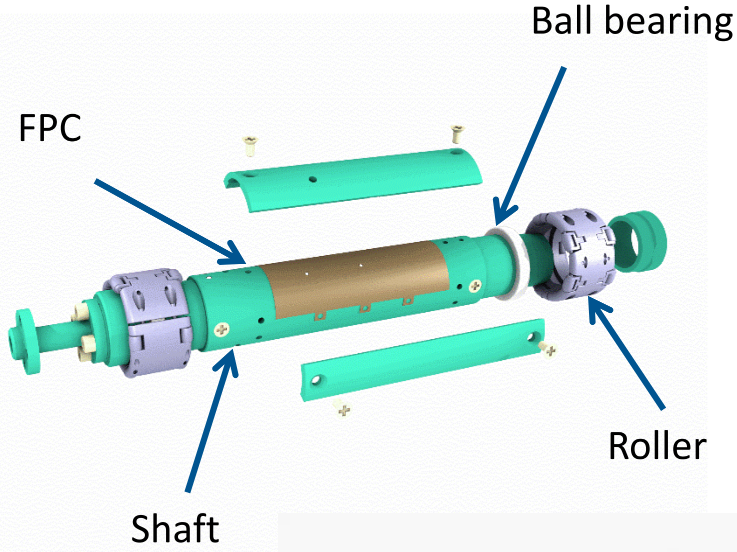
Hall Probe

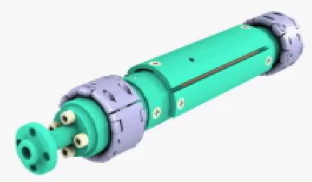
Radial PCB coil

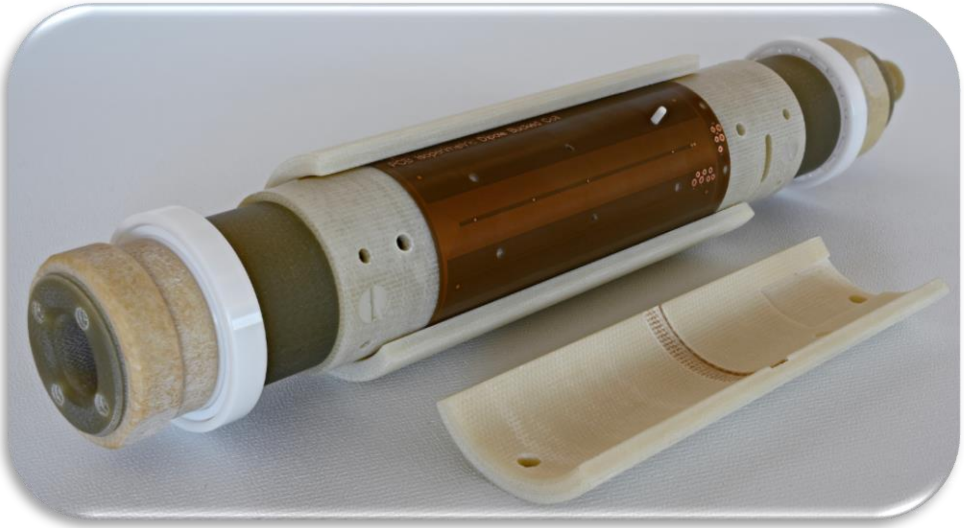


Technical Details

Iso-Perimetric Transducer Production (2nd prototype)







Prototype assembly [13]

- shaft EPGC203 (G11)
- ceramic ball bearings
- 3D printed rollers

[13] P. Arpaia, **G. Caiafa**, to be submitted IEEE Transactions on Instrumentation and Measurement, 2018.

Technical Details

Calibration and Proof of Principle

Technical Details

Calibration [13]

First Prototype

	Design	Calibrated	Error %
Main Coil	0.12960	0.12855	0.81
Comp. Coil	0.12981	0.13323	-2.63

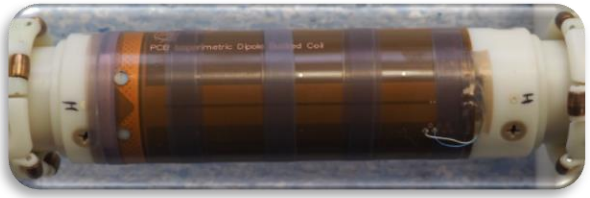
Second Prototype

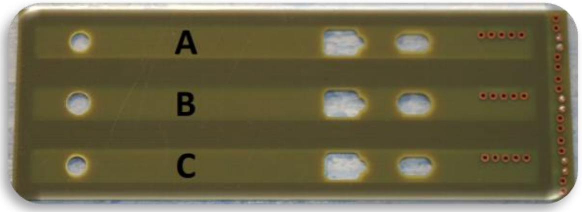
	Design	Calibrated	Error %
Main Coil	0.12960	0.1292	-0.3
Comp. Coil	0.12981	0.1295	-0.2

Calibration in a reference dipole magnetic field uniformity 10 µT

Technical Details

Proof of Principle

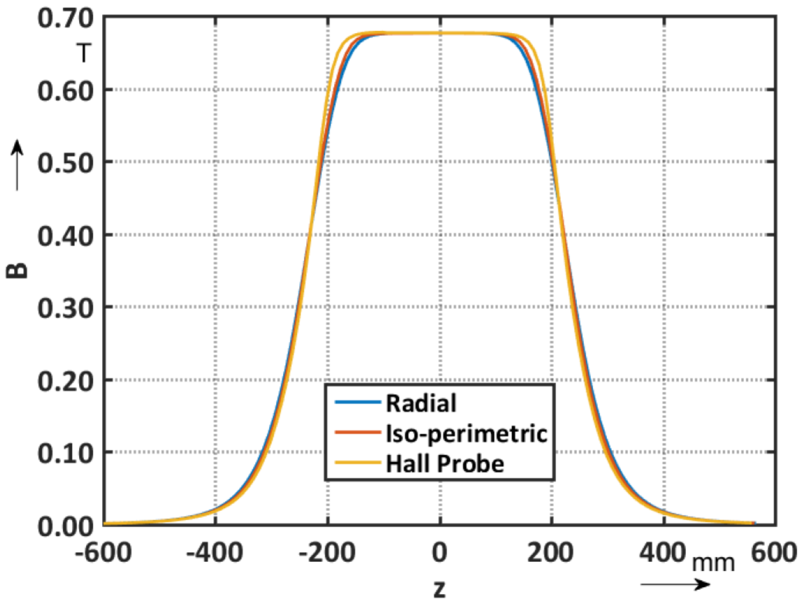




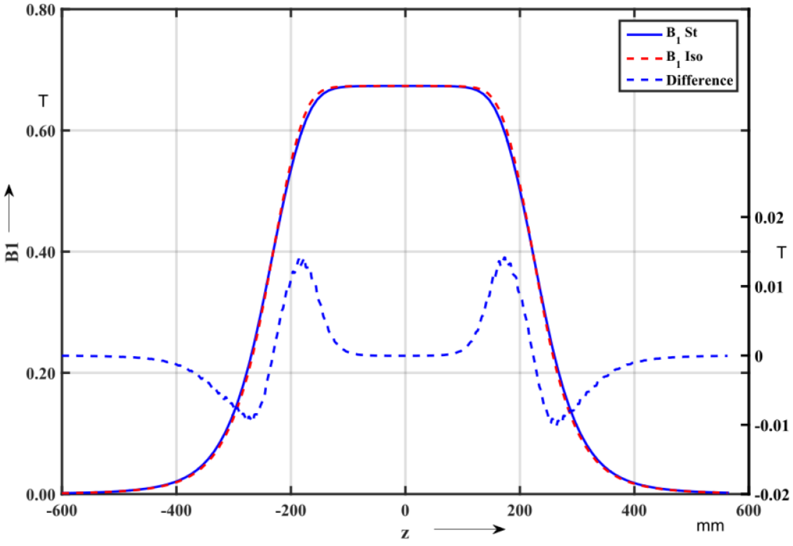
🟥 Iso-Perimetric

🟦 Radial

🟨 Hall Probe



B_1 field component



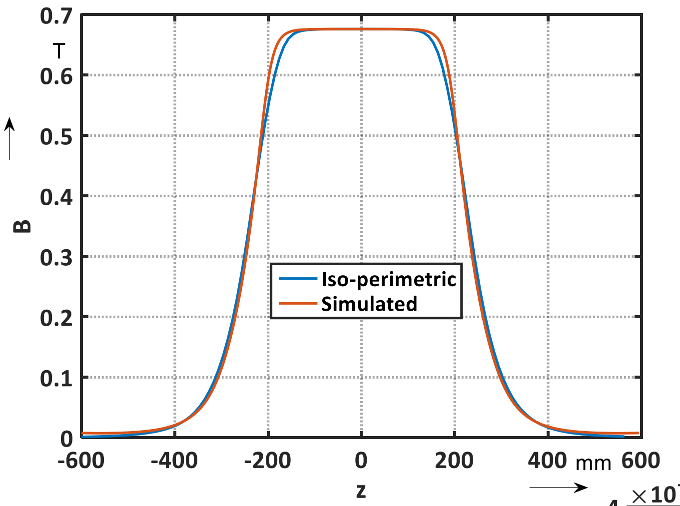
Difference Radial – Iso-perimetric coil

Technical Details

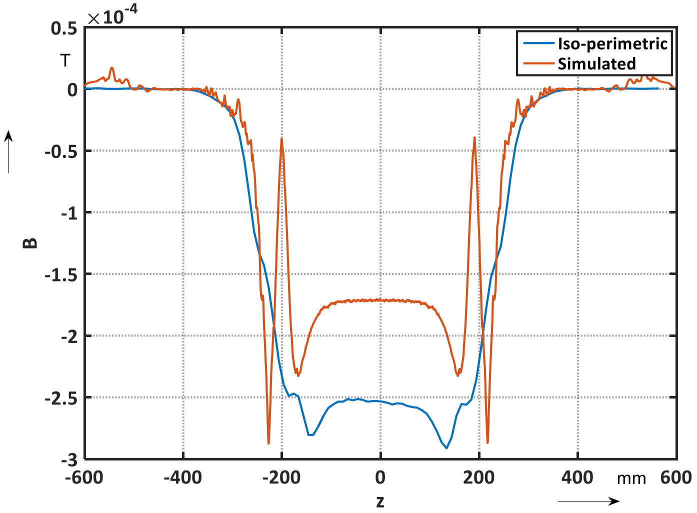
Ref. [3] [5]

Proof of Principle

Measured transversal field distribution of a bending magnet (Dipole)



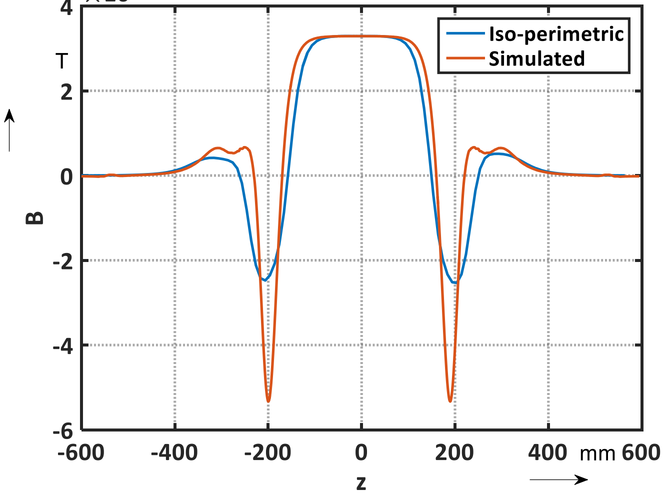
B_1 field distribution



B_5 field distribution

🟥 Simulated

🟦 Measured

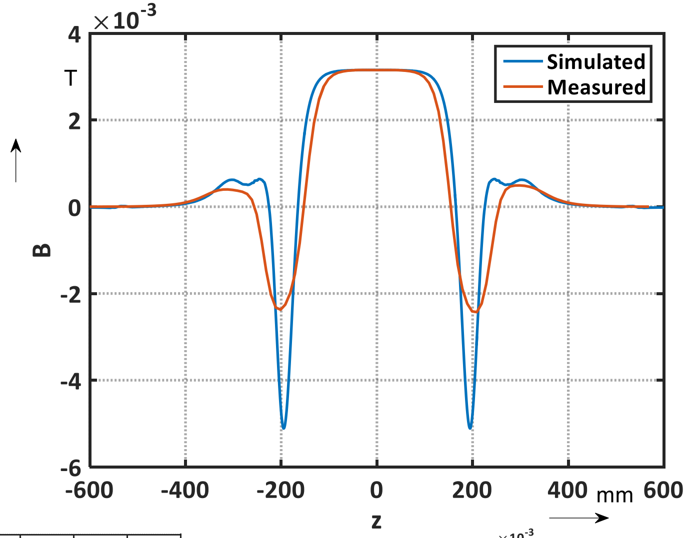


B_3 field distribution

Technical details

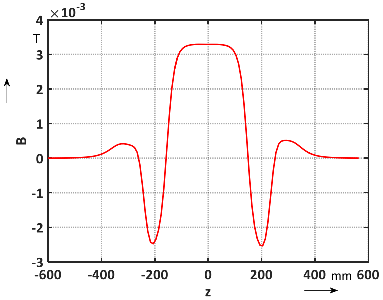
Proof of Principle

The measured longitudinal field profile is a convolution between the field profile and the sensitivity function of the transducer $\widetilde{B}_n(r_0,z) = B_n(r_0,z) \star k_n(r_0,z)$



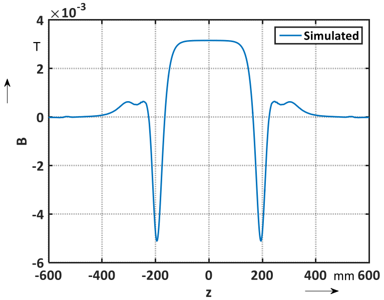
▬ Simulated B_3 field profile

▬ Measured B_3 field profile



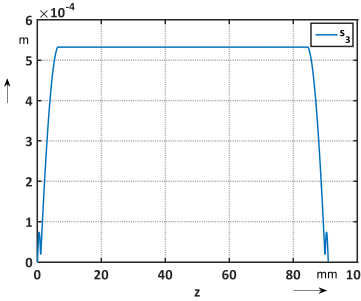
Measured B_3 field component

=



Computed B_3

*



Sensitivity function s_3

Technical Details

Proof of Principle: Deconvolution of Measured Data

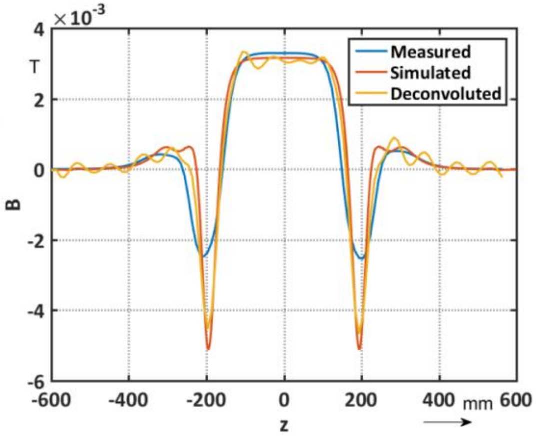
The measured data are affected by noise $\widetilde{B}_n(r_0,z) = \Big(s_n(z) * B_n(r_0,z)\Big) + n(z)$

In frequency domain $\mathscr{F}\{\widetilde{B}_n(r_0,z)\} = \mathscr{F}\{s_n(z)\}\mathscr{F}\{B_n(r_0,z)\} + \mathscr{F}\{n(z)\}$

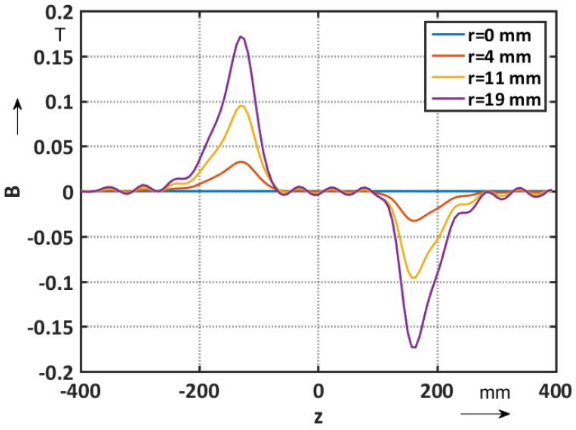
The deconvolution $\mathscr{F}\{\hat{B}_n(r_0,z)\} = \dfrac{\mathscr{F}\{\widetilde{B}_n(r_0,z)\}}{\mathscr{F}\{s_n(z)\}}$ can be solved by using the Wiener-Kolmogorov

$$\mathscr{F}\{W(z)\} = \frac{1}{\mathscr{F}\{s_n(z)\}} \frac{|\mathscr{F}\{s_n(z)\}|^2}{|\mathscr{F}\{s_n(z)\}|^2 + \frac{\mathbb{E}[\mathscr{F}\{n(z)\}]^2}{\mathbb{E}[\mathscr{F}\{B_n(r_0,z)\}]^2}}$$

- ➢ **SNR of the expected profile needed**
- ➢ **Noisy results**



Deconvoluted B_3 field component



Reconstructed B_z field component using the pseudo-multipole method

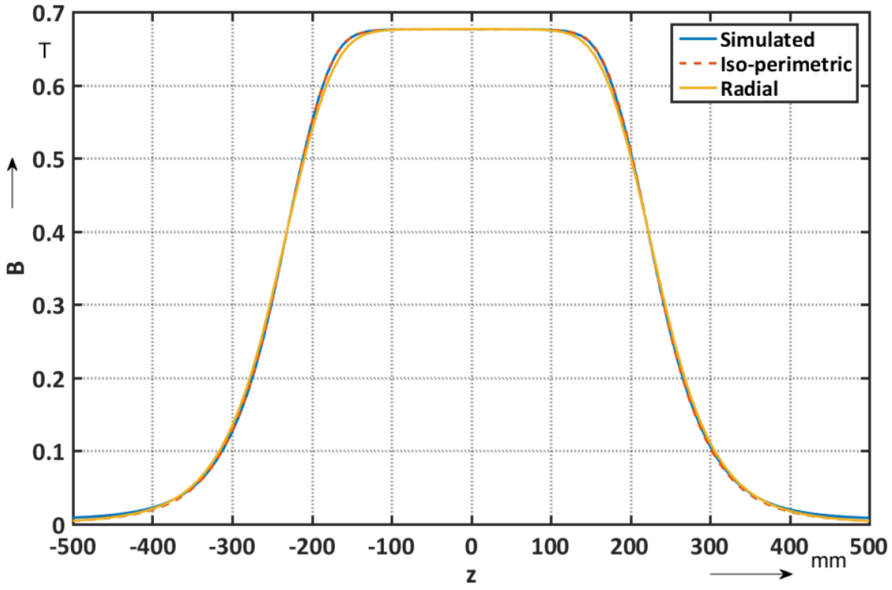
Technical details

Proof of Principle: Convolution of Computed Data

The deconvolution technique (Wiener-Kolmogorov filtering) needs the expected SNR of the reconstructed signal, furthermore the deconvolution results are noisy

Instead, applying the convolution between the simulated field profiles and the coil sensitivity functions, is possible to compare directly measurements and FEM results

The study of the beam dynamics could rely on simulated data validated by measurements

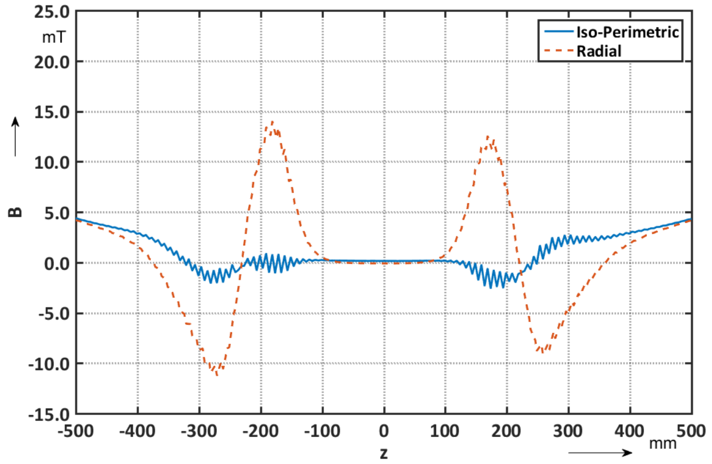


Convoluted B_1 field distribution

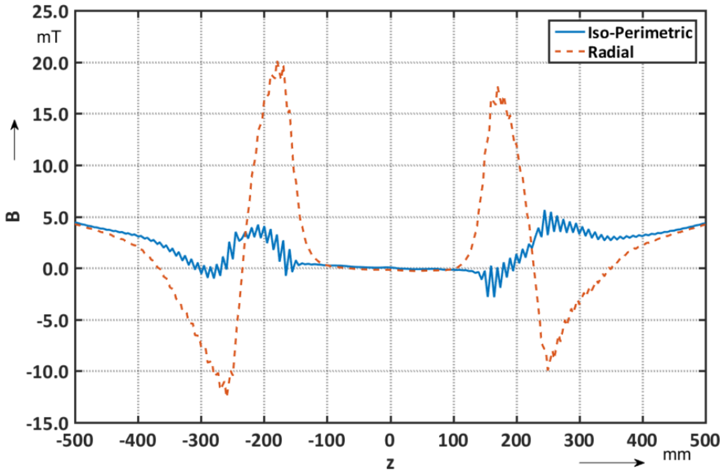
Technical details

Proof of Principle: Convolution of Computed Data

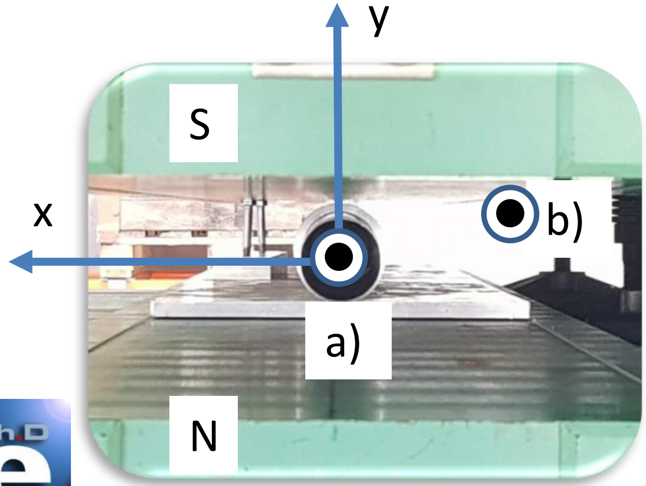
Differences between the convoluted and the measured signal from Iso-perimetric (blue) and radial coil (red)



a)



b)

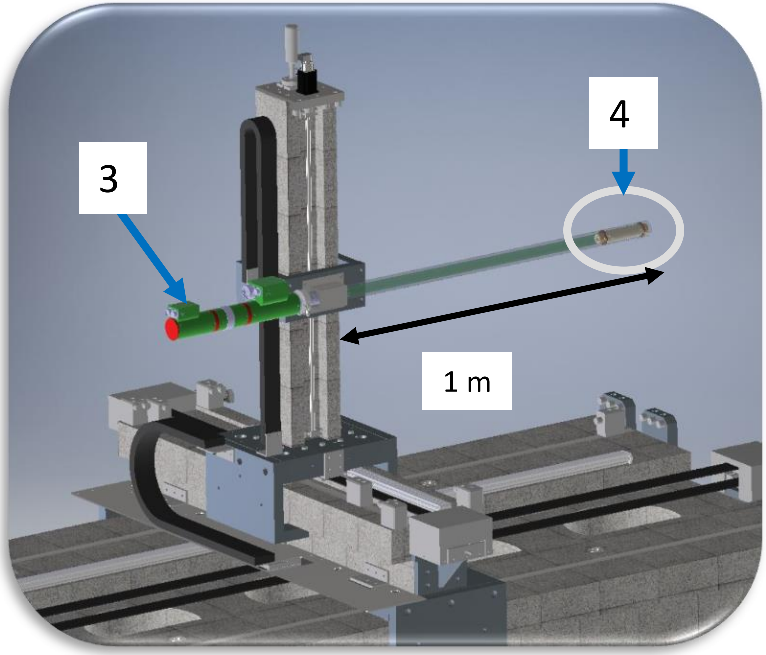


a) Magnet aperture center
b) Off-center

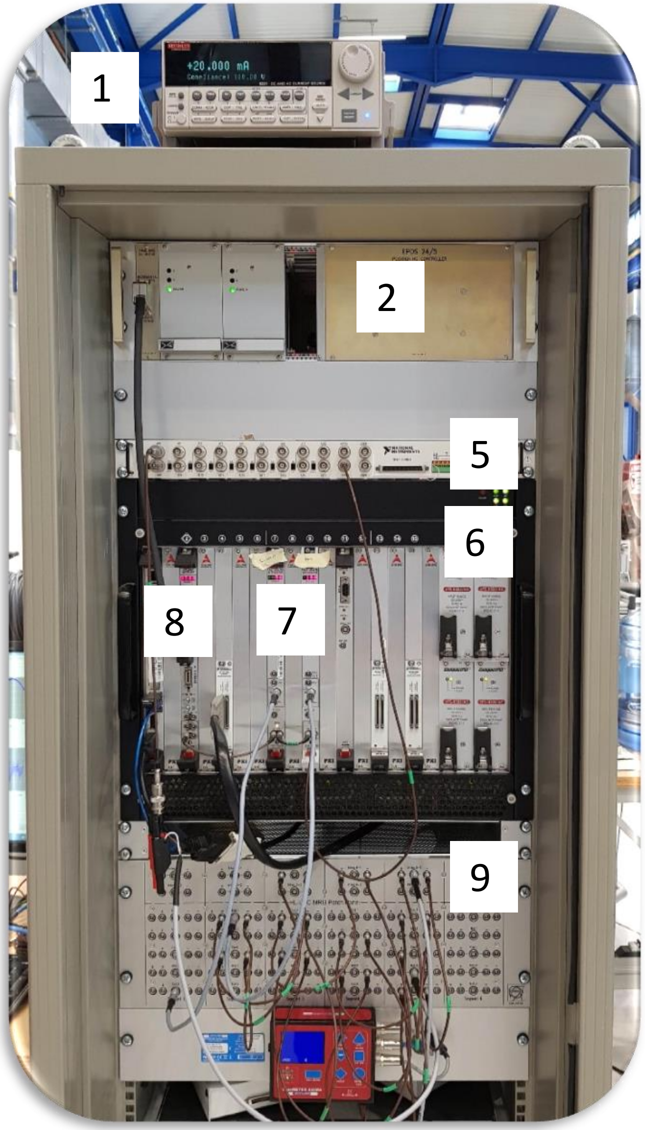
Measurement System

Technical details

Measurement System



1) DC Current Source
2) Motor control
3) Motor Unit
4) Sensor
5) NI DAQ
6) PXI
7) FDI
8) Encoder Board
9) Patch Panel



Measurement Bench

- Versatile
- Reliable motor unit
- Positioning error less than 50 µm

Product (I)

Journal:

11) “*A Rotating-Coil Magnetometer for Scanning Transversal Field Harmonics in Acelerator Magnets*”, submitted to **Scientific Reports- Nature**, September 2018

12) “*Design, production, and metrological characterization of a flexible PCB coil for sensing local, transversal fields in accelerator magnets*”, to be submitted to **Sensor and Actuators A: Physical**, October 2018

13) “*Concept design, assembling and calibration of a transducer based on iso-perimetric induction coil sensor*”, to be submitted to **IEEE Transactions on Instrumentation and Measurement**, October 2018

Conference:

14) “Design of an Iso-Perimetric Coil for a Transversal Field Scanner”, **International Magnetic Measurement Workshop (IMMW20)**, Diamond Light Source, Oxfordshire (UK) June 2017

15) “*An Iso-Perimetric Rotating-Coil Magnetometer*”, **IEEE SENSORS 2018**, New Delhi, India 2018

Product (II)

Poster:

16) "A Magnetic Measurement System for Extracting Pseudo-Multipoles in Accelerator Magnets", **2nd PACMAN workshop**, Debrecen (Hungary) June 2016

17) "*A Rotating-Coil Magnetometer for Scanning Transversal Field Harmonics*", **CERN Doctoral Student Assembly**, Geneva 19 April 2018

18) "*A rotating-coil magnetometer for the scanning of transversal field harmonics in particle accelerator magnets*", **International Measurement Confederation** (IMEKO), Belfast 201

IMEKO World Congress 2018, Best Poster Presentation Award, by the Instrument Science and Technology Group of the Institue of Physics

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2) ZANGRANDO, Dino; WALKER, Richard P. A stretched wire system for accurate integrated magnetic field measurements in insertion devices. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1996, 376.2: 275-282.

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6) Zhu, Y., Chen, F., Kang, W., Chen, W., Yang, M., and Wu, X. (2018). Accurate calculation of field quality in conventional straight dipole magnets. Radiation Detection Technology and Methods, 2(1):14.

7) S. Sanfilippo, “Hall Devices: Physic & Application to Field Measurements”.

8) Bolshakova I, Holyaka R, Erashok V, Kumada M. High precision mapper for cyclotron magnet. IEEE transactions on applied superconductivity. 2004 Jun;14(2):1818-21.

9) De Matteis E. Magnetic field mapper based on rotating coils(Doctoral dissertation, CERN).

10) Arpaia P, Buzio M, De Matteis E, Russenschuck S. A rotating coil transducer for magnetic field mapping. Journal of Instrumentation. 2015 Jun 11;10(06):P06006.

Thank you for your attention

Any questions?

Ph.D. Gianni Caiafa