



Gianni Caiafa

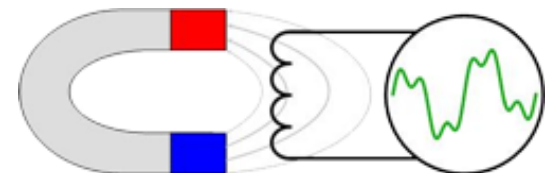
Tutors: Pasquale Arpaia –Stephan Russenschuck

XXXI Cycle - 1st year presentation

A magnetic measurement system for
extracting pseudo-multipoles in
accelerator magnets



UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II



Magnetic Measurements



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

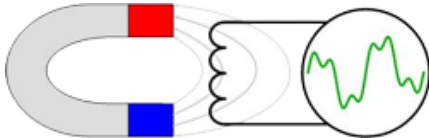


Ph.D. student XXXI Cycle Information Technology
and Electrical Engineering, DIETI

Instrumentation & Measurement
for Particle Accelerator Lab



Member of Instrumentation & Measurement for
Particle Accelerator Lab IMPALAB



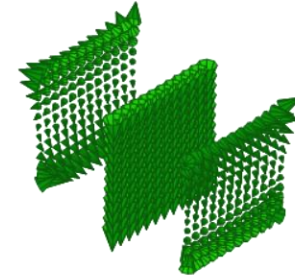
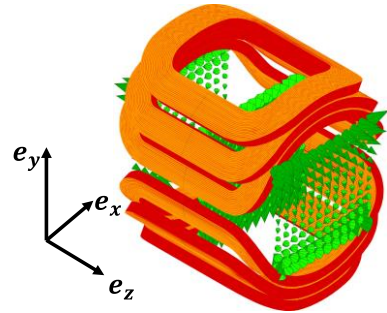
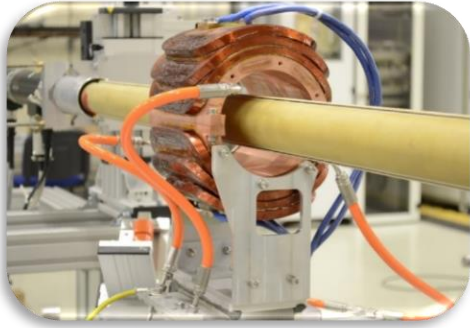
Magnetic Measurements

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)



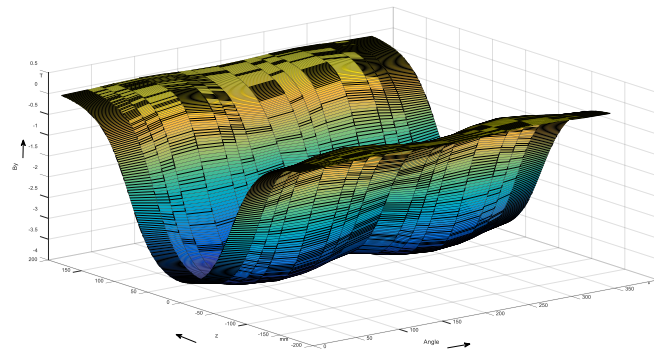
Research Objective

Measure the local field distribution in accelerator magnets

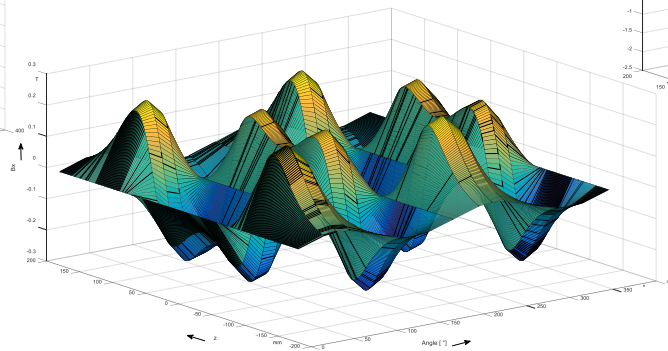


The field distribution in the end-regions of the magnet can be reconstituted from measurements on the boundary surface applying the concept of pseudo-multipoles [1]

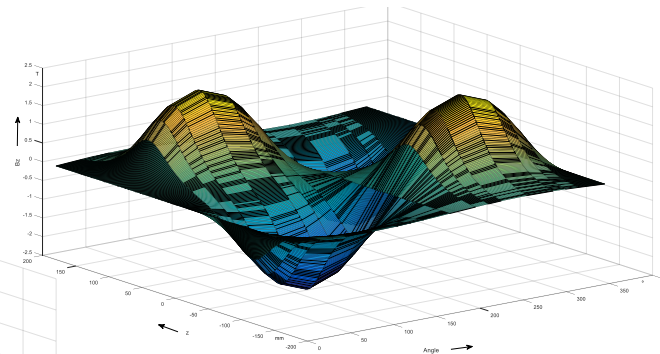
B_y component



B_x component



B_z component

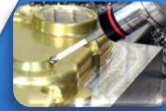


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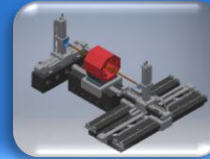
[1] B. Erdélyi, M. Berz, M. Lindemann "Differential algebra based magnetic field computations and accurate fringe field maps"

Project Structure

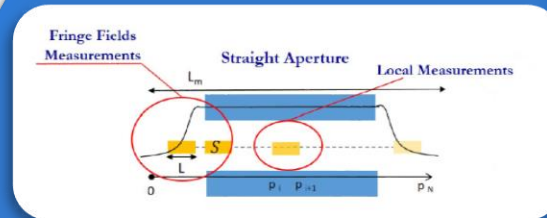
Metrological characterization



Flexible, high-precision measurement system



Rotating coil measurement



Mathematical model of the Pseudo-Multipoles Analysis

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

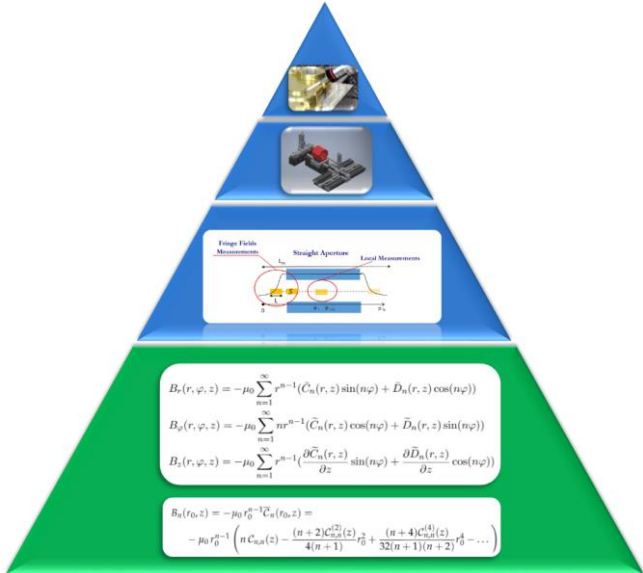
$$B_\varphi(r, \varphi, z) = -\mu_0 \sum_{n=1}^{\infty} n r^{n-1} (\tilde{C}_n(r, z) \cos(n\varphi) + \tilde{D}_n(r, z) \sin(n\varphi))$$

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

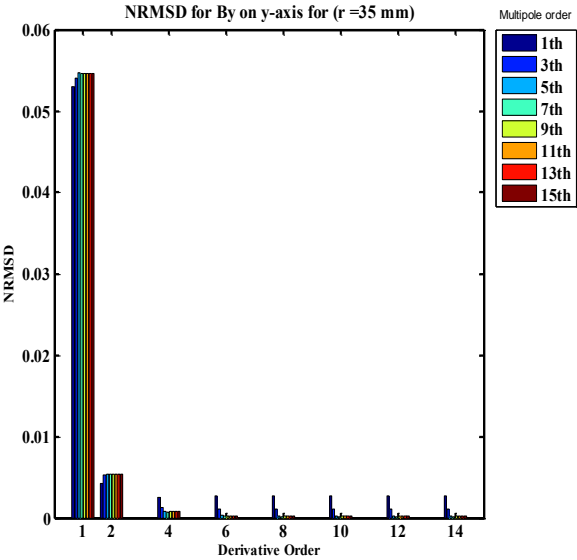
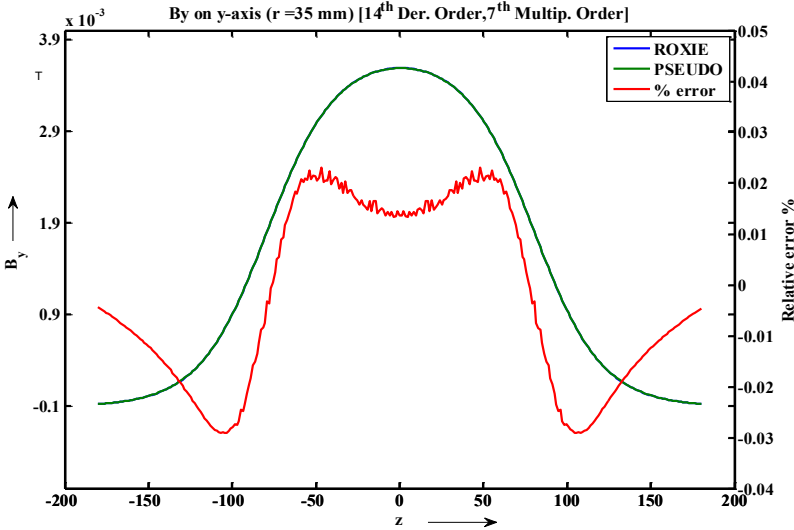
$$B_n(r_0, z) = -\mu_0 r_0^{n-1} \bar{C}_n(r_0, z) = -\mu_0 r_0^{n-1} \left(n C_{n,n}(z) - \frac{(n+2)C_{n,n}^{(2)}(z)}{4(n+1)} r_0^2 + \frac{(n+4)C_{n,n}^{(4)}(z)}{32(n+1)(n+2)} r_0^4 - \dots \right)$$

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Completed Steps

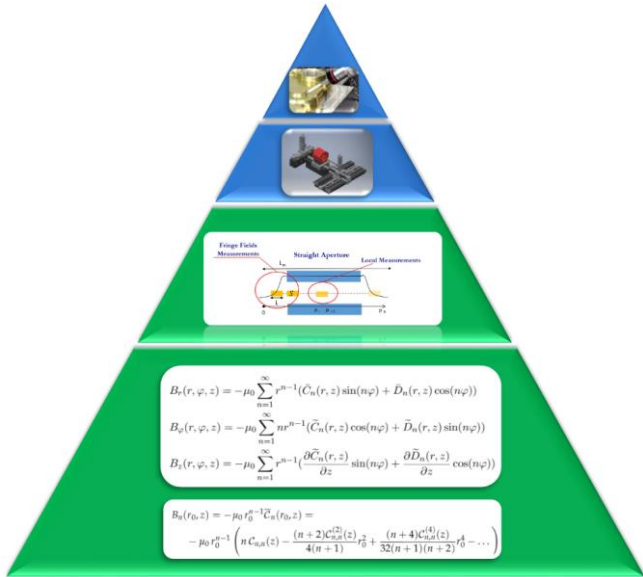
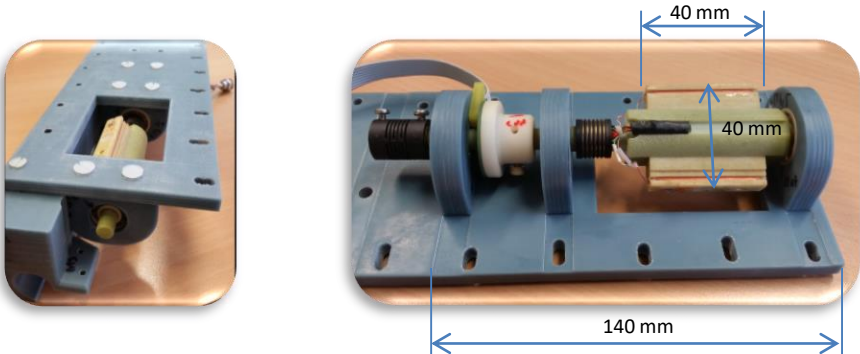


Mathematical model validation

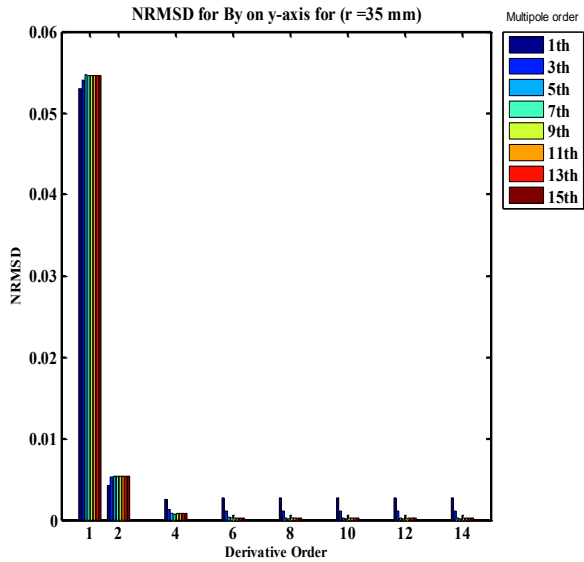
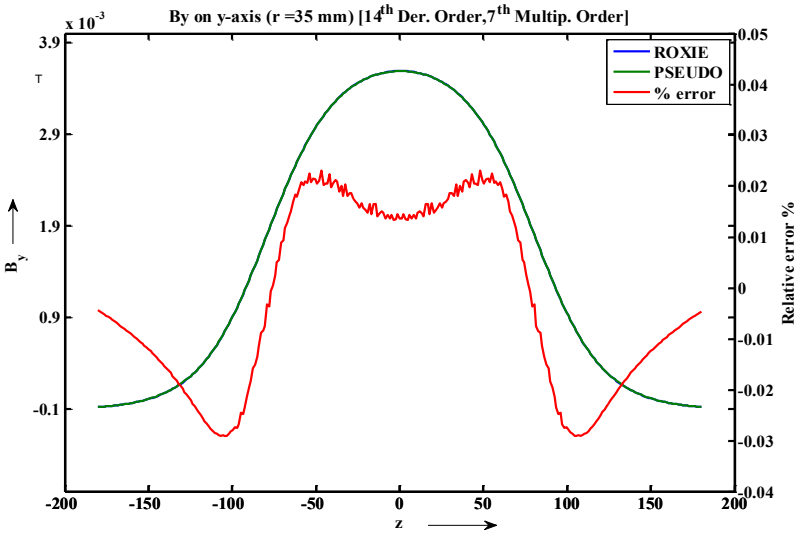


Completed Steps

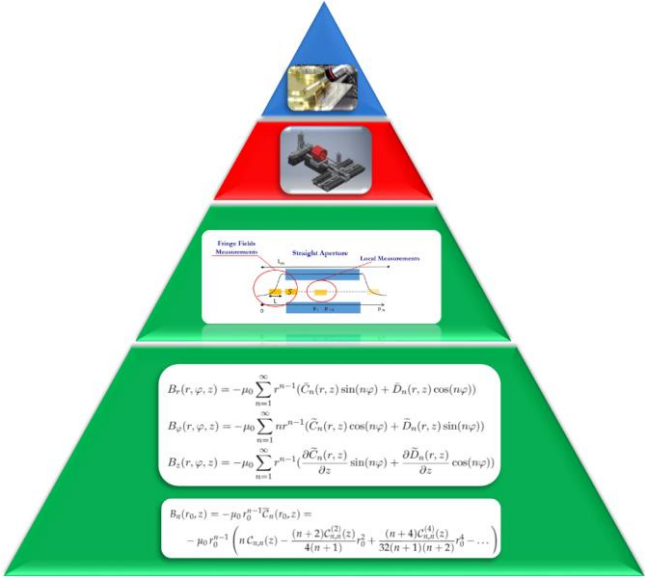
Design and prototyping of a longitudinal carriage system



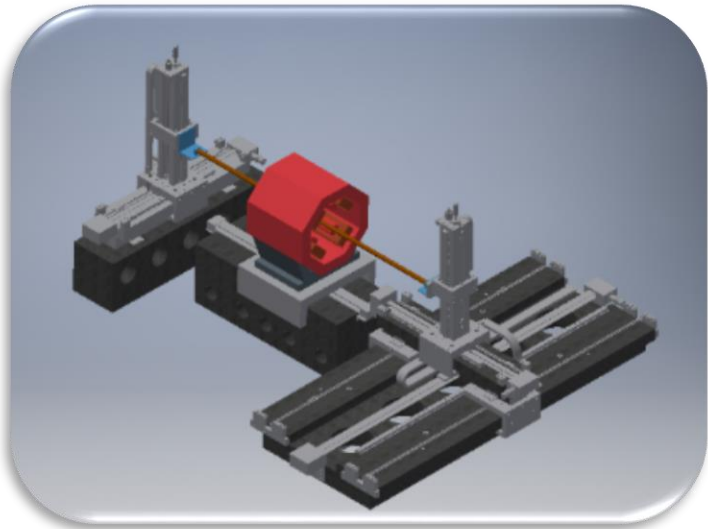
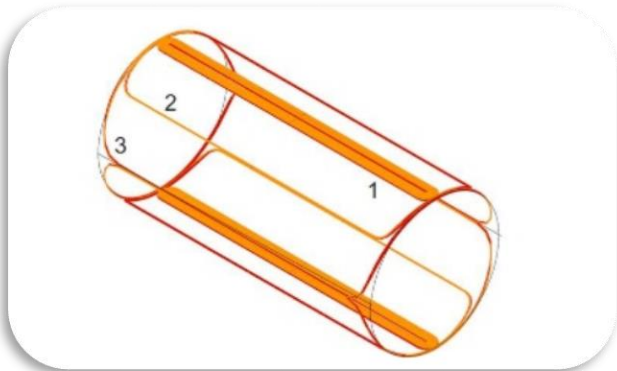
Mathematical model validation



Next Steps

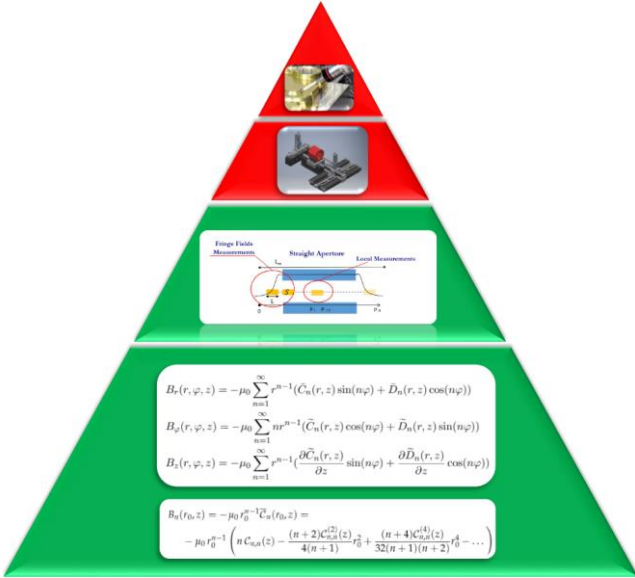


Study and design of an iso-perimetric coil and measurement system

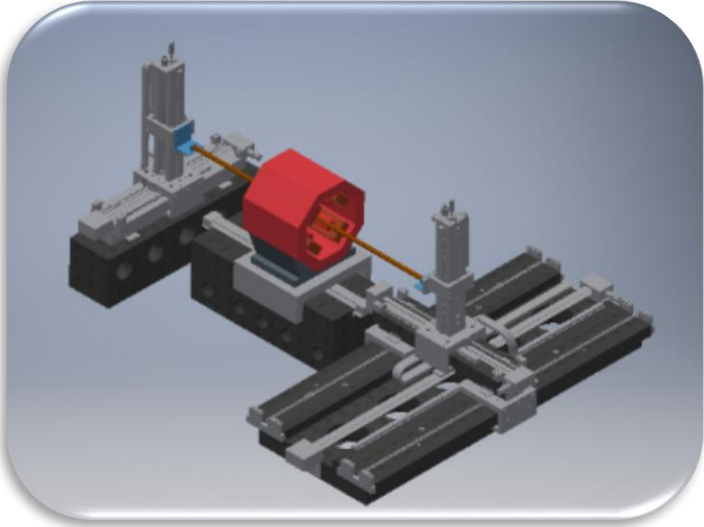
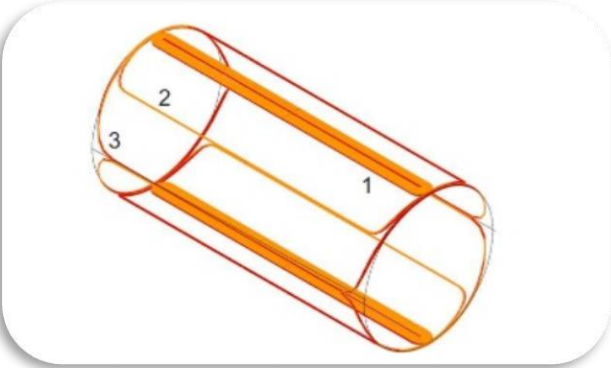


Next Steps

Measurement system setup and metrological characterization




Study and design of an iso-perimetric coil and measurement system





Publications

Poster for the 2nd PACMAN workshop, “A Magnetic Measurement System for Extracting Pseudo-Multipoles in Accelerator Magnets”, held in Debrecen (Hungary) June 2016



A Magnetic Measurement System for Extracting Pseudo-Multipoles in Accelerator Magnets

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European Organization for Nuclear Research (CERN), TE Department, 1211 Geneva 23, Switzerland

ABSTRACT

For accelerator magnets such as capture solenoids, fragment separator dipoles, and insertion quadrupoles, it is important to measure not only the integrated field errors but also the local field distributions in the magnet extremities. In three-dimensional field problems, the transversal multipole coefficients do not constitute a complete orthogonal function set. This gives rise to pseudo-multipoles in Fourier-Bessel series that can also account for field variations in axial direction. The magnetic measurement section of CERNA TE Department have started to design, construct, and characterize metrologically a measurement bench composed of high precision mechanics with integrated real-time automatic control and drive system, encoders, and measurement transducers with isotropic search coils. A suitable post-processing tool is being developed based on the theory of pseudo-multipoles as well as field reconstruction from boundary data.

Scientific challenges stem from the need to calculate higher-order derivatives of the measured flux densities, which in turn boosts the requirements of the data acquisition systems and digital integrators, as well as the mechanical stability of the bench and transport system. Other challenges stem from the coil design, which results in convoluted signals because of the nonnegligible thickness and the short length of the sensing coils.

MATHEMATICAL MODEL

The scaling laws derived from the integrated (two-dimensional) field harmonics in accelerator magnets cannot be used in the 3D case because these field harmonics do not constitute a complete orthogonal function set. Applying the concept of pseudo-multipoles, the field distribution in the end-regions of the magnet can be reconstructed from measurements on the boundary surface, that is, the transversal multipole field errors over a short, isoperimetric coil.

In a simply-connected, cylindrical domain, free of magnetised material and current sources, the field components can be calculated from a magnetic scalar potential obeying the Laplace equation:

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

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

$$\phi_{0n}(r, \varphi, z) = \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left(C_{n,l,k}(z) \sin(n\varphi) + D_{n,l,k}(z) \cos(n\varphi) \right)$$

Inserting this expression into the Laplace Equation yields a recursive equation for the coefficients and we obtain:

$$\phi_{0n}(r, \varphi, z) = \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left(C_{n,l,k}(z) \sin(n\varphi) + D_{n,l,k}(z) \cos(n\varphi) \right)$$

Where the $C_{n,l,k}(z)$ and $D_{n,l,k}(z)$ are the normal and skew components, as follows:

$$C_{n,l,k}(z) = C_{n,l}(z) \left(\frac{C_{l,k}(z)}{4(n+1)^2} + \frac{C_{l,k}(z)}{32(n+1)(n+2)} \right) + \dots$$

$$D_{n,l,k}(z) = D_{n,l}(z) \left(\frac{D_{l,k}(z)}{4(n+1)^2} + \frac{D_{l,k}(z)}{32(n+1)(n+2)} \right) + \dots$$

The field components within the bore of the magnet are given by:

$$B_r = -\mu_0 \frac{\partial \phi_{0n}}{\partial r}, \quad B_\varphi = -\mu_0 r \frac{\partial \phi_{0n}}{\partial r}, \quad B_z = -\mu_0 \frac{\partial \phi_{0n}}{\partial z}$$

and therefore with

$$C_{n,l,k}(z) = C_{n,l}(z) \left(\frac{n+2}{4(n+1)} \right) + \frac{n+4}{32(n+1)(n+2)} \dots$$

$$B_r(r, \varphi, z) = -\mu_0 \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left(C_{n,l,k}(z) \sin(n\varphi) + D_{n,l,k}(z) \cos(n\varphi) \right)$$

$$B_\varphi(r, \varphi, z) = -\mu_0 \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left(C_{n,l,k}(z) \sin(n\varphi) + D_{n,l,k}(z) \cos(n\varphi) \right)$$

$$B_z(r, \varphi, z) = -\mu_0 \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left(C_{n,l,k}(z) \sin(n\varphi) + D_{n,l,k}(z) \cos(n\varphi) \right)$$

Easier results are obtained for expressing the vertical field component on the horizontal plane:

$$\frac{\partial}{\partial z} B_z(r, \varphi, z=0) = -\mu_0 \left(C_{1,0,1}(z) + \frac{C_{1,0,1}(z)}{12} r^2 - \frac{C_{1,0,1}(z)}{60} r^4 + 3C_{3,0,1}(z) r^2 - \frac{3C_{3,0,1}(z)}{48} r^4 + \frac{3C_{3,0,1}(z)}{48} r^6 + 7C_{5,0,1}(z) r^4 - \frac{7C_{5,0,1}(z)}{24} r^6 + \dots \right)$$

Multipole extraction from measured data:

$$B_z(r, z) = -\mu_0 \sum_{k=0}^{\infty} \sum_{l=0}^{\infty} \left(C_{n,l,k}(z) \sin(n\varphi) + D_{n,l,k}(z) \cos(n\varphi) \right)$$

RESULTS AND ANALYSIS

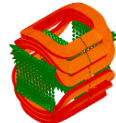
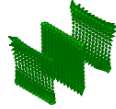
The mathematical model has been validated comparing the y -component of the magnetic field along the magnet axis, calculated with the CERN field computation program ROXIE. The bar graphs show the residual (RMS) related to the main field component, for different multipole orders of the leading term n and its higher-order derivatives. The study was done for the field reconstruction on the measurement radius (40SD mm).

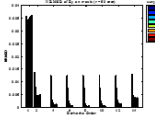
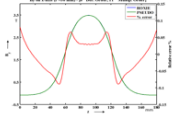
$$RMSD = \sqrt{\frac{\sum_{i=1}^N (B_{y,i} - B_{y,i}^{ROXIE})^2}{N}}$$

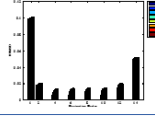
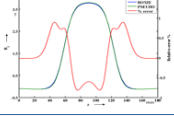
Computed field
 B_y Reconstructed from pseudo-multipoles
 N Number of field points along the axis
 B_y Central value of B_y field component

$$NRMSD = \frac{RMSD}{B_y}$$

where

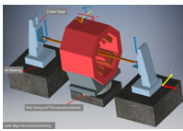



FUTURE DEVELOPMENTS

In order to measure the field profile in accelerator magnets we are developing a precise and stable positioning system for rotating coils and moving fluxmeters. The main idea is to use two independent stages (with 3 degrees of freedom) combined with a magnet-mounting table for roll, swing, and tilt alignment.



Gianni Caiafa

9

Next Years

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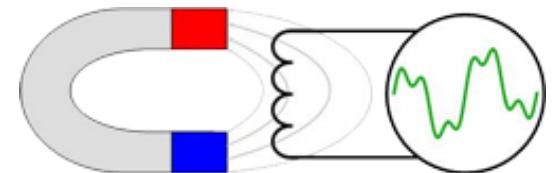
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Seminars	5	0	0	0.5	3	0.5	6.2	10	5							0	0							0	10	10-30
Research	35	0	3	7	10	7	7	34	45							0	60							0	34	80-140
	60	4	3	7.5	23	17	13	67	60	0	0	0	0	0	0	0	60	0	0	0	0	0	0	0	67	180



THANK YOU FOR
YOUR ATTENTION!



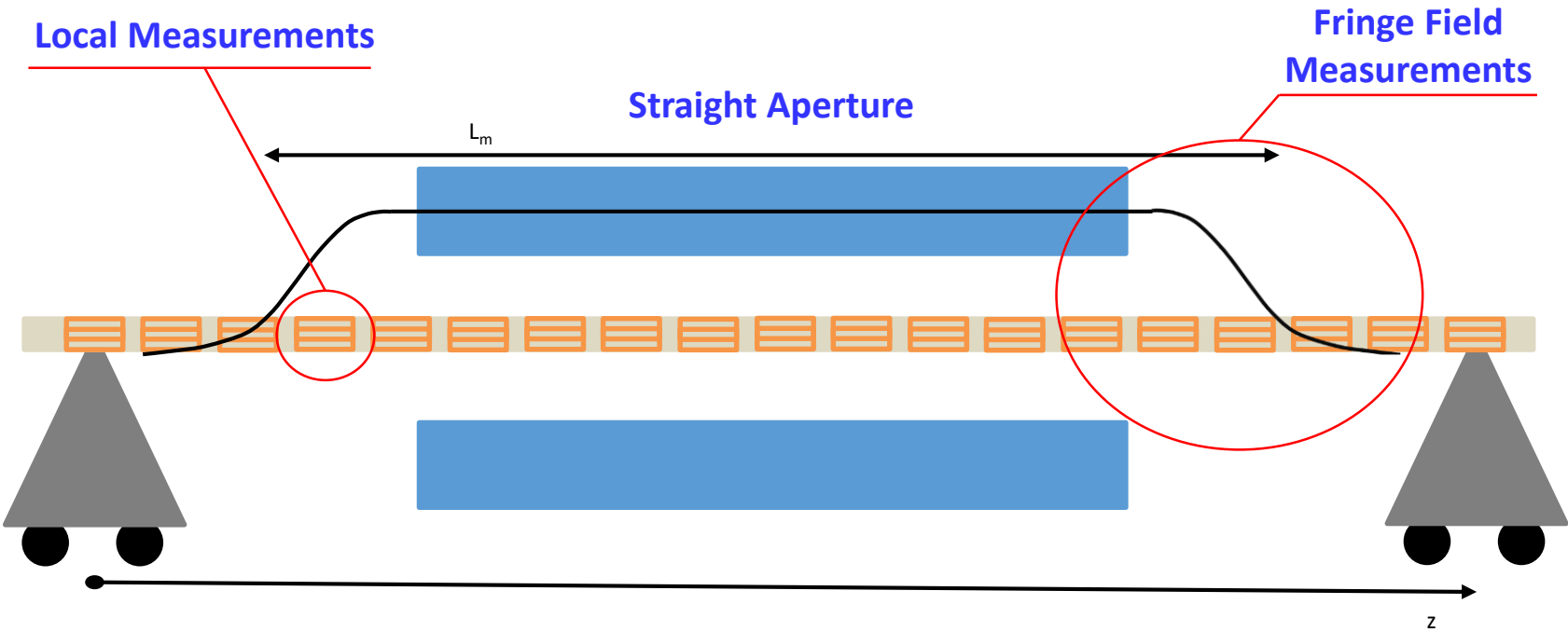
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FEDERICO II



Magnetic Measurements

Gianni Caiafa

Long shaft



Short shaft

