PhD in Information Technology and Electrical Engineering

Università degli Studi di Napoli Federico II

PhD Student: Gianni Caiafa

XXXI Cycle

Training and Research Activities Report – Third Year

Tutors: Prof. Pasquale Arpaia – Prof. Stephan Russenschuck

1. Information

PhD Candidate: Caiafa Gianni

MSc title: Master’s degree in Electrical Engineering (cum laude), University of Naples Federico II

Doctoral Cycle: XXXI – ITEE- University of Naples Federico II

Fellowship type: Special Doctoral Program at CERN of Genève

Tutors: University tutor - Prof. Pasquale Arpaia
CERN tutor - Prof. Stephan Russenschuck

2. Study and Training activities

a. Courses

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b. Seminars

- “*HiLumi-FCC Innovation Course*”, organized by CERN HiLumi, CERN, March 21st 2018, (4 CFU)
- “*Accelerators for Medicine*”, organized by Maurizio Vretenar, CERN, June 12th 2018, (0.5 CFU)
- “*Italo Gorini 2018*”, Doctoral Summer School promoted by the Italian “*Electrical and Electronic Measurement*” (GMEE), CERN, September 10th – 14th 2018, (4 CFU)

c. External courses

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3. Research activities

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

For magnetic measurements of accelerator magnets, the induction-coil magnetometer is still the best transducer in terms of linearity, repeatability, reliability and accuracy. Induction coils are applied to measure the field strength, direction and field errors expressed as higher-order field harmonics, (S. Russenschuck n.d.), (Sammut 2009). The magnetic measurements of accelerator magnets are usually performed with shafts, containing a number of induction coils, that are longer than the magnet length and therefore cover also the fringe field regions. In fact, measuring the integrated transversal field components is often sufficient to validate the design and characterize accelerator magnets, in particular for magnet-to-magnet reproducibility in larger series.

In other cases, the local field distribution measurements are required. This is the case for fringe-field dominated magnets and when the measurements are to be used for track reconstruction in mass spectrometers, (Schnizer 2011), (Yanagisawa 2008). Fringe field-dominated magnets are short magnets with relatively wide apertures, where the effect of the magnet ends is not negligible, (Zhu 2018), (Berz 2000).

The knowledge of the local field distribution in the magnets is also important for the study of the beam dynamics of insertion regions where the β-function changes rapidly, (Aiba 2018).

The field distributions at the magnet extremities cannot be developed into Fourier series (i.e. the classical field harmonics), because the trigonometric functions do not constitute a complete orthogonal function set of the field solution, (S. Russenschuck, Rotating-and translating-coil magnetometers for extracting pseudo-multipoles in accelerator magnets 2017). This gives rise to Fourier-Bessel series and the so-called pseudo-multipoles, (Venturini 1999) and (Xu 2014), which depend on the magnetic field variation along the magnet axis.

In literature, we could find many field measurement systems based on different technologies, like Hall sensors, Nuclear Magnetic Resonance (NMR), rotating-coil and wire technologies. Not all of them are suitable for acquiring the local field distribution, (Davies 1992).

NMR transducers are very accurate for the main field, e.g., Metrolab PT2025 NMR, with ±5 and ±0.1 ppm of absolute and relative accuracy, respectively. However, they are not suitable for gradient measurements (e.g. fringe fields) and have limited lower range of operation.

One possibility is to measure the longitudinal profile by mapping the magnet bore with a 3D Hall sensor, (Takeda, Extraction of 3D field maps of magnetic multipoles from 2D surface measurements with applications to the optics calculations of the large-acceptance superconducting fragment separator BigRIPS 2013) and (Dixiang 2007), mounted on a displacement stage.

Hall probes, in fact, are widely used for local mapping of straight and curved magnets, (Ying-Shun 2011), (Hirose 2004). Main advantages are high spatial resolution due to the size of the sensing element, a wide range of field. Main disadvantages are the relatively low accuracy (0.1%) due to their nonlinear characteristic, the temperature dependence of the metrological performance and secondary effects like the planar effect. Moreover, the mechanical limit of these systems, and i.e. the measurement precision, is the difficulty to align the Hall probe characterized to small sensing element, with respect to the mechanical system.

Another solution is to use a translating-coil scanner on the magnet mid-plane, (Bolshakova 2004). In the latter case, however, the transversal resolution (and the highest order of the field harmonics) is limited by the track widths of the single coils.

An innovative way to measure the local field distribution was presented in (De Matteis 2016) ,where a rotating coil transducer, (Arpaia, A rotating coil transducer for magnetic field mapping 2015), and a train-like system for longitudinal motion and positioning inside the magnet bore, based on rotating coils was developed. This innovative transducer was developed with (i) small-size sensing coil elements, e.g. for space charge computations, (ii) accurate transport, for longitudinal displacements inside the magnet gap, and (iii) adequate magnetic compatibility, for negligible interference with the measurand field.

In (S. Russenschuck, Rotating-and translating-coil magnetometers for extracting pseudo-multipoles in accelerator magnets 2017), it was proven that the classical rotating-coil magnetometers, (De Matteis 2016), cannot be used in regions where a significant axial field component is present. In fact, the extraction of pseudo-multipoles from transversal field measurements on a reference radius, requires a coil that intercepts only the radial field component, and thus is free of the voltage induced by the axial field component. The main objective of my research activities has been based on design, procure, validate and calibrate a magnetometer to perform local field distribution measurements. Besides, the link between measurements and the pseudo-multipole mathematical model was found and experimentally validate.

My third year of research activity has been concentrated on:

-*The design of the transducer for proof of principle*. The first prototype was based on 3D printing technology and was realized to show the main characteristics of the developed sensor. The purpose of the first prototype was to proof the functionality of the iso-perimetric coil sensor and to show the differences between traditional (radial) and iso-perimetric coil. For this reason, the two different sensors were installed on the same shaft (same transducer).

-*The sensor and transducer production and the validation tests*. Due to the complexity of the sensors geometry, three different manufacturing technology were evaluated for the production: 1) winding directly on a cylindrical mandrel, 2) sputtering deposition of conducting material on a cylindrical shaft and 3) mounting a flexible printed circuit on a cylindrical shaft. The flexible printed circuit (FPC) technology was chosen to guarantee high precision on the track positioning, high reproducibility and the production of multiple layers.

A preliminary test to validate the sensor production was based on the electric continuity and the resistance measurements of the 4 layers connected in series. This is a really effective method for checking the absence of open circuits, but on the contrary, it does not allow to verify the absence of short-circuit between the tracks. In fact, in case of short circuit between two or more close tracks, the measured resistance does not allow to identify the short. For this reason, a preliminary functional test was performed following the procedure adopted for the calibration of standard coil. It consists in insert the sensor in a reference magnet (reference dipole with a magnetic field uniformity of 1 10^{-5} T) and measure the electromotive force induced on it by a rotation of 180°. The produced transducer, moreover, must be calibrated in to verify, from the magnetic point of view, the main important parameters such as: area and measurement radius.

The requirements for the developed transducer for field mapping were the ability to be no-sensitive for the z-field component and to measure the local field distribution along the all magnet length including the fringe field regions. For this reason, the sensor must be as short as possible to reduce the convolution along the longitudinal direction, have high sensitivity for high harmonic orders, able to accommodate different sensing coils, easy to displace in the magnet bore and have the possibility, by appropriate instrument, to measure the relative position in the magnet bore with a precision of ±50 µm. The first prototype for proof of principle was made in ACCURA 25. The shaft is then supported by two ceramic ball bearings connected on rollers (the rollers are used to translate the transducer inside a support tube).

-*The proof of principle of the developed transducer.* As a proof of principle, magnetic measurements were carried out on transfer-line dipole magnet. The dipole has an air gap of 100 mm x 134 mm. The longitudinal profiles of the field harmonics were measured both by a classical radial coil and by the new iso-perimetric coil. A first multipole scanning was performed along the centre of the magnet, where the transversal field distribution is almost symmetric. Along this trajectory, the magnetic flux density has only B_3, B_5, and higher-order odd multipole components (harmonics). In a second run, the magnet was mapped along a track located close to the pole. In this way, higher-order skew and normal field components were expected. Computing the difference between the signals coming out from the two sensors in each position was possible to highlight the effect of the z-field component in the radial coil. This effect, as expected, is higher in case of the displaced track (close to the magnet pole). Using the classical coil, voltages are induced in the extremity, which affect the measured B_n component that, consequently, cannot be used for extracting pseudo-multipoles.

-*The transducer calibration*. The produced transducer has been calibrated in the reference magnets to obtain the coil area and the mounting radius of the radial and iso-perimetric coil. For the quadrupole calibration, a mathematical description for the measuring radius computation was required.

-*The measurements on field*. After the calibration procedure, the first experimental measurements were performed in the reference dipole. Scope of the measurement campaign was to ensure the absence of spurious harmonics and to compute the compensation ratio and the standard deviation. Furthermore, measurements on the edge of the magnet were performed.

-*The design, the assembly and the calibration of the second prototype*. After the experience on the first prototype, a second prototype was conceived, designed, built and calibrated.

-*The application of the mathematical model.* During the first year, the pseudo-multipole method was described and validate using simulated date. Having performed measurements on field, the mathematical model was applied to compute the field description using measured data. It required the resolution of a deconvolution problem on the measured data applying the Wiener filter.

Other activities:

This year has been characterized by the organization of the PhD School Italo Gorini at CERN. As member of the organizing committee, I was involved in the budgeting, resource optimization, organization of visits at CERN, and all the concerning regarding the school.

4. Product

- Paper: "*Axial Flux Permanent Machine Design for Low Speed High Torque Application*", 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA).
- Paper: "*A rotating-coil magnetometer for the scanning of transversal field harmonics in particle accelerator magnets*", International Measurement Confederation (IMEKO), Belfast 2018.
- Paper: "*An Iso-Perimetric Rotating-Coil Magnetometer*", IEEE SENSORS 2018, New Delhi, India 2018.
- Paper: "*A Rotating-Coil Magnetometer for Scanning Transversal Field Harmonics in Accelerator Magnets*", submitted to Scientific Reports- Nature, September 2018.
- Paper: "*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.
- Paper: "*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.
- Poster: "*A Rotating-Coil Magnetometer for Scanning Transversal Field Harmonics*", CERN Doctoral Student Assembly, Geneva 19 April 2018.

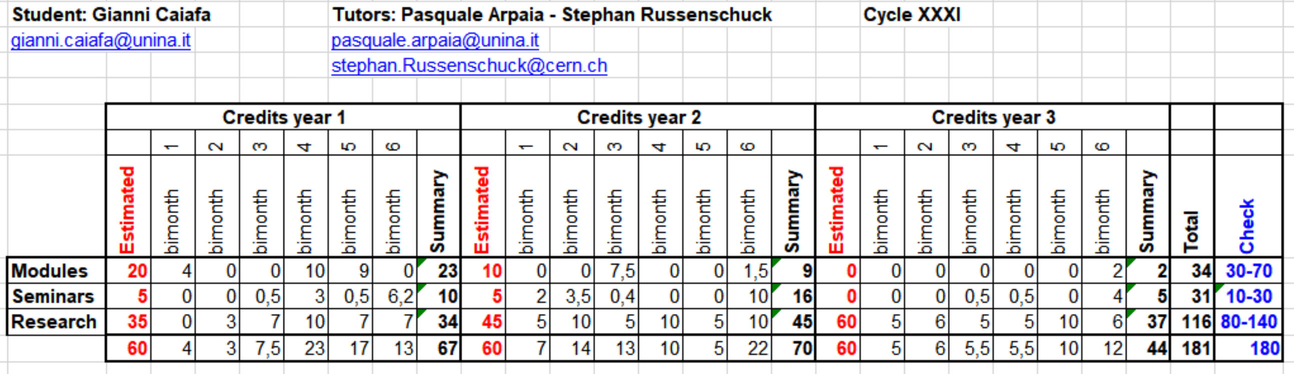
- Poster: “*A rotating-coil magnetometer for the scanning of transversal field harmonics in particle accelerator magnets*”, International Measurement Confederation (IMEKO), Belfast 2018.

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

5. Tutorship

Competitive doctoral program at CERN of Genève. I spent the whole third year at CERN.

6. Credit summary



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	Credits year 1								Credits year 2								Credits year 3									
		1	2	3	4	5	6			1	2	3	4	5	6			1	2	3	4	5	6			
	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	Summary	Estimated	bimonth	bimonth	bimonth	bimonth	bimonth	bimonth	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

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
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
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

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