PhD in Information Technology and Electrical Engineering
Università degli Studi di Napoli Federico II

PhD Student: Vittorio Ferrentino

Cycle: XXXVII

Training and Research Activities Report

Year: First

Tutor: Prof. Pasquale Arpaia

Co-Tutor: Dr. Ewen Hamish Maclean (CERN)

Date: December 13, 2022

1. Information:

- **PhD student:** Vittorio Ferrentino
- **DR number:** DR995870
- **Date of birth:** 17/02/1995
- **Master Science degree:** Electrical Engineering **University:** University of Naples Federico II
- **Doctoral Cycle:** XXXVII
- **Scholarship type:** CERN Doctoral Student Programme
- **Tutor:** Prof. Pasquale Arpaia
- **Co-tutor:** Dr. Ewen Hamish Maclean (CERN)

2. Study and training activities:

Activity	Type[1]	Hours	Credits	Dates	Organizer	Certificate[2]
Project Vac: Can a Text-to-speech Engine Generate Human Sentiments?	Seminar	1	0.2	28.02.2022	Department of Physics Ettore Pancini and DIETI	N
Study on particle physics, beam dynamics and a general introduction to linear optics and accelerator operations. Overview on beam measurement techniques in particle accelerators and on the PS accelerator design. Preparation of a new paper on the analysis of thermal transients in a superconducting combined-function magnet for hadron therapy gantry.	Research		4	01.01.2022 – 28.02.2022		
Global and Cluster Synchronization in complex network and beyond	Seminar	1	0.2	10.03.2022	Prof. Marco Coraggio, Scuola Superiore Meridionale	Y
Computational single-cell biology – From one-to-many cells	Seminar	1	0.2	23.03.2022	DIETI	Y
From basic principles in spintronics to some	Seminar	1	0.2	31.03.2022	Scuola Superiore	Y

recent developments toward spin-orbitronics					Meridionale	
Living well within planetary Limits: is it possible? And what can physicists contribute?	Seminar	2	0.4	05.04.2022	CERN	Y
Design Thinking	Seminar	5	1	05.04.2022	Center for Advanced Internet Studies (CAIS), Bochum, Germany	Y
Potential and challenges of next generation railway signaling systems: Moving Block and Virtual Coupling	Seminar	1	0.2	06.04.2022	Prof. Valeria Vittorini (DIETI)	Y
Towards a political philosophy of AI	Seminar	2	0.4	11.04.2022	Department of Physics Ettore Pancini and DIETI	N
Towards AI-Driven Cancer Precision Medicine	Seminar	1	0.2	22.04.2022	DIETI	Y
Everything you always wanted to know about the Internet (but were afraid to ask)	Seminar	4	0.8	28.03.2022 29.03.2022 30.03.2022 01.04.2022	CERN	Y
Study on beam dynamics, the CERN PS accelerator and its Main Unit design, beam instrumentations (Beam Position Monitor and BBQ). Study on tune-shift and feed-down effect in the CERN PS-BSW magnets with beam measurements in the CERN Control Center (CCC) and comparison with MAD-X simulations.	Research		7.4	01.03.2022 - 30.04.2022		
Scientific writing	Course	12	3	03.05.2022 - 23.05.2022	CERN	Y

My first steps in French	Course	18	6	04.05.2022 - 30.05.2022	CERN & Supercomm Group	Y
ITER, the magnets and the road to the first plasma	Seminar	1	0.2	12.05.2022	CERN	Y
5G Academy: Fixed Wireless Access	Seminar	6	1.2	17.05.2022	Prof. Antonia Maria Tulino (DIETI)	Y
5G Academy: AR for remote use of measurement instrumentation	Seminar	2	0.4	24.05.2022	Prof. Antonia Maria Tulino (DIETI)	Y
Vine robots: design challenges and unique opportunities	Seminar	1	0.2	31.05.2022	Dr. Mario Selvaggio (DIETI)	Y
PhD4PhD: A Student's speaking – Thermoacoustics for renewable energies	Seminar	1	0.2	01.06.2022	Prof. Pasquale Arpaia (DIETI)	Y
Probing and infusing biomedical knowledge for pre-trained language models	Seminar	2	0.4	07.06.2022	Prof. Francesco Cutugno (DIETI)	Y
PhD4PhD: A student's speaking - Robotic assistance: pros and cons of a new technology	Seminar	1	0.2	23.06.2022	Prof. Pasquale Arpaia (DIETI)	Y
Study on the PS Main Unit magnetic model, on optics at injection in the PS with measurements in the CCC during Machine Development in April 2022 and comparison with 2021 data. Beam optics measurements in the CCC for the 2022 LHC Commissioning and the PS.	Research		2.2	01.05.2022 - 30.06.2022		
5G Academy: Introduction to intellectual property management	Seminar	2	0.4	19.07.2022	Prof. Antonia Maria Tulino (DIETI)	Y
Study on the beam transverse motion and tune-related resonance	Research		5.6	01.07.2022 - 31.08.2022		

conditions. Analysis of the PS Main Unit Opera 3D model to evaluate the field map and harmonics. Beam optics measurements in the CCC for the 2022 LHC Commissioning and for the analysis of the PS 10 GeV cycle in bare-machine conditions.						
Metrology and Machine Learning for Brain Computer Interfaces	Course	14	2.4	13.09.2022 - 18.10.2022	Prof. Pasquale Arpaia (DIETI)	Y
5th Future-IoT PhD School: IoT meets Autonomy 2022	Doctoral School	45	3	29.08.2022 - 02.09.2022	Prof. Marc-Oliver Pahl, IMT Atlantique, Rennes, France	Y
CERN Accelerator School (CAS): Introduction to Accelerator Physics 2022; Kaunas, Lithuania.	Course	65	12	18.09.2022 - 01.10.2022	CERN	Y
Study on the tune stability in the PS during the 10 GeV cycle from beam measurements, and comparison with MAD-X predicted tunes. Analysis of the simulated field harmonics in the PS Main Unit Opera 3D model with different integration methods. Optics measurements in the CCC for the 2022 LHC Commissioning.	Research		1.6	01.09.2022 - 31.10.2022		
Cybercrime and Information Warfare: National and International Actors	Seminar	2	0.4	18.11.2022	Prof. Simon Pietro Romano, Prof. Roberto Natella (DIETI)	N
Privacy and Data	Seminar	2	0.4	22.11.2022	Prof. Simon	N

Protection					Pietro Romano, Prof. Roberto Natella (DIETI)	
Study on the PS-MU Opera model to crop it. Analysis of the discrepancies among the full and cropped model. Implementation of the 10 GeV cycle current in the Opera model and its harmonics analysis. Analysis of the formulas to convert the simulated harmonics in Opera to magnet strengths for MAD-X. Participation to two technical trainings for MAD-X. Beam optics measurements in the CCC for testing the 2023 configuration.	Research		10	01.11.2022 - 31.12.2022		

1) Courses, Seminar, Doctoral School, Research, Tutorship
2) Choose: Y or N

2.1. Study and training activities - credits earned

	Courses	Seminars	Research	Tutorship	Total
Bimonth 1	**0**	**0.2**	**4**	**0**	**4.2**
Bimonth 2	**0**	**3.6**	**7.4**	**0**	**11**
Bimonth 3	**9**	**2.8**	**2.2**	**0**	**14**
Bimonth 4	**0**	**0.4**	**5.6**	**0**	**6**
Bimonth 5	**17.4**	**0**	**1.6**	**0**	**19**
Bimonth 6	**0**	**0.8**	**10**	**0**	**10.8**
Total	**26.4**	**7.8**	**30.8**	**0**	**65**
Expected	**30 - 70**	**10 - 30**	**80 - 140**	**0 – 4.8**	

3. Research activity:

The PhD research activities are carried out at the European Organization for Nuclear Research (CERN), Geneva, Switzerland. They are mostly focused on the CERN Proton Synchrotron (PS) accelerator, which is oldest accelerator at CERN. With a circumference of 628 m, the PS consists of 277 roomtemperature magnets (dipole main units, injection magnets, extraction magnets, and so on). It accelerates protons and heavy ions from the injection energy of 2 GeV up to 26 GeV. In the PS tunnel there are 100 dipole C-shaped combined-function Main Unit (MU) magnets, each of them composed of 10 blocks: 5 focusing blocks (focusing half-unit) and 5 defocusing blocks (defocusing half-unit). Each MU is powered with 3 different normal conducting coils: the main coil, which generates the main field in the magnet aperture, and two additional circuits, namely the Figure-of-Eight Loop (F8L) and the Pole Face Windings (PFW), which are needed to generate higher magnetic field components to keep the beam circulating.

For such a complex system, simulations predicting the performance of the machine are needed. In this context, the project is mostly focused both on the optics and the magnetic modeling of the PS-MU. The general idea is to improve both models to have a better description of the beam optics in the accelerator, as well as a finite-element model to properly describe the magnetic field map in the magnet aperture. Moreover, the two models are strictly linked as the magnetic field and the related harmonics computed from the magnetic model can be used as input for the beam optics simulations. The beam optics is simulated with the Methodical Accelerator Design (MAD-X) tool, which is largely used in the accelerator community, while the finite-element model solver Opera 3D is used for the magnetic modeling of the MU.

Furthermore, the project aims to compare and benchmark the optics and magnetic modeling predictions with beam optics measurements, which have been carried out during the whole year in the CERN Control Center (CCC). Such measurements consist, for instance, in measuring the beam orbit by means of Beam Position Monitors (BPMs) located along the accelerator, and tune (defined as the number of oscillations of the beam in one turn in the vertical or horizontal plane) through the BBQ system, which was designed at CERN to specifically measure the tune. During these measurements, the beam is normally excited with specific kicker magnets.

The first topic I focused on was the feed-down effect from eddy currents during the injection in the PS. The beam, extracted from the Proton Synchrotron Booster (PSB) accelerator, is injected into the PS. The injection process is complex as the beam is initially injected off-center from the closed designed orbit in the PS. To allow the beam to survive the injection, the injector magnets in the PS (BSW40, BSW42, BSW43 and BSW44) are pulsed at injection to adjust the beam orbit over hundreds of turns. The pulsing of these magnets and the related fast field changes generate sextupole eddy-currents in the vacuum chamber. The beam, initially injected off-center the designed closed orbit, is perturbed by the quadrupolar field component related to the feed-down of this sextupolar field, which can result in a significant tune-shift.

In order to study the effect of the feed-down on the tune-shift at injection due to the pulsing of each injector magnet, optics measurements were carried out pulsing one by one the BSW magnets. The pulsing-driven beam orbit was measured by means of the BPMs. Subsequently, the beam orbit measurements were processed offline with a FFT algorithm in Python to compute the tune-shifts for each BSW's pulsing. The results from the FFT showed that the tune-shifts depended proportionally by the amplitude of the BSW's pulsing but with the opposite sign, meaning that if the beam orbit moved through the negative direction (horizontal or vertical) then the tune (horizontal or vertical) increased during the BSW's pulsing, and vice versa.

Furthermore, the orbit variation along the horizontal axis Δx was computed as the difference among the average horizontal beam position just before the pulsing and the average horizontal beam position during the BSW excitation, for each BPM along the ring, for each BSW pulsing. The measured Δx was compared with the simulated ones in MAD-X, pulsing, in simulation, singularly each BSW. The comparison showed discrepancies between the MAD-X BSW model and the beam measurements. In particular, an opposite sign and a factor between 2 and 3 was found among the measured and simulated Δx. These differences in Δx resulted in differences among the measured and simulated tune-shifts in MAD-X. This allowed to correct the model of the BSW magnets in MAD-X by means of optics measurements.

Before the start of the 2022 LHC Commissioning and Run 3 start, the optics of the PS at injection was analyzed to ensure a correct operation of the machines. In particular, optics measurements were performed to measure the horizontal and vertical beta-beating (defined as the relative difference between the measured and nominal β function) and the horizontal and vertical tunes. The PS optics at injection, namely the horizontal and vertical tunes and beta-beating, was compared with the optics in 2021. From this comparison it resulted that the horizontal beta-beating at injection in the PS was very similar to one in 2021, while the vertical beta-beating was reduced of 5% at maximum. Similarly, the horizontal tunes in 2022 and 2021 were very similar, while the vertical tune-shift measured in 2022 was lower than in 2021.

After these introductory topics, the analysis of the optics and magnetic modeling of the PS-MU started. As mentioned above, the MU are very complex magnets due to their different coils and the particular pole geometry, which allows to generate a combined-function field in the magnet aperture. To get started modeling it, it was chosen to start with the simplest configuration of the machine, namely the bare machine, meaning that all the additional circuits are off (PFW and F8L) and only the main coil is powered. This means that, in these conditions, the main coil is the only responsible of the magnetic field components in the magnet aperture and the related beam optics. The top energy at which the PS can run without any additional circuits turned on is 10 GeV, as above this energy the iron starts saturating and the higher magnetic field components from the additional circuits are required to keep the beam circulating.

The 10 GeV cycle was set up and beam-based measurements were performed in the CCC to evaluate the optics at 10 GeV. In particular, tunes and chromaticity were measured, and the related data acquired to be processed offline. As a starting point, the measured tunes and chromaticity were compared to the predicted ones from MAD-X with an existing effective model. The magnet strengths of the already existing PS-MU model in MAD-X were obtained in the past from the matching with old tunes and chromaticity measurements. The comparison between the new tune and chromaticity measurements and the MAD-X predicted ones with the existing effective model showed quite significant difference. For this reason, a new effective model was created, through the matching algorithm in MAD-X, with the new optics measurements. The comparison between the optics measurements and the new effective model significantly reduced the discrepancies between optics measurements and the optics predicted from MAD-X. This was a clear example of how the optics measurements allow to create or improve an effective model, through the matching algorithm in MAD-X, which better describe the real machine.

The other half of the project consists in the magnetic modeling of the PS-MU. Firstly, the finite-element model solver Opera 3D was studied, both for the modeling and the post-processing. The magnetic modeling of the PS-MU in Opera 3D started with an existing straight model of the PS-MU in CERN database. After a preliminary analysis, it was spotted that it presented issues in the boundary conditions, which were not correctly set to represent the real machine (the field along the horizontal axis was tangential, while it must be normal to it to make the beam circulating driven by the Lorenz force). For this reason, the first effort was direct to properly modify the boundary condition in the existing PS-MU Opera 3D model. When this was done, a first set of simulations was run with the default current in the model, with both linear and non-linear iron, and linear and non-linear solver to take confidence with the

software, its features and the model itself. The simulations converged and it was observed that the boundary conditions made finally sense. Some plots of the 2D magnetic field along the longitudinal and the horizontal axis were produced to analyze the field map in the PS-MU.
The project aims to calculate the magnetic field harmonics (dipole, quadrupole, sextupole, and so on) from the magnetic model and insert them in the MAD-X MU model as magnet strengths to simulate the beam optics. To do that, once the Opera 3D simulations were completed, the harmonics were calculated in post processing in Opera itself with two different approaches: the first one calculated the harmonics along a cylindrical surface of a desired length and reference radius along the magnet; the second computed the harmonics along a circle which, through a loop, shifted along the longitudinal direction, allowing to evaluate the harmonics at different longitudinal coordinates and plot the field harmonics along the whole MU. The results in terms of magnetic field harmonics amplitude and their variation along the longitudinal axis were assessed and approved by magnet design experts at CERN.
From this analysis, some issues arose. It was highlighted that the existing magnetic model of PS-MU was extremely heavy and not manageable at all. For such reasons, it was not feasible of proceeding with the existing model and contemporary adding new features, such as a finer mesh (which would allow to describe better the field but making the model even heavier), or to curve the magnet (as it is in the real machine) adding the tapped air gaps. These aspects led to the need of having a lighter, shorter and more manageable model: a cropped model. Many attempts were done to find the best approach to be followed in order to create a cropped model as close as possible to the original model (full model). The critical aspects consisted in finding the more correct plane where to cut the full model and, once this is done, correctly assign the boundary conditions. It was decided to realize a cropped model with only one-half unit (the focusing or defocusing one), thus the full model was cut in the transition area between the two half-units. Different results in terms of 2D magnetic field and related harmonics were obtained including or not the air gap in the transition area. For this reason, it was decided to include in the cropped model with one half-unit also ~20cm of the other half-unit, which only included the iron and not the air gaps. This allowed to set the tangential field boundary condition in the plane of cut where the field is really tangential (in the iron). The cropped model with one half-unit plus ~20cm of the other half-unit was compared with the original full model in terms of 2D magnetic field and its quadrupolar component. The comparison showed that the differences between the two models were lower than the 1%. This allowed to have a lighter, smaller and more manageable model with respect to the full model, without losing in field quality information, on which is possible to add new features to make the model closer to the real machine.
To combine both aspects of the project, namely the magnetic and the optics modeling of the PS-MU, the 3D Opera magnetic model was simulated under the 10 GeV cycle current, which value was known from the measurements performed in the CCC. Once the 10 GeV current was inserted as input in the Opera 3D model, the simulation was launched with a non-linear solver to have a better description of the field map. Once it was completed the harmonics were computed in Opera itself in post-processing at a reference radius of 35mm in unit of Tesla.
However, as mentioned above, MAD-X does not contain directly the magnetic field harmonics, instead it considers the magnet strengths. The formulas to convert the harmonics computed from Opera (in unit of Tesla at a reference radius) in magnet strengths for MAD-X were found, analyzed and discussed with MAD-X experts. Once these formulas were applied, the magnet strengths for the 10 GeV current obtained from the Opera 3D model harmonics were compared with the magnet strengths of the aforementioned effective model in MAD-X. The result of this comparison was that they were in good approximation and presented differences on the 3rd significant digit.

Free time during nights, weekends and working days was devoted to help the Optics Measurements and Corrections (OMC) team for the beam optics measurements in the CCC for the 2022 LHC Commissioning and Run 3.

4. Research products:

[1] Scientific paper:

- Title: Analysis of powering and quench protection of the SIGRUM superconducting combined-function dipole magnet
- Authors: Vittorio Ferrentino, Pasquale Arpaia, Antonio Gilardi, Mikko Karppinen, Charilaos Kokkinos, Emmanuele Ravaioli
- Journal: IEEE Transactions on Applied Superconductivity
- Current status: Submitted

5. Conferences and seminars attended

No conferences attended. For seminars, please, take a look to the table above.

6. Activity abroad:

No activities carried out abroad.

7. Tutorship

No tutorship activities.