Vittorio Ferrentino

Optics and Magnetic Modeling of the CERN Proton Synchrotron Main Units and beam-based measurements

Tutor: Prof. Pasquale Arpaia

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

Cycle: XXXVII

Year: Second

My background

- **MSc degree in Electrical Engineering at the University of Naples Federico II**
  - Thesis “Analysis of thermal transients in a superconducting combined-function magnets for hadron therapy gantry”. Collaboration with CERN, Switzerland, Geneva
  - Tutors: Prof. Pasquale Arpaia and Prof. Annalisa Liccardo
- **PhD in Information Technology and Electrical Engineering (ITEE)**
  - Start date: 1 January 2022
  - Tutor: Prof. Pasquale Arpaia
- **Partner Organization and Scholarship type:**
  - European Organization for Nuclear Research (CERN): enrolled supernumerary under the UNINA-CERN agreements and the CERN Doctoral Student Programme
  - **Research group/laboratory:**
  - Instrumentation & Measurement for Particle Accelerator Lab (IMPALab-Unina)
  - CERN sections: BE-ABP-LNO and TE-MSC-NCM. Optics measurements and corrections team (OMC)

Research field of interest

- The main research field of interest is the modelling of magnets and beam dynamics in particle accelerators and beam-based measurements
- The PhD project is focused on the optics and magnetic modeling of CERN Proton Synchrotron (PS) accelerator Main Units (MUs), which is one of the injectors of the Large Hadron Collider (LHC), and their validation with beam-based measurements

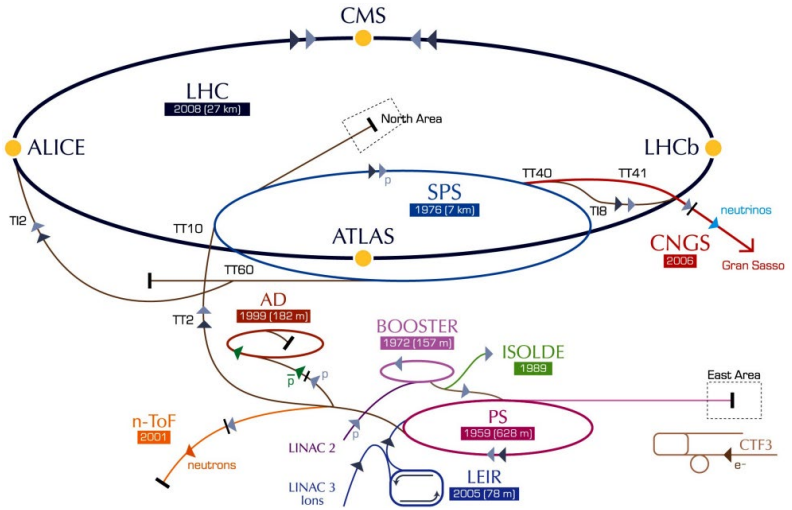


Figure from https://home.cern/science/accelerators/proton-synchrotron

Summary of study activities (1)

- **Courses/PhD schools**:
  - 2023 Spring School on Transferable Skills (Unina)
  - Academic Entrepreneurship (Unina)
  - Standard Model of Fundamental Interactions (Unina – SSM)
  - Introduction to Deep Learning (Unina – SSM)
  - Big Data Architecture and Analytics (Unina)

Attestation

With final exam

Summary of study activities (2)

- **Courses/PhD schools**:
  - 2023 Spring School on Transferable Skills (Unina)
  - Academic Entrepreneurship (Unina)
  - Standard Model of Fundamental Interactions (Unina – SSM)
  - Introduction to Deep Learning (Unina – SSM)
  - Big Data Architecture and Analytics (Unina)
- **Seminars:**
  - 5G Academy: Open Digital Framework (DIETI)
  - Multi-Robot Control of Heterogeneous Herds (DIETI-SSM)
  - Analysis and Control of Function Brain Networks (DIETI-SSM)
  - High Power Targetry R&D Program with the RaDIATE Collaboration and target perspectives in framework of Snowmass (CERN)
  - Learning gene association networks using single-cell RNA-seq data: a graphical model approach (DIETI)

Summary of study activities (3)

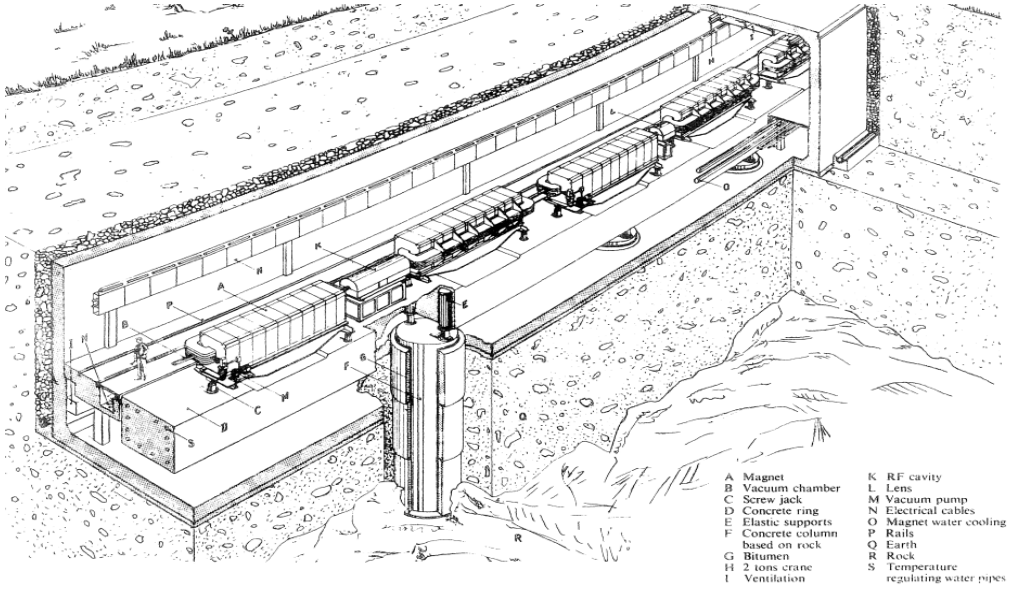
- **Seminars:**
  - Accurate and Efficient Numerical Modelling Methods for Superconducting Circuit Quantum Information Processing Devices (DIETI)
  - How to publish under the CARE-CRUI Open Access Agreement with IEEE (DIETI)
  - Bremsstrahlung Beam-Size Effects and FCC-ee Beam Lifetime (CERN)
  - Nanoneuro: the power of nanoscience to explore the frontiers of neuroscience (DIETI)
  - Optimization of a mobile clinic routing and scheduling problem in equitable vaccination outreach (DIETI)
  - Traffic Engineering with Segmented Routing: optimally addressing popular uses cases (DIETI)
  - Slawosz Uznanski - A CERN staff member, now ESA astronaut (CERN)
  - “Rainbow´ Storage Ring Nuclear Transmutation with Spin Control Capability (CERN)
  - Optimization of the High-Brightness Beam Performance of CERN PSB with H- injection (CERN)
  - Beam Physics Research in IOTAFAST at Fermilab (CERN)

Summary of study activities (4)

- **Seminars:**
  - Beam Physics Research in IOTAFAST at Fermilab (CERN)
  - Research in Energy Storage Systems for Automotive, Aerospace and Grid-connected Systems at the Ohio State University Center for Automotive Research (DIETI)
  - The design of the ENUBET beamline (CERN)
  - Reinforcement learning in CERN's accelerator & beyond (CERN)
  - Neutrinos in the lab and in the cosmos (2/3) (CERN)
  - Mixed Reality human-robot interface for remote operations in accelerator facilities (CERN)
  - Picariello Lectures on Data Science – Robotics meets AI and 5G: Future is now (DIETI)
  - Diffusive models and chaos indicators for non-linear betatron motion (CERN)
  - Ensuring Electronic Reliability Against CERN's Radiation Environment (DIETI)
  - Picariello Lectures on Data Science - Artificial Intelligence for Ocean Dynamics (DIETI)
  - ICALEPCS 2023 Summary & ATS Flash Presentation Seminar (CERN)

Research activity: Overview (1.1) - Problem

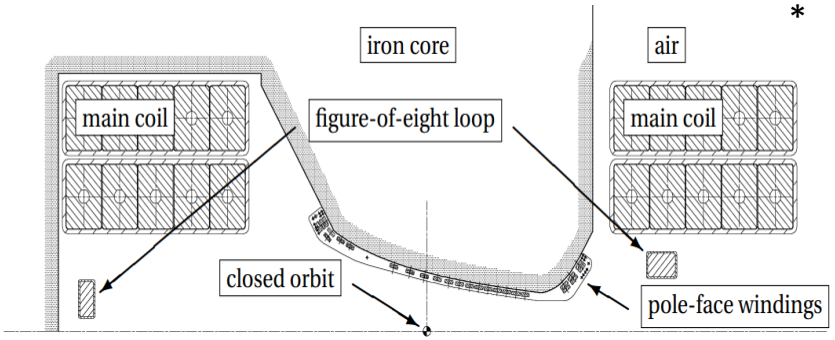
- **CERN Proton Synchrotron (PS): main features**
  - 277 normal conducting magnets
  - Accelerates protons and ion beams from 2 GeV up to 26 GeV kinetic energy

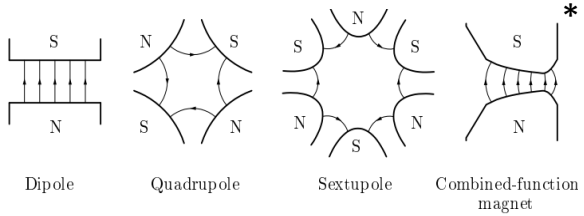


Picture from: The CERN Proton Synchrotron magnets – Report design

Research activity: Overview (1.2) - Problem

- **100 Main Units (MUs):**
  - C-shaped iron blocks
  - Each of them powered with 3 coils: Main Coil and two additional circuits (F8L and PFW). Additional circuits off → bare-machine configuration
  - Pole shape designed to create a combined function magnetic field

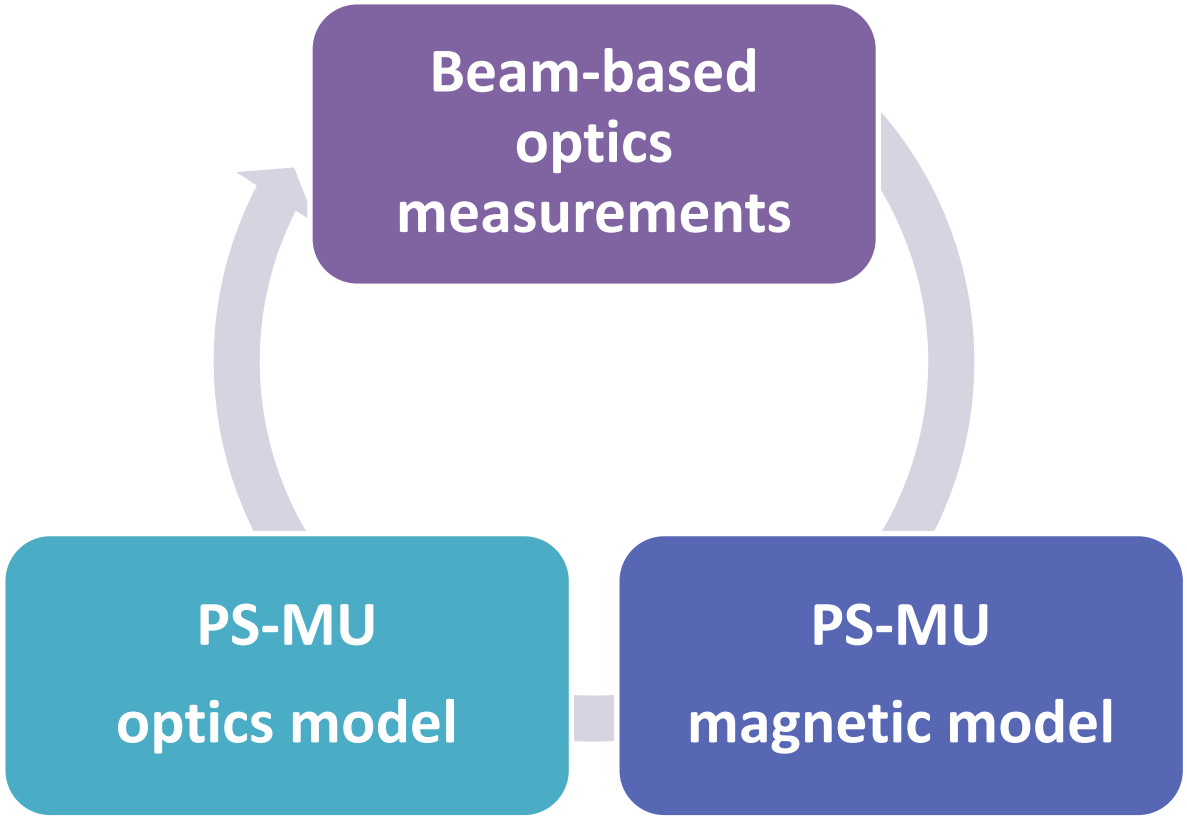




* Pictures from: The CERN Proton Synchrotron magnets – Report design

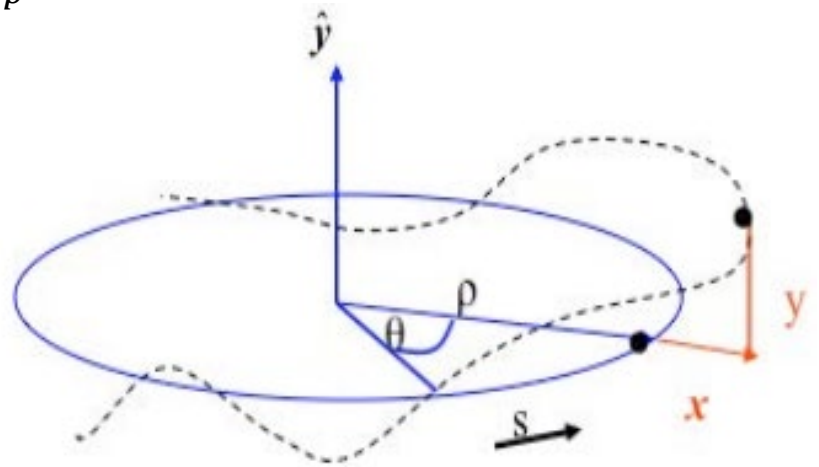
Research activity: Overview (2) - Methodology

- **Are we able to predict the beam dynamics?**



Research activity: Overview (3.1) – Results and validation

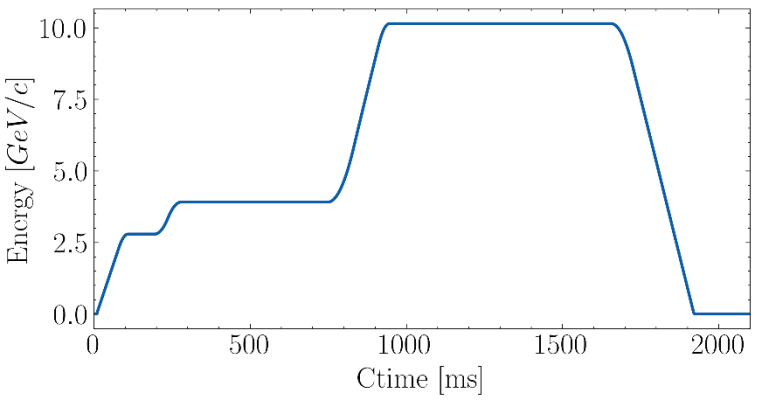
- **Two main parameters for beam dynamics optics studies:**
  - Horizontal/vertical tune $Q_{x/y}$: number of beam oscillations per turn in the horizontal/vertical plane. Cannot be an integer (or half-integer) number → resonances
  - Chromaticity $Q'_{x/y} = \frac{\frac{\Delta Q}{Q}}{\frac{\Delta p}{p}}$

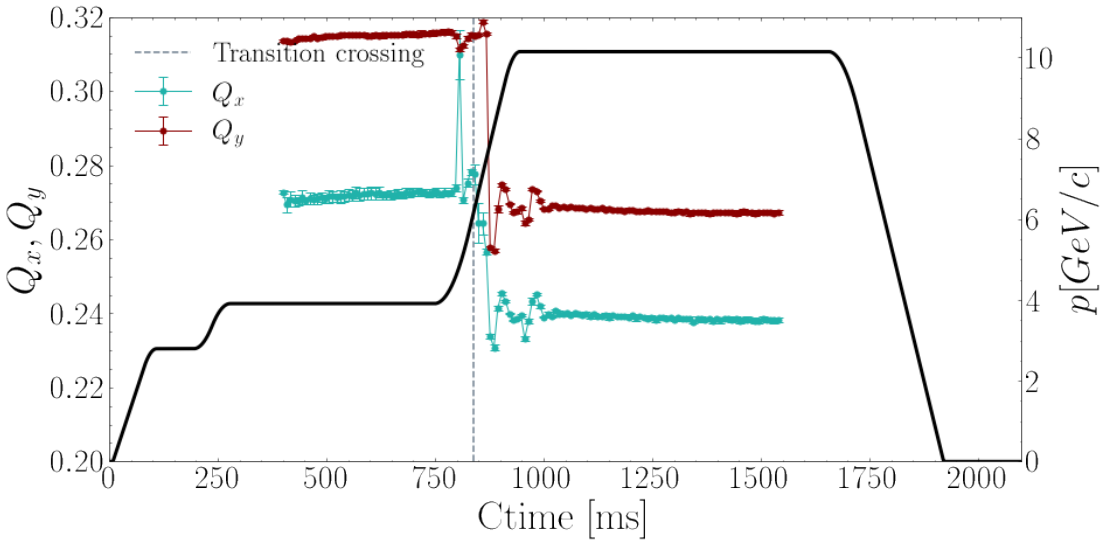


Picture from: https://cds.cern.ch/record/1693320/files/CERN-2014-005-p21.pdf

Research activity: Overview (3.2) – Results and validation

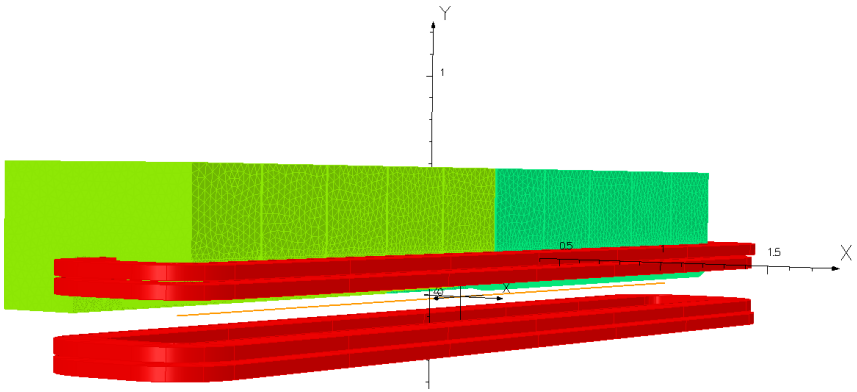
- **Optics measurements:**
  - Many power cycles created to measure the optics at different energies from 2.8 GeV to 23 GeV (2.8, 5, 7, 10, 14, 18, 23) in bare-machine:

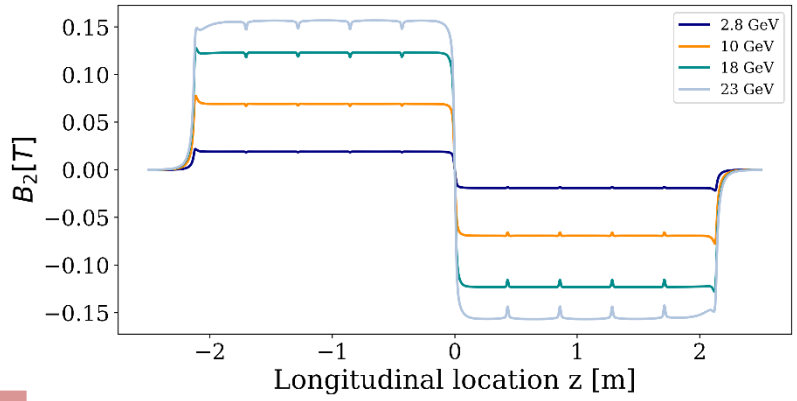




Research activity: Overview (3.3) – Results and validation

- **Validation of the models through optics measurements:**
  - Magnetic model and harmonics computation in Opera 3D*:



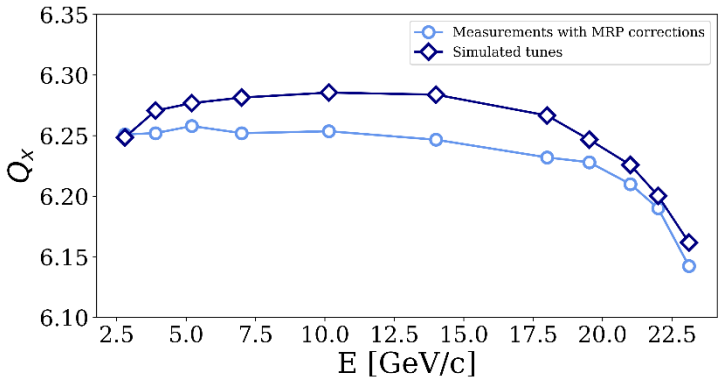


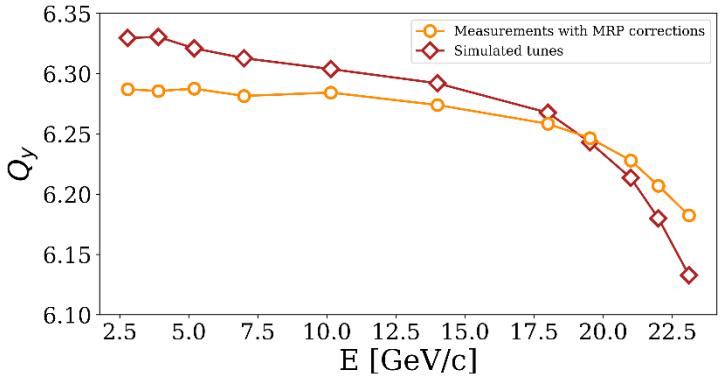
Beam Dynamics simulation tool: Methodical Accelerator Design (MAD-X)**

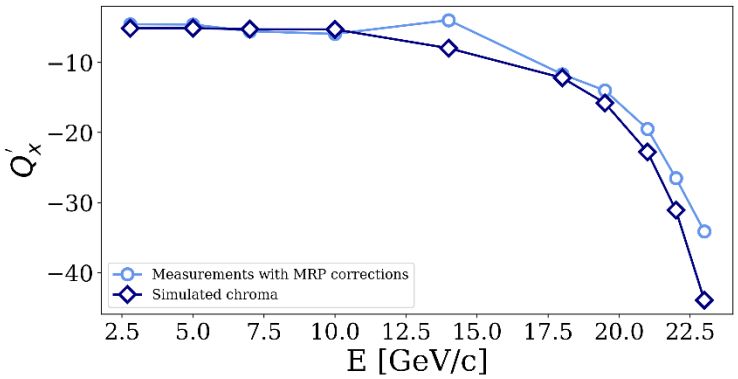
* http://www.rcnp.osaka-u.ac.jp/~sakemi/OPERA/ref-3d.pdf
**https://mad.web.cern.ch/mad/

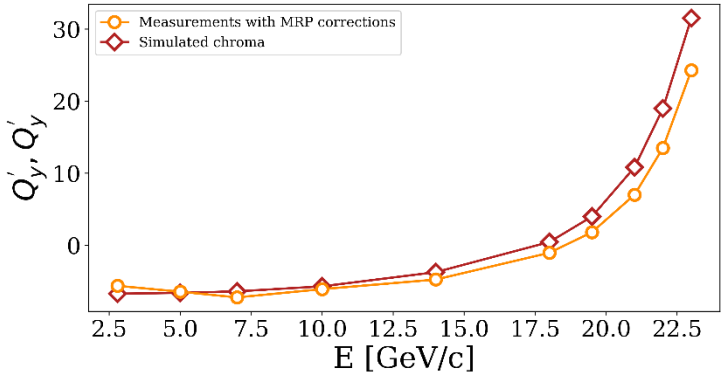
Research activity: Overview (3.4) – Results and validation

- **Validation of the models through optics measurements:**
  - Comparison of the measured and simulated optics



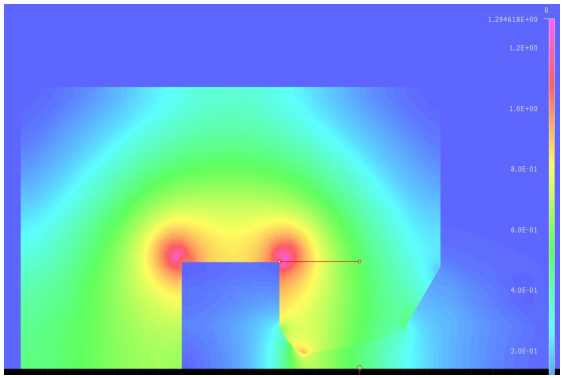




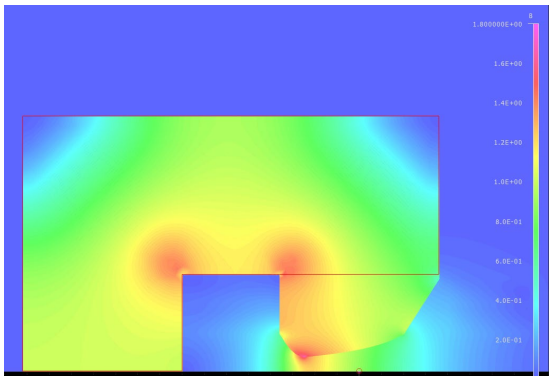


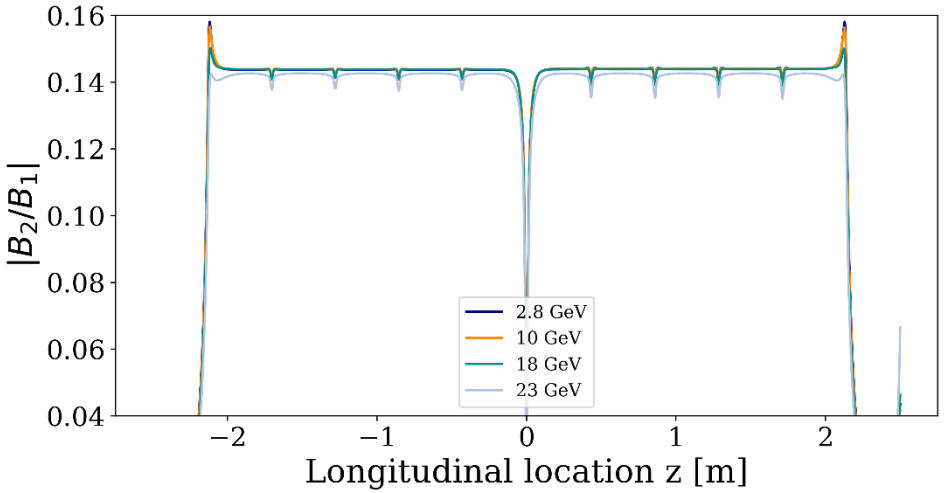
Research activity: Overview (3.5) – Results and validation

- **Validation of the models through optics measurements:**
  - Saturation of the optics due to the saturation of the harmonics
  - 10 GeV



  - 18 GeV:





Products

[1]	**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; Status: **Published**: in 2023.
[2]	**Title**: First operational dodecapole correction in the LHC; **Authors**: J. Dilly, V. Ferrentino, M. Le Garrec, E. H. Maclean, L. Malina, T. Persson, T. Pugnat, L. van Riesen-Haupt, F. Soubelet, and R. Tomás; **Journal**: Physical Review Accelerators and Beams (PRAB); **Status**: Published in 2023.

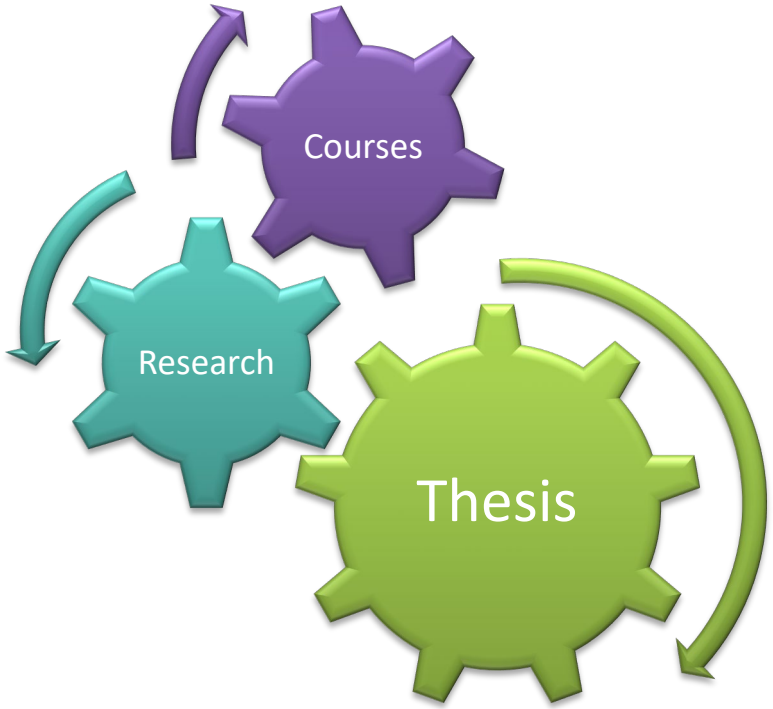
Products

[3]	**Title**: Optics Correction Strategy for Run 3 of the LHC; **Authors**: T. Persson, J.Cardona, F. Carlier, A. Costa Ojeda, J. Dilly, H. García Morales, V. Ferrentino, E. Fol, M. Hofer, E.J Høydalsvik, J. Keintzel, M. Le Garrec, E.H. Maclean, L. Malina, F. Soubelet, R. Tomás, L. Van Riesen-Haupt, and A. Wegscheider; **Conference**: 13th International Particle Accelerator Conference (IPAC); **Status**: Published in 2023.
[4]	**Title**: Challenges of K-modulation measurements in the LHC Run 3; **Authors**: F. Carlier, A. Costa Ojeda, J. Dilly, V. Ferrentino, E. Fol, M. Hofer, J. Keintzel, M. Le Garrec, T. Levens, E. H. Maclean, T. H. B. Persson, F. Soubelet, R. Tomás Garcia, L. Van Riesen-Haupt, A. Wegscheider; **Conference**: 14th International Particle Accelerator Conference (IPAC); **Status**: Accepted in 2023.
[5]	**Title**: LHC Run 3 optics corrections; **Authors**: F. Carlier, J. Cardona, A. Costa Ojeda, R. De Maria, J. Dilly, V. Ferrentino, E. Fol, M. Hofer, J. Keintzel, M. Le Garrec, E. H. Maclean, T. H. B. Persson, F. Soubelet, G. Trad, R. Tomás Garcia, L. Van Riesen-Haupt, A. Wegscheider; **Conference**: 14th International Particle Accelerator Conference (IPAC); **Status**: Accepted in 2023.

Summary of activities

II year	Courses PhD Schools	Seminars	Research	Tutorship	Total
Completed	20	6.8	42.2	0	69
Expected	10-20	5-10	30-45	0-1.6	60

Next year



Ad hoc Courses

- Courses from the ITEE program to reinforce technical and soft skills

Models

- Magnetic model: simulate the bending of the real magnets and add the additional circuits into it;
- Optics model: new objects and different integration

Measurements

- New beam-based optics measurements to analyze the impact of the additional circuits on the measured optics and validate the models

Conferences

- 15th International Particle Accelerator Conference (IPAC)

Many thanks to the ITEE Board, ITEE tutors and colleagues for the attention