Vittorio Ferrentino

Magnetic and optics modeling of accelerator's main magnets and validation via beam-based measurements: case study at the CERN Proton Synchrotron

Tutor: Prof. Pasquale Arpaia co-Tutor: Ewen Hamish Maclean (CERN)

Cycle: XXXVII Year: Third

Candidate's information

- MSc degree: Electrical Engineering at DIETI, UNINA, Naples, Italy
- DIETI Research group/laboratory: IMPALab
- PhD start date: 01st January 2022
- PhD end date: 31st December 2024
- Scholarship type: Enrolled as supernumerary under the UNINA-CERN agreements and CERN Doctoral Student Programme
- Partner company: European Organization for Nuclear Research (CERN)

Summary of study activities

- Ad hoc courses/PhD schools:
  - Scientific writing;
  - My first steps in French;
  - Metrology and Machine learning for Brain Computer Interfaces;
  - CERN Accelerator School (CAS): Introduction to Accelerator Physics
  - 5th Future-IoT PhD School: IoT meets Autonomy 2022
  - 2023 Spring School on Transferable Skill
  - Academic Entrepreneurship
  - Standard Model of Fundamental Interactions
  - Introduction to deep learning
  - Big Data Architecture and Analytics
  - Numerical Methods for Thermal Analysis, Modelling and Simulation: Application to Electronic Devices and Systems
  - Learn English with Confidence – Niveau B2+

Summary of study activities

- Seminars: mainly focused on the artificial intelligence (AI), deep learning and machine learning, quantum mechanics, development of technologies for environment sustainability, data analysis, etc. Mostly joined during I and II year.
  - I year: 20 seminars → 7.8 credits
  - II year: 25 seminars → 6.8
  - III year: 4 seminars → 1.4

- Conferences: joined the 15th International Particle Accelerator Conference (IPAC) in Nashville, Tennessee, US;
  - Presented two papers as first author, and contributed to three other papers

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Research area

The main research area of interest is the combined magnetic and optics modelling of main magnetic units in particle accelerators for beam parameters predictions.

The case study is centred on the CERN Proton Synchrotron (PS) accelerators Main Unit (MU) magnets, which is part of Large Hadron Collider's injector chain and plays a vital role in delivering high quality and stable beams to downstream accelerators.

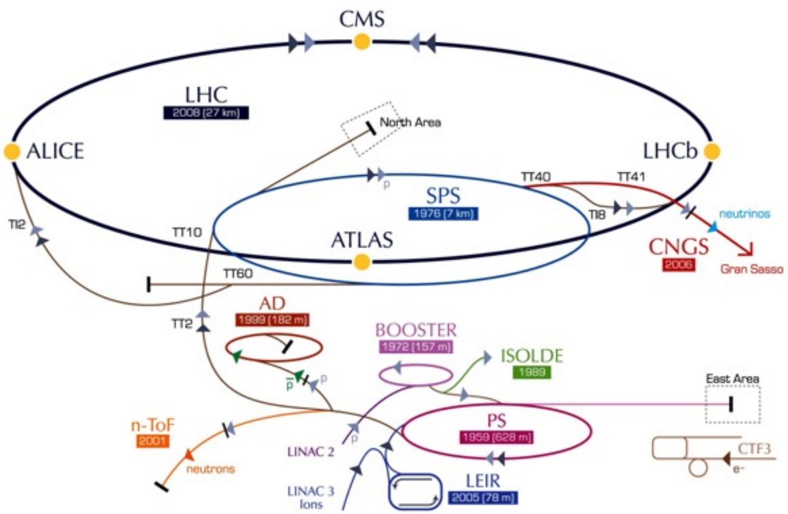

Figure from https://home.cern/science/accelerators/proton-synchrotron

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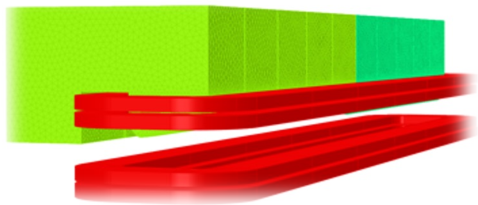
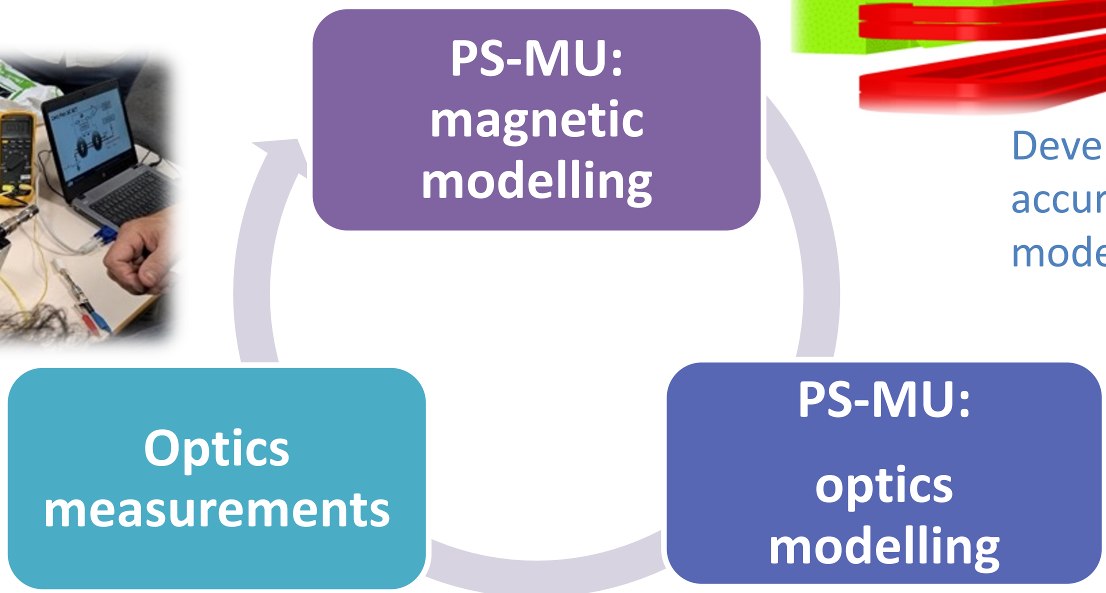
Research results

Research activities led to remarkable results in the three main research area of interest:

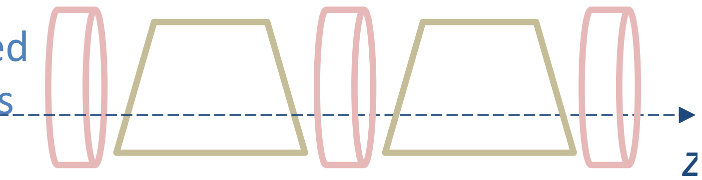


Developed a new flexible, accurate, time-efficient 3D model in Opera 3D



Successfully validated the models' predictions.
Some interesting outcomes for operational applications

- New optics model based on predicted harmonics
- Predictions showed excellent agreement with measurements



Research products

Published international journal papers:

[P1]	V. Ferrentino, P. Arpaia, A. Gilardi, M. Karppinen, C. Kokkinos, E. Ravaioli, *Analysis of Powering and Quench Protection of the SIGRUM Superconducting Combined-Function Dipole Magnet,* **IEEE Transactions on Applied Superconductivity,** Vol. 33, number 7, pp. 1-8, 2023, DOI: 10.1109/TASC.2023.3296281.
[P2]	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, *First operational dodecapole correction in the LHC,* **Physical Review Accelerators and Beams (PRAB),** Vol. 26, pp. 121001, Dec. 2023, DOI: 10.1103/PhysRevAccelBeams.26.121001.
[P3]	R. Tomás, F. Carlier, F. Chudoba, L. Deniau, J. Dilly, V. Ferrentino, S. Horney, M. Hostettler, J. Keintzel, S. Kostoglou, M. Le Garrec, E.H. Maclean, T. Nissinen, K. Paraschou, T. Persson, M. Solfaroli, F. Soubelet, A. Wegscheider and J. Wenninger, *Optics for Landau damping with minimized octupolar resonances in the LHC,* **Journal of Instrumentation (JINST),** Vol. 19, pp. T05010, May 2024, DOI: 10.1088/1748-0221/19/05/T05010.

Research products

International journal papers under internal review:

[P4]	V. Ferrentino, P. Arpaia, D.G. Cotte, V. Di Capua, A. Gilardi, A. Huschauer, M. Karppinen, E.H. Maclean, M. Pentella, T. Persson, R. Tomas Garcia, and L. Von Freeden, *Optics energy dependence within the CERN Proton Synchrotron Main Units,* **Physical Review Accelerators and Beams (PRAB).**
[P5]	E.H. Maclean, V.Ferrentino, M. Le Garrec, W. Van Goethem, S. Horney, K.Paraschou, R. Tomas *Measurement and correction of forced RDTs to improve machine models and performance* **Physical Review Accelerators and Beams (PRAB).**

Research products

International conference papers:

[P6]	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 RiesenHaupt, and A. Wegscheider, *Optics Correction Strategy for Run 3 of the LHC,* **13th International Particle Accelerator Conference (IPAC),** Bangkok, Thailand, 12 - 17 Jun 2022, pp.1687-1690, Publisher JACoW IPAC 2022, DOI: http://dx.doi.org/10.18429/JACoW-IPAC2022-WEPOST008,
[P7]	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 RiesenHaupt, A. Wegscheider, *Challenges of K-modulation measurements in the LHC Run 3,* **14th International Particle Accelerator Conference (IPAC),** Venice, Italy, 7 - 12 May 2023, pp. 531-534, JACoW Publishing, Geneva, Switzerland, DOI: 10.18429/JACoW-IPAC2023-MOPL014
[P8]	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, *LHC Run 3 optics corrections,* **14th International Particle Accelerator Conference (IPAC),** Venice, Italy, 7 - 12 May 2023, pp. 535-538, JACoW Publishing, Geneva, DOI: 10.18429/JACoW-IPAC2023-MOPL015.

Research products

International conference papers:

[P9]	M. Le Garrec, K. Paraschou, F.S. Carlier, V. Ferrentino, E.H. Maclean, J. Dilly, R. Tomas, *Measurement and modelling of decapole errors in the LHC from beam-based studies,* **14th International Particle Accelerator Conference (IPAC),** Venice, Italy, 7 - 12 May 2023, pp. 567-570, JACoW Publishing, Geneva, Switzerland, DOI: 10.18429/JACoWIPAC2023-MOPL024.
[P10]	V. Ferrentino, P. Arpaia, D.G. Cotte, A. Gilardi, A. Huschauer, M. Karppinen, E.H. Maclean, T. Persson, R.Tomás Garcia, L. Von Freeden, *Energy dependence of PS Main Unit Harmonics,* **15th International Particle Accelerator Conference (IPAC);** Nashville, TN, US, 19 - 24 May 2024, pp. 1036-1039, JACoW Publishing, Geneva, Switzerland, DOI: 10.18429/JACoW-IPAC2024-TUPC15.
[P11]	V. Ferrentino, P. Arpaia, A. B. Carazo, J. Cardona, F. S. Carlier, J. Dilly, E. Fol, A. Gilardi, M. Hofer, S. J. Horney, J. Keintzel, M. Le Garrec, E. H. Maclean, T. Nissinen, T. Persson, F. Soubelet, R. Tomás Garcia, W. Van Goethem, A. Wegscheider, *LHC 2023 Ion Optics Commissioning,* **15th International Particle Accelerator Conference (IPAC),** Nashville, TN, US, 19 - 24 May 2024, pp. 99-102, JACoW Publishing, Geneva, Switzerland, DOI: 10.18429/JACoW-IPAC2024-MOPC20.

Research products

International conference papers:

[P12]	T. Persson, A. B. Carazo, F. Carlier, J. Cardona, F. Chudoba, J. Dilly, R. De Maria, S. Fartoukh, V. Ferrentino, E. Fol, S. J. Horney, U. Kar, J. Keintzel, M. Le Garrec, E. H. Maclean, T. Nissinen, F. Soubelet, K. Skoufaris, G. Trad, R. Tomás, L. Van Riesen-Haupt, W. Van Goethem, A. Wegscheider, **LHC Optics Commissioning in 2023 and 2024,** *15th International Particle Accelerator Conference (IPAC),* Nashville, TN, US, 19 - 24 May 2024, pp. 67-70, JACoW Publishing, Geneva, Switzerland, DOI: 10.18429/JACoW-IPAC2024-MOPC12.
[P13]	S. J. Horney, E. Maclean1, P. Burrows, F. Carlier, J. Dilly, L. Deniau, V. Ferrentin, E. Fol, M. Hofer, J. Keintzel, M. Le Garrec, T. Persson, L. van Riesen-Haupt, F. Soubelet, R. Tomás, A. Wegscheider, *Sextupole RDTs in the LHC at Injection and in the Ramp,* **15th International Particle Accelerator Conference (IPAC),** Nashville, TN, US, 19 - 24 May 2024, pp. 71-74, JACoW Publishing, Geneva, Switzerland, DOI: 10.18429/JACoW-IPAC2024-MOPC13.
[P14]	R. Bruce, A. Carazo, F. Carlier, M. D’Andrea, J. Dilly, I. Efthymiopoulos, S. Fartoukh, V. Ferrentino, S. Horney, M. le Garrec, E. Maclean, D. Mirarchi, T. Nissien, T. Persson, S. Redaelli, M. Solfaroli Camillocci, R. Tomás García, F. F. Van der Veken, A. Wegscheider, Evolution of Special, *LHC Optics Configurations Run 3 Update,* **15th International Particle Accelerator Conference (IPAC),** Nashville, TN, US, 19 - 24 May 2024, pp. 83-86, JACoW Publishing, Geneva, Switzerland, DOI: 10.18429/JACoW-IPAC2024-MOPC16

PhD thesis overview

General problem:

Knowledge and understanding of beam optics are vital for operation of particle accelerators. Accurate predictive optics models of the machine are far from straightforward to get. In most cases, **operation** and **modeling** of main magnetic units have followed an **empirical approach** based on empirical data.

Old empirical data, control systems, and approaches might become invalid over time due to hardware changes and changing demands/constraints of downstream machines/ experiments. Hence, predictive models of the beam optics, which do not rely on empirical data are needed.

Objective:

Assess the possibility of **predicting** the **beam dynamics** and the **optics dependence** on energy within the particle accelerators, starting from field harmonics predictions provided by a magnetic model of the main magnetic units in the machine, used in an optics model for beam dynamics simulations.

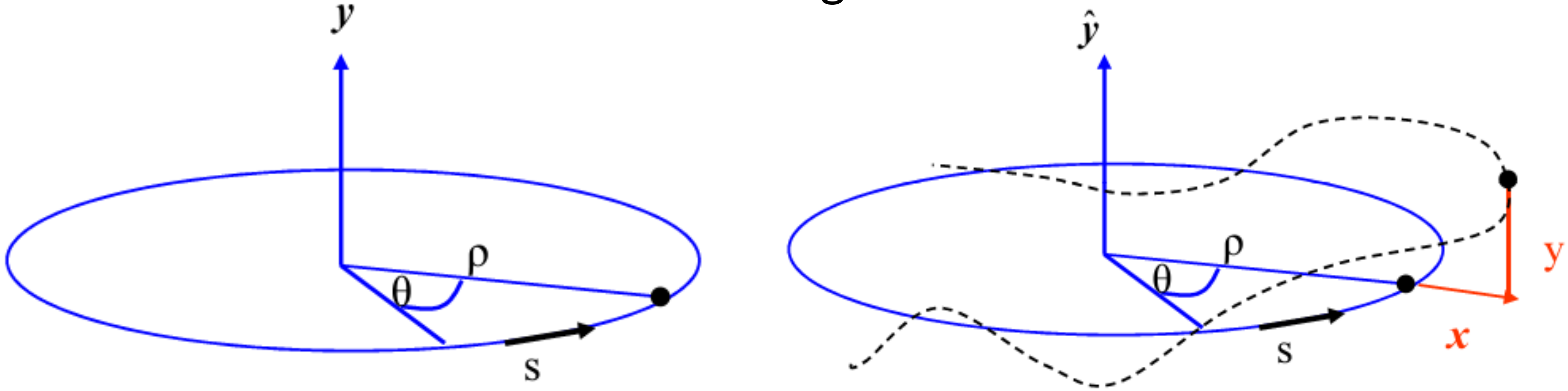
Case study: CERN Proton Synchrotron, interesting due to its complexity.

Methodology:

- Development **of finite-element magnetic model** of PS main magnetic units.
- Computation of **field harmonics**;
- Development of a MU **optics model** based on predicted harmonics
- **Benchmarking** of the combined magnetic and optics models' predictions through **beam-based measurements**

PhD thesis – Beam dynamics (1)

Ideal particle beams in accelerators are designed to move on **reference orbit**.



They rather **oscillates** around the ideal orbit. Defining a coordinate system rotating with the ideal particle, x and y are the horizontal and vertical transverse planes, while s is the longitudinal coordinate, tangential to the particle motion.

- Equation of motion (harmonic oscillator):

$$x''(s) - k(s)x(s) = 0$$

- Solution:

$$x(s) = \sqrt{\varepsilon\beta}\cos(\varphi(s) + \varphi_0)$$

β = β function, ε emittance; → define beam size → Magnet aperture size → costs

Collisions → stable beams → some **parameters under control**:

- **Tune**: number of oscillations in the horizontal/vertical plane
- **Chromaticity**: $Q' = \frac{\frac{\Delta Q}{Q}}{\Delta p/p}$

Pictures: https://cas.web.cern.ch/sites/default/files/lectures/frascati-2008/holzer-1.pdf

PhD thesis – Beam dynamics (2)

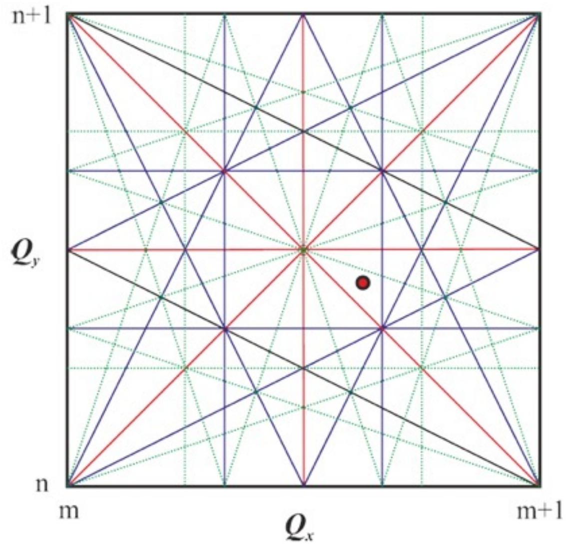
Collisions → stable beams → some parameters under control:

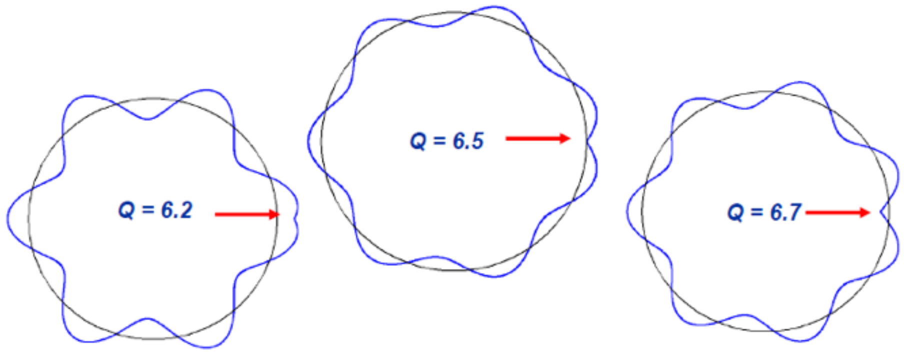
- **Tune Q'**: number of oscillations in the horizontal/vertical plane
- **Chromaticity** $Q' = \frac{\frac{\Delta Q}{Q}}{\Delta p/p}$

p = beam momentum

Very important: tunes must not be integers, or half-integer, or a simple fraction:

- Resonance condition (beam will get lost):
  - $nQ_x + mQ_y = N$, with n, m, N integers





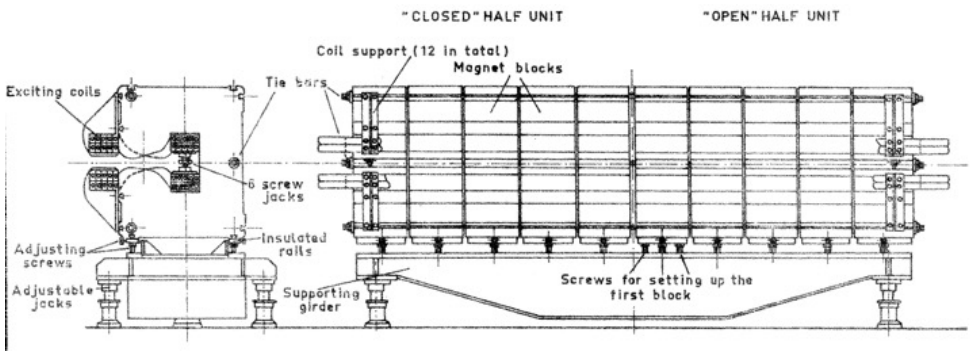
Left picture::https://arxiv.org/pdf/2107.02614
Right : https://arxiv.org/pdf/2004.14001

PhD thesis – Proton Synchrotron (1)

CERN Proton Synchrotron is the first accelerator built at CERN, accelerating the first protons in 1959.

- Accelerator features
  - Circumference of 628 m
  - **277** room-temperature **magnets** (dipole main-units, injection magnets, extraction magnets, etc.)
    - **100 Main-Units (MUs)**

- MUs consist in dipolar C-shaped **combined-function magnets**:
  - Each of them divided in **10 blocks**, 0.417 m each
    - **5 focusing (F)** and **5 defocusing (D)**
    - Tapped **Air Gaps between each block** and in the **F/D transition area**

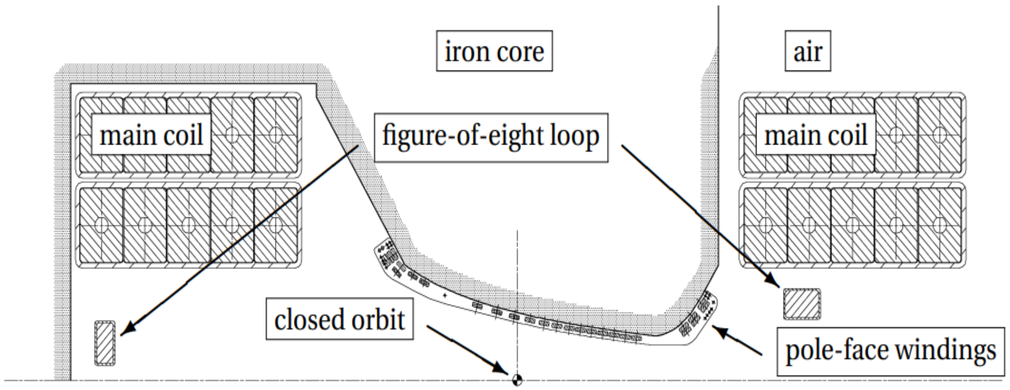


Left picture: https://cds.cern.ch/record/2423241
Right: The CERN Proton Synchrotron magnets – Report design

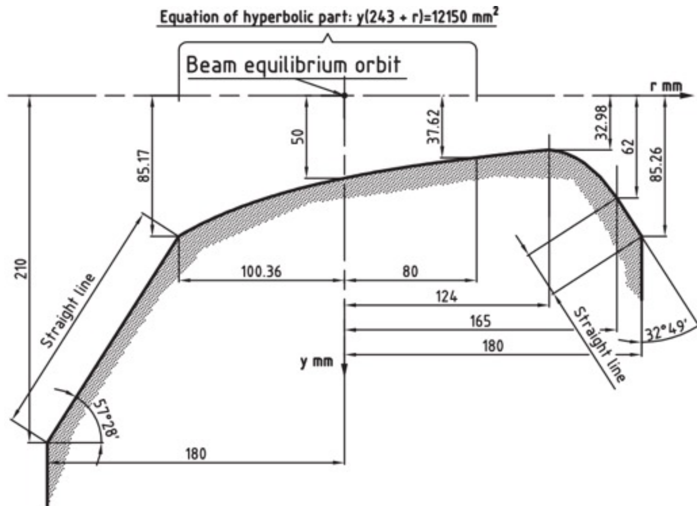
PhD thesis – Proton Synchrotron (2)

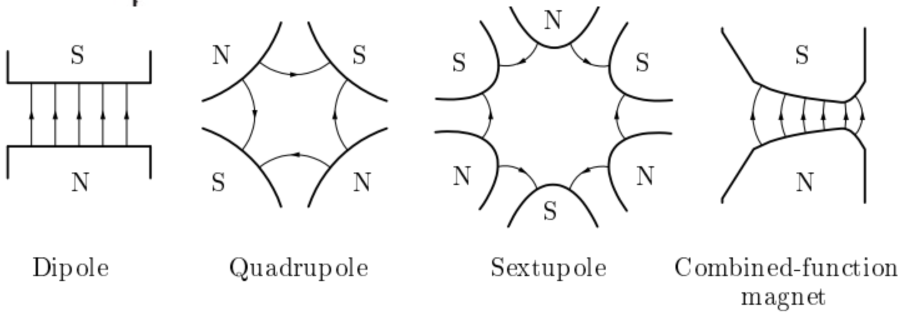
MU are powered with 3 different coils:

- Main coil creating the main field
- Additional circuits to correct higher order components
  - Figure-of-eight loop (F8L)
  - Pole Face Windings



Hyperbolic pole designed to generate a combined-function magnetic field in the aperture:

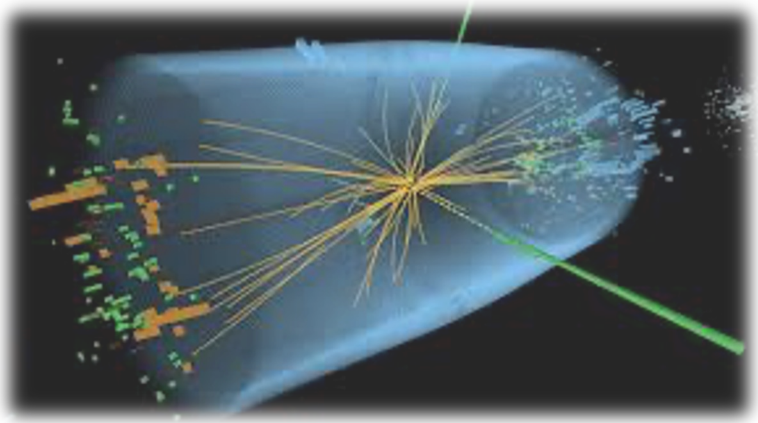




https://cds.cern.ch/record/2423241

PhD thesis – Need for PS-MU models

After the discovery of the Higgs' boson with the LHC in 2012, beam requirements from LHC itself and new other experiments have required upgrades to the machine:



"High-Luminosity LHC (HiLumi) project aims to crank up the performance of the LHC in order to increase the potential for discoveries after 2030. The objective is to increase the integrated luminosity by a factor of 10 beyond the LHC's design value. It will produce at least 15 million Higgs bosons per year, compared to around three million from the LHC in 2017." – CERN, HiLumi page

HiLumi
HL-LHC PROJECT

We need models of the machines and their components (magnets, RF cavities, beam, etc.) to help inform operational decision about how to run the machine (e.g., choice of working points, extraction energies, improve control of the machine.

Left picture: https://home.cern/fr/news/series/lhc-physics-ten/higgs-boson-what-makes-it-special
Right: https://hilumilhc.web.cern.ch/

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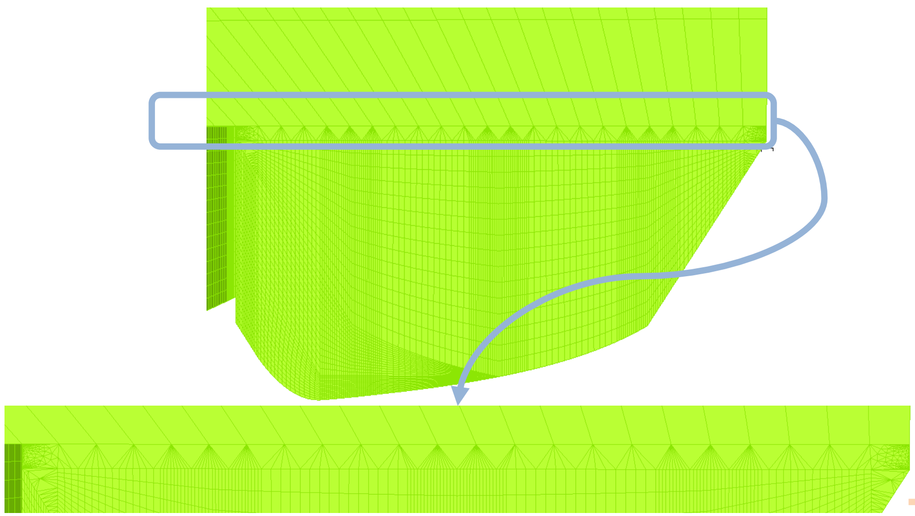
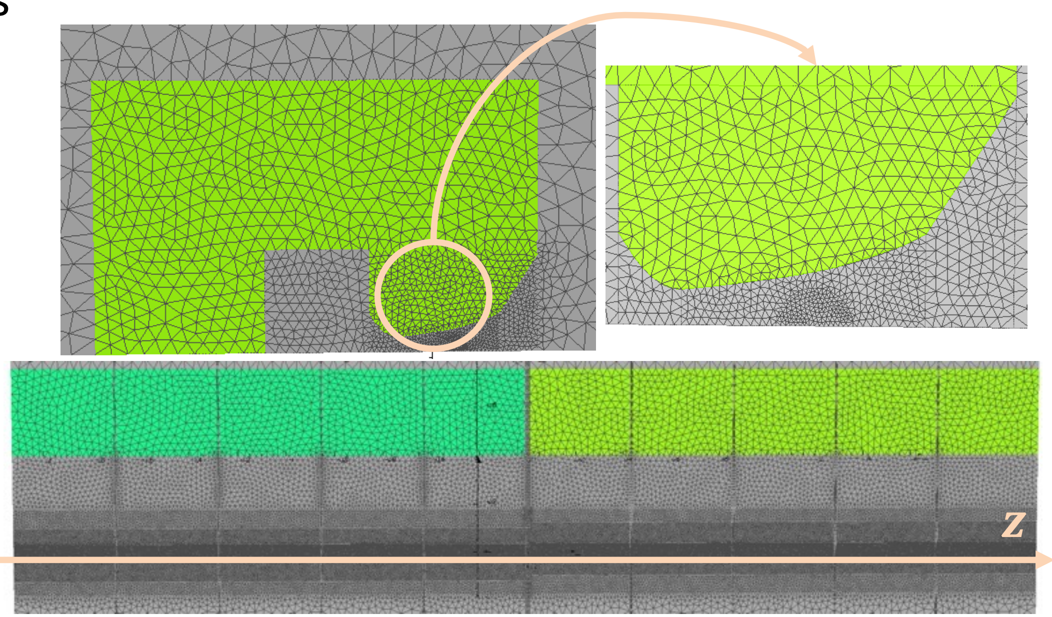
PhD thesis – PS-MU modelling (1)

Pre-existing magnetic model in Opera 3D showed **limitations**:

- Very **heavy**, **long computation times** (order of days)
  - **Mesh** was found not to be appropriate for the MU geometry
  - Unmatched mesh between pole and iron yoke created tiny angles domain, which slowed down the simulations

- Mesh **redesigned** with tetrahedral elements which adapts better to the complicated MU pole shape
  - **Simulations times** notably **reduced** (~6h)
  - Models' **predictions agreed** with **magnetic measurements** with error below 1%

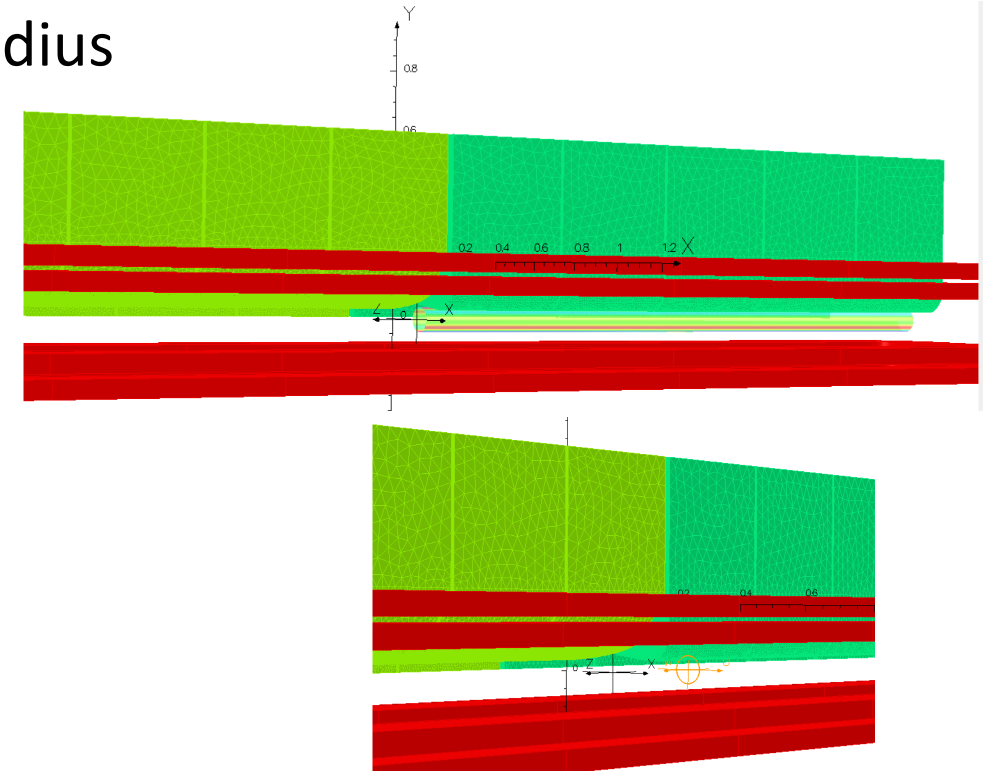




PhD thesis – PS-MU modelling (2)

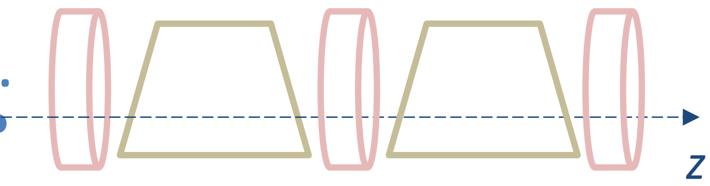
Field harmonics computed in Opera itself along a circle or cylindrical surface of defined radius

→ Harmonics computed from Opera **used** as input for a new PS-MU **optics model** in **MAD-X**.



- **Old mode**l did not attempt to predict the optics dependance on energy, **defining** the field **harmonics** to **match** beam-based **measurements**
- did **not include** the **quadrupolar** field from the magnet extremities (**fringe fields**)
- **New model include quadrupole from fringe fields** and is **defined** at **multiple energies** to assess the optics dependance with energy

Both models are static → they do not include dynamic effects.
Can we use it for predictions in dynamic powering conditions?



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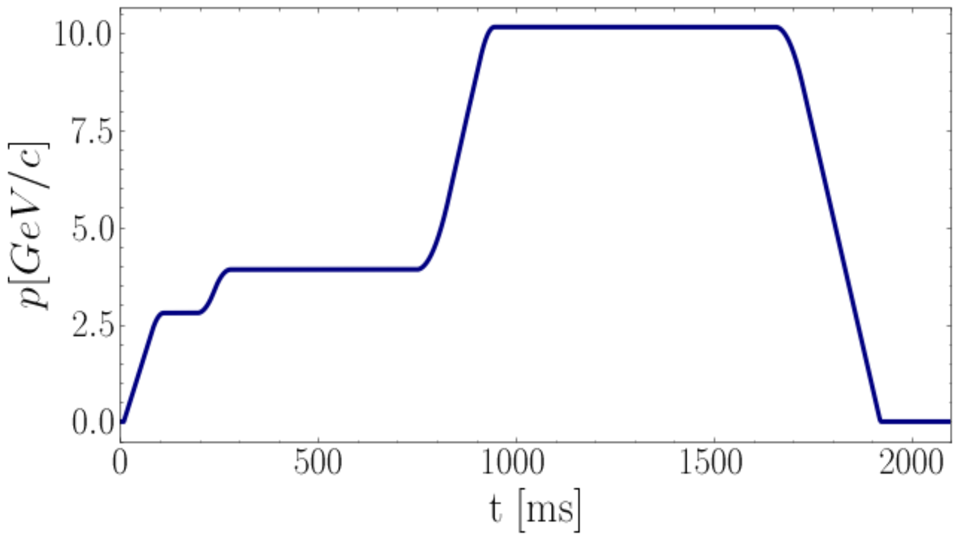
PhD thesis – Models' validation (1)

- Many **bare-machine cycles** were created to analyze the optics dependence on energy in bare-machine (additional circuits off)
  - Each cycle presents a **plateau** at a **specific energy** where the current/field/energy are constant
    - Lowest energy was 2.79 GeV (injection energy), highest was 23 GeV, above which the beam did not survive the ramp

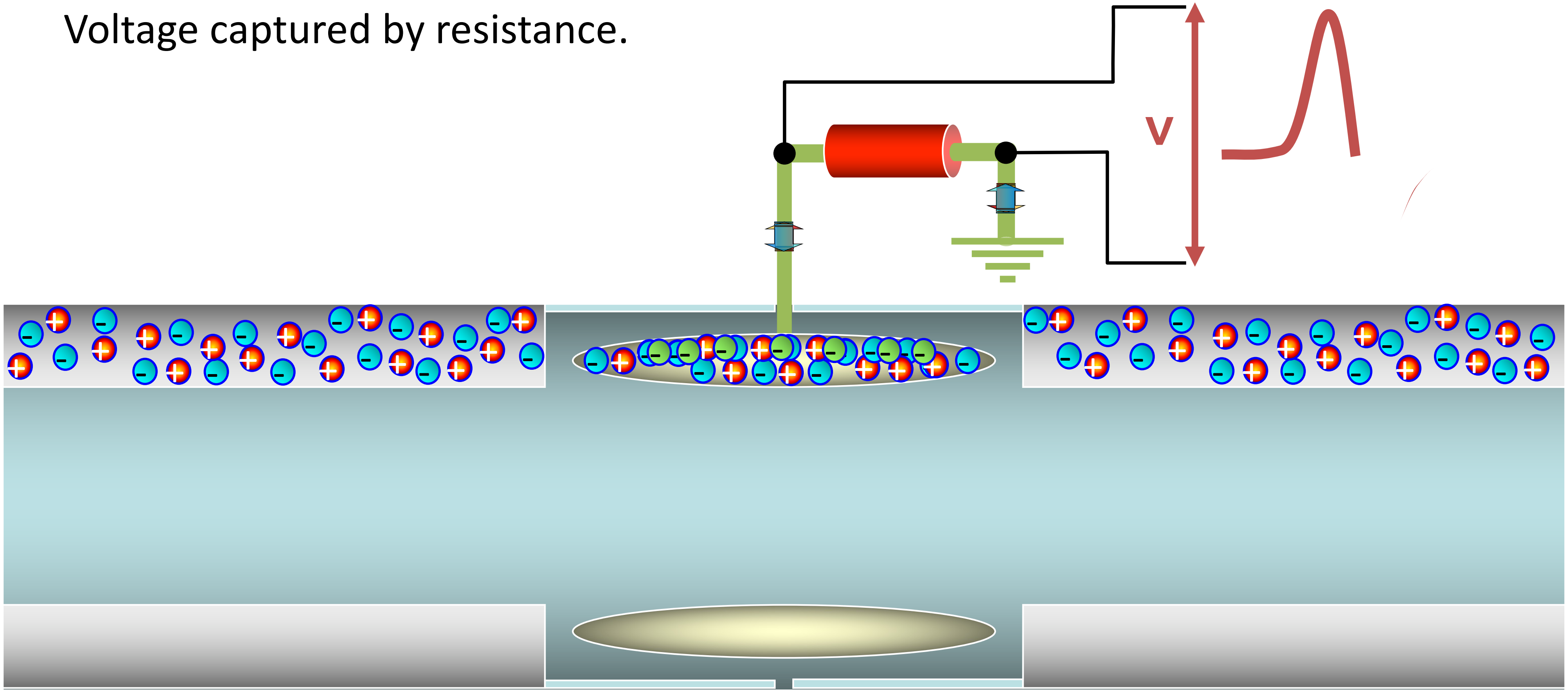
Plateau Energy (GeV)	Main coil current (A)	Measured field (T)
2.79	531	0.1328
5.25	998	0.2500
7.00	1329	0.3331
10.14	1925	0.4830
14.04	2668	0.6684
18.00	3428	0.8570
23.11	4443	1.100



PhD thesis – Models' validation (2)

Beam orbit is captured at each turn by **Beam Position Monitors (BPMs)** placed around the ring.

When beam passes through the pipe, $p^+ - e^-$ **charges** on the wall **separates**. Voltage captured by resistance.

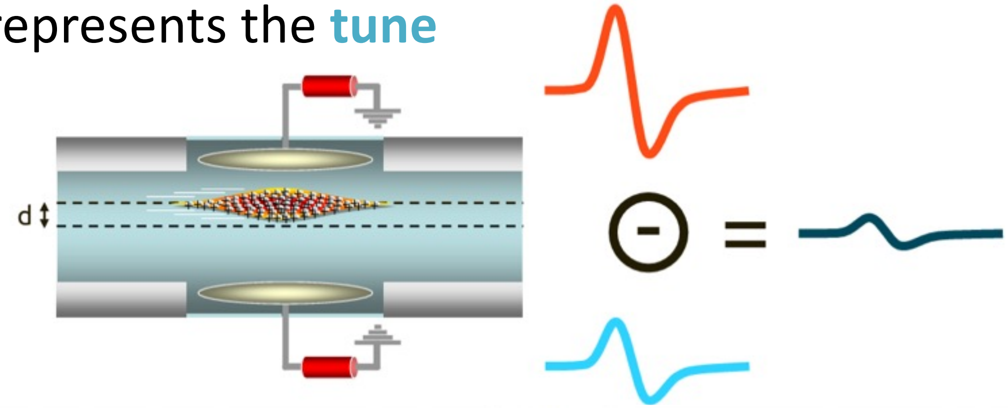


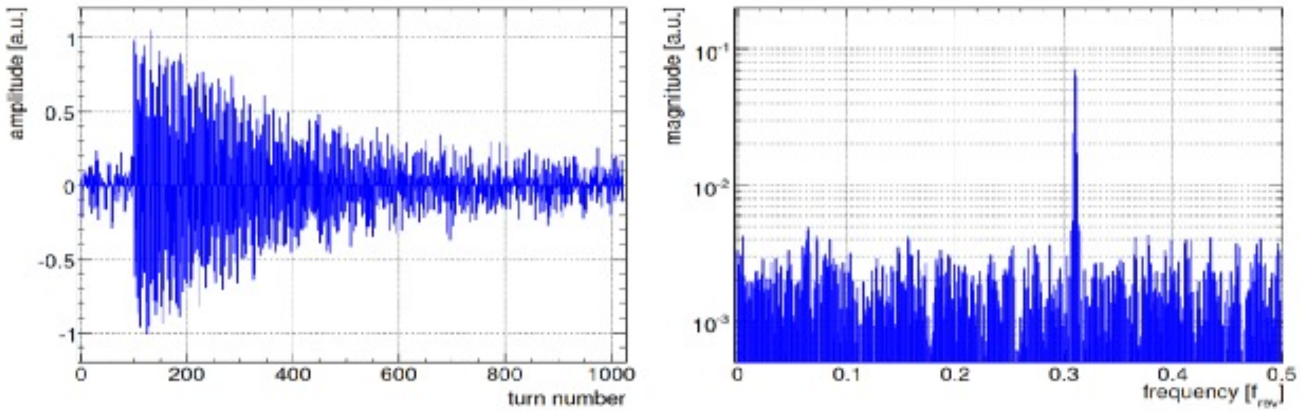
https://indico.cern.ch/event/1380440/contributions/6176016/attachments/2964390/5214876/cas24_bi1_mk.pdf

PhD thesis –Models' validation (3)

To measure the beam optics, **particles** are **excited** at certain frequency (typically close to their natural frequency) → **transverse oscillations**.

Beam **orbit** is captured at each turn by Beam Position Monitors (BPMs) placed around the ring. Turn by-turn-data are processed with **FFT** algorithm → **Peak** in the spectrum represents the **tune**

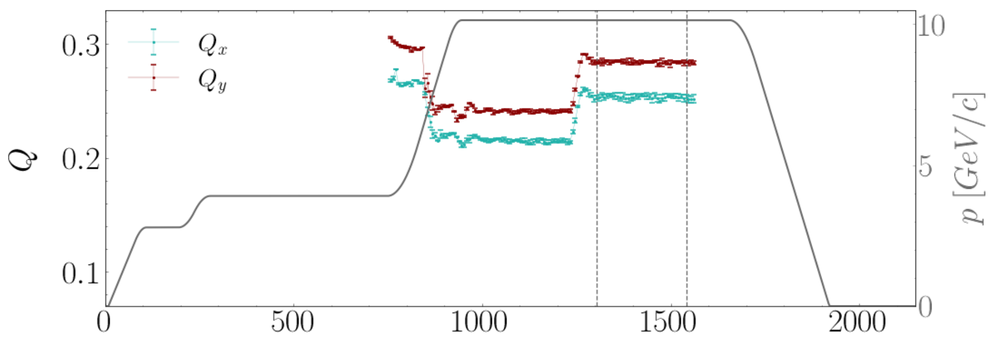




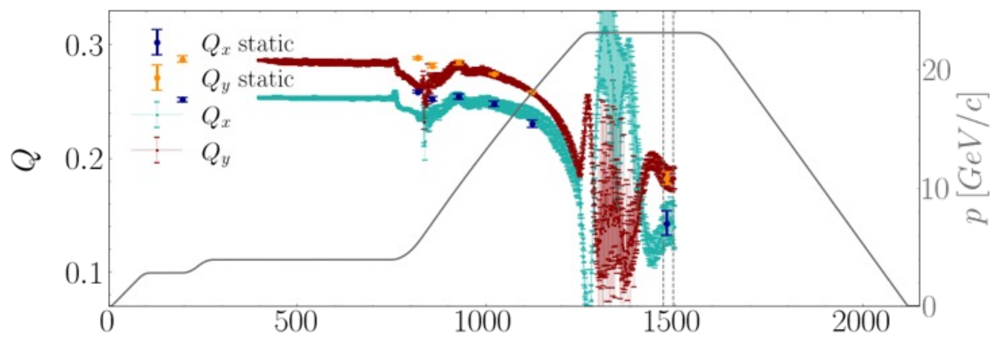
https://indico.cern.ch/event/1380440/contributions/6176033/attachments/2965355/5216903/cas24_bi2_mk.pdf

PhD thesis – Models' validation (4)

- **Static tune measurements** carried out on the **individual plateaus** (static powering current/field) in bare-machine
  - Example power cycle 10 GeV plateau



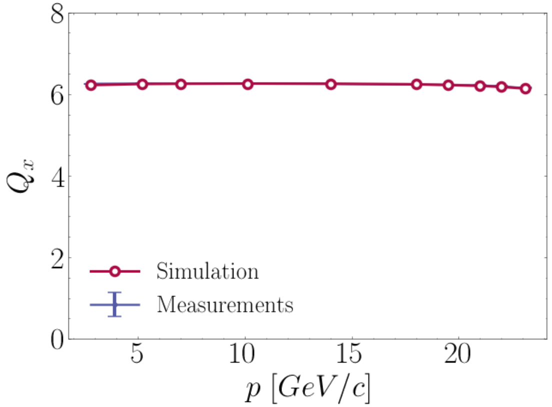
- **Dynamic tune measurements** on the ramp to 23 GeV plateau

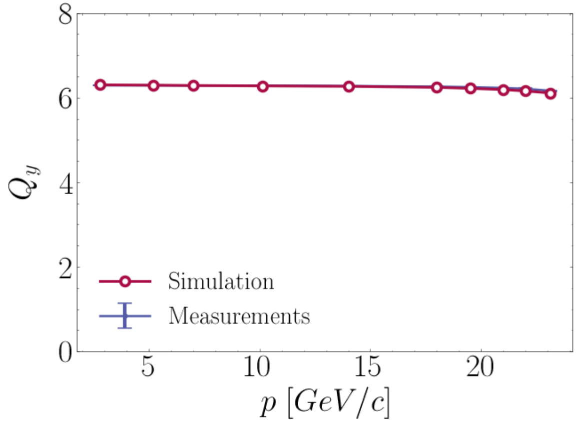


Good **agreement** between **static** and **dynamic measurements** at each energy level → dynamic effects (eddy-currents) on the ramp do not affect tune and chromaticity measurements in bare-machine → Models which do not include these effects, can be used for measurements on the ramp

PhD thesis – Models' validation (5)

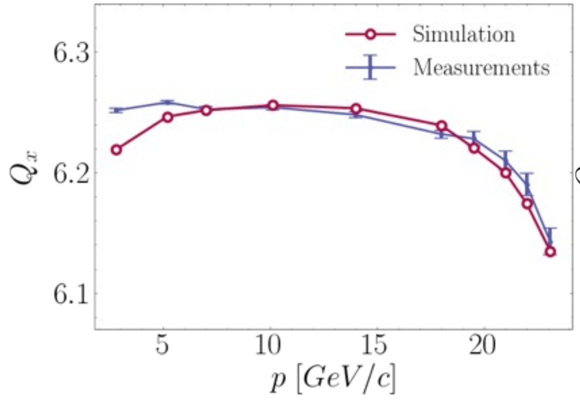
- **Bare-machine models' benchmarking** (tune Q on the left, chromaticity Q' on the right):

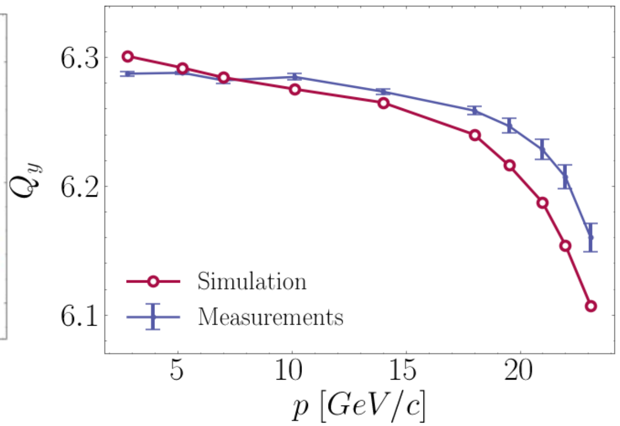


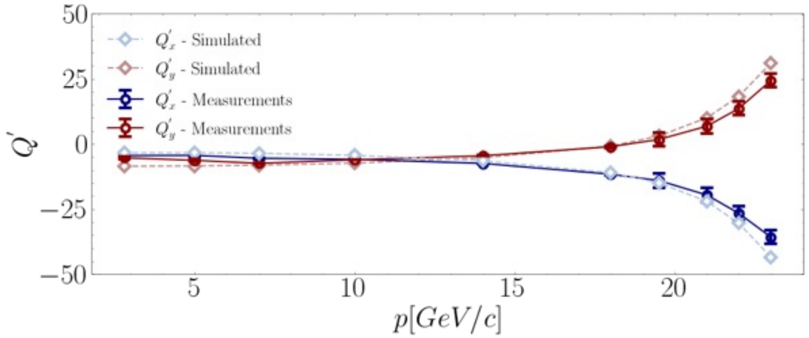


PhD thesis – Models' validation (5)

- **Bare-machine models' benchmarking** (tune Q on the left, chromaticity Q' on the right):



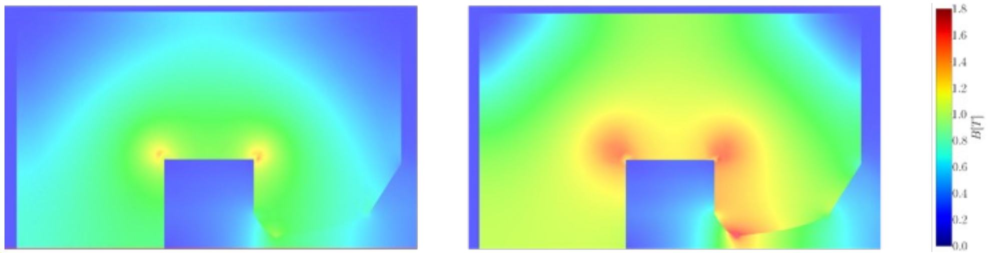


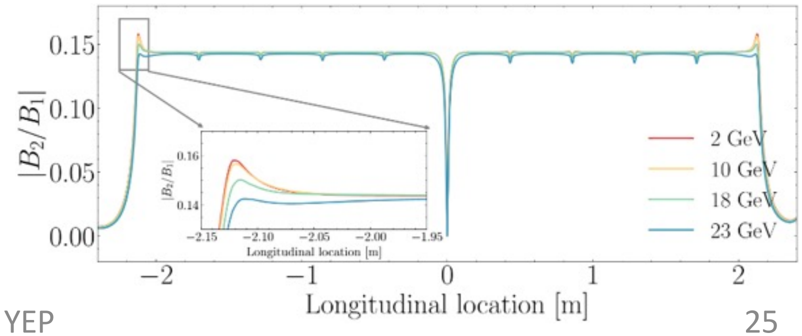


Good agreement observed between models' predictions and beam-based measurements, **error below 1%** over the whole range of energy adopted.

Observed a **decrease** of both **tune** and **chromaticity** due to iron saturation, particularly in its edges. **Quadrupolar** component generated by MU **saturates faster than dipolar.**

PREVIOUS MODELS DID NOT CAPTURE THIS EFFECT





PhD thesis – Conclusion

Accelerators require continuous upgrades to meet evolving user requirements.

Digital twins of these machines become essential to predict beam stability and evaluate new possible working points.

Magnetic and optics models of accelerator's main magnets play a key role to evaluate new operational scenario and improve machine performance.

CERN Proton Synchrotron (PS) is equipped with 100 Main Units magnets (MU). PS-MU magnetic model has been improved with a new meshing structure and its predictions are aligned with magnetic measurements.

PS-MU optics model, based on the predicted harmonics from the magnetic model, was improved including quadrupolar field from fringe fields and were defined at multipole energies to evaluate the optics dependence on energy.

Beam-based measurements in bare-machine showed the negligible impact of dynamic eddy-currents effects on tune and chromaticity.

Agreement between models' predictions and beam-based measurements was excellent both in bare-machine and with auxiliary circuits --> new control system for tune and chromaticity based on models is planned.

After these results, many teams at CERN are considering to apply this method to other machines, where they really lack in predictive models. Operational impact on the design of new settings in bare-machine for many experiments and current calibration based on predicted magnetic length saturation from model.