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

by

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*A mamma, papa' e Ilaria,
per aver accettato e sopportato il peso della distanza,
per avermi dato coraggio,
per l'amore incondizionato.*

*A Mary,
"del mio sogno, la parte migliore,
sei quel vento che soffia da sempre,
ma che riesce a non farmi cadere,"
a te, piu di chiunque altro, dedico
questo tanto desiderato e sofferto traguardo*

MAGNETIC AND OPTICS MODELING OF ACCELERATOR'S MAIN MAGNETS AND VALIDATION VIA BEAM-BASED MEASUREMENTS: A CASE STUDY AT THE CERN PROTON SYNCHROTRON

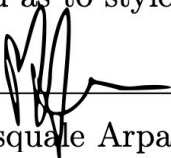
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Napoli, February 25, 2025



Vittorio Ferrentino

Abstract

Digital twins of main accelerator magnets play a vital role in the design, operation, and development of particle accelerators, as well as in optimizing beam performance. This involves the development of accurate magnetic models to predict the field distribution within the magnet aperture, along with optics models to predict the beam dynamics around the machine. The CERN Proton Synchrotron (PS) accelerator features 100 combined-function Main Unit (MU) magnets, generating the main magnetic field in the machine. The modeling of these magnetic units is a unique challenge, aiming to capture the multipolar field distribution within the aperture and the non-linearities from saturation of the iron yoke and the presence of air gaps between consecutive iron blocks within the same unit. Over the past decades, various efforts have aimed to create accurate digital twins of the PS-MU, striving to incorporate the complexities of their magnetic and optical behavior. Operation and optics modeling of the PS-MUs have been historically carried out with empirical beam-based studies. This thesis proposes to evaluate whether, starting from a proper magnetic model and using the predicted harmonics as input to optics simulations, it is possible to accurately predict the beam dynamics behavior in the PS. The predictions from the combined magnetic and optics models are later benchmarked with dedicated beam-based measurements. This work also explores the implications of magnetic length saturation effects on momentum computation, providing valuable operational insights into the interplay between magnetic and beam optics modelling, showing the potential of the developed PS-MU digital twins to optimize machine performance.

Keywords: optics, measurements, modeling, beam, magnet, accelerator.

Sintesi in lingua italiana

Copie digitali delle principali unita' magnetiche in acceleratori di particelle costituiscono un elemento chiave nella progettazione, funzionamento e sviluppo degli acceleratori di particelle e l'ottimizzazione delle performance del fascio. Cio' coinvolge lo sviluppo di accurati modelli magnetici per predire la distribuzione di campo nell'apertura dei magneti, e modelli ottici per predire la dinamica del fascio nella macchina. L' acceleratore Proton Synchrotron (PS) del CERN e' caratterizzato dalla presenza di 100 principali unita' magnetiche a funzione combinata, chiamate Main Unit (MU), responsabili di creare il principale campo nell'acceleratore. La modellizzazione di tali unita' magnetiche rappresenta una notevole sfida, che mira a catturare la distribuzione di campo multipolare nell'apertura magnetica e le non linearita' presenti nelle MU provenienti, ad esempio, dalla saturazione del ferro e dagli strati di aria che separano blocchi consecutivi di ferro entro la stessa unita' magnetica. Negli ultimi decenni, numerosi sforzi sono stati rivolti a creare accurate copie digitali delle MU del PS, tentando di incorporare le criticita' legate alle loro caratteristiche magnetiche ed ottiche. La modellizzazione ottica e l'operazione delle PS-MU sono stati effettuati, storicamente, con studi empirici sul fascio. Questa tesi, invece, si propone di valutare se, partendo da un modello magnetico delle MU e usando le armoniche di campo simulate come input per simulazioni di dinamica del fascio, e' possibile predire accuratamente la dinamica del fascio nel PS. Le predizioni dei modelli sono poi validate mediante dedicate misure sul fascio. La tesi esplora, inoltre, le implicazioni della saturazione della lunghezza magnetica sul calcolo dell'energia del fascio, fornendo suggerimenti sul legame tra modellazione magnetica e ottica, mostrando il potenziale dei modelli sviluppati per ottimizzare le performance della macchina.

Parole chiave: ottica, misure, modelli, fascio, magneti, acceleratore.

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Contents

Abstract	i
Sintesi in lingua italiana	iii
Acknowledgements	xi
List of Acronyms	xvii
List of Figures	xxxiii
List of Tables	xxxviii
List of Symbols	xl
Introduction	4
1 Background concepts in accelerator physics	5
1.1 Electromagnetic fields and particle trajectories	6
1.1.1 Magnetic field description with multipolar expansion	8
1.2 Equation of motion and optics parameters	13
1.2.1 Transverse motion: Hill's equation	15
1.2.2 Tune and resonance conditions	16
1.2.3 Momentum spread: dispersion and chromaticity . . .	18
1.3 Beam instrumentation	21
1.3.1 Beam Position Monitors	21
1.3.2 Base Band Tune	24
1.4 Beam-based measurements	25

1.4.1	Linear optics measurements techniques	25
1.4.2	Chromaticity measurements	28
2	The CERN Proton Synchrotron accelerator	29
2.1	Main magnets	30
2.1.1	MU coil circuits	33
2.2	Field and beam-based measurements instrumentation	38
2.2.1	Magnetic field measurements	40
2.2.2	Beam diagnostic	41
2.3	Software architecture for machine control	43
3	Modeling of the Proton Synchrotron main magnets: state of the art	47
3.1	PS-MU Modeling: addressing challenges and key aspects . .	48
3.2	Finite-element magnetic modeling of the PS main magnets .	50
3.2.1	Packing factor	51
3.2.2	Magnetic properties and hysteresis	51
3.2.3	Model geometry	52
3.2.4	Boundary conditions and symmetries	53
3.3	Optics modeling of the PS main magnets	55
3.3.1	Methodical Accelerator Design - X	56
3.3.2	Pre-existing optics model	58
4	Combined modeling of PS main magnets	61
4.1	Assessment of pre-existing PS-MU models	62
4.1.1	Magnetic model investigation	62
4.1.2	Optics model investigation	64
4.2	A new magnetic model of the Proton Synchrotron main magnets	65
4.2.1	Meshing structure	66
4.2.2	Field harmonics computation	71

4.2.3	Mesh sensitivity analysis	74
4.2.4	Model validation against magnetic measurements . .	76
4.3	New MU optics model	78
4.3.1	From magnetic to optics model	79
5	Beam-based measurements for models validation	81
5.1	Measurements setup and methodology	82
5.2	Beam-based measurements in bare-machine	87
5.2.1	Measurements on flat-cycle at injection energy . . .	88
5.2.2	Beam-based measurements at higher energies	89
5.3	Saturation-induced effects in measurements	93
5.3.1	Benchmarking of static and dynamic measurements .	96
5.3.2	Mitigation of MRP variability and remanent field on the measurements	97
5.4	Effect of corrections on the measurements	98
5.5	Impact of F8L circuit on the beam-based measurements . .	106
5.5.1	Effect of F8L harmonics at injection energy	107
5.5.2	Effect of F8L harmonics on the 10.14 GeV/c plateau	110
5.5.3	Effect of F8L harmonics on the 18.00 GeV/c plateau	114
5.5.4	F8L harmonics effects on the measurements: outcome	119
5.6	Impact of PFW circuits on the beam-based measurements .	120
5.6.1	PFW effects on the measurements: outcome	126
5.7	Combined effect of F8L and PFW with LHC cycle powering settings	128
5.8	Discussion and outcome	134
6	Models' benchmarking against beam-based measurements	135
6.1	Bare-machine models' validation	136
6.1.1	Predicted vs. measured tunes: a comparative analysis	136
6.1.2	Quadrupole saturation from magnetic model	139

6.1.3	Model improvement driven by magnetic length saturation predictions	141
6.1.4	Corrections for momentum computation	145
6.1.5	Simulated effect of momentum corrections	149
6.1.6	Predicted vs measured chromaticity	151
6.2	Predictions from auxiliary circuits	152
6.2.1	Validation of tune and chromaticity predictions with F8L circuit	153
6.2.2	Validation of tune and chromaticity predictions with PFW circuit	158
6.3	Predictions from simultaneous powering of MU coils	161
6.4	Advanced optics studies	164
6.4.1	Beta-beating	165
6.4.2	Chromatic optics-beating	167
6.4.3	Optics measurements with degraded closed orbit	172
7	Conclusions	179
A	Tune and chromaticity measurements in bare-machine with MRP corrections	185
A.1	Chromaticity measurements with PFW	188
	Bibliography	193
	Author's publications	207

List of Acronyms

The following acronyms are used throughout the thesis.

AD	Antiproton Decelerator
BI	Beam Instrumentation
BPM	Beam Position Monitor
BBQ	Base Band Tune
BLM	Beam Loss Monitor
FPGA	Field Programmable Gate Array
F8L	Figure-of-Eight Loop
FE	Finite Element
FEM	Finite Element Model
FFT	Fast Fourier Transform
HL-LHC	High Luminosity Large Hadron Collider
LEIR	Low Energy Ion Ring
LHC	Large Hadron Collider

LIU	LHC Injectors Upgrade
LSA	LHC Software Architecture
MAD	Methodical Accelerator Design
MC	Main Coil
MD	Machine Development
MRP	Mean Radial Position
MTE	Multi Turn Extraction
MU	Main Unit
OMC	Optics Measurements and Corrections
PLL	Phase Locked Loop
PU	Pick-up
PFW	Pole Face Windings
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
RF	Radio Frequency
SPS	Super Proton Synchrotron
TbT	Turn-by-Turn

List of Figures

1.1	Ideal particle (red dot) motion represented by the solid black curve, real particle motion described by dashed blue curve. Reference coordinate system xyz in gray, O center of gyration. ρ is the bending radius of the particle's trajectory . . .	7
1.2	Pure normal magnets of order $n = 1$ (dipole), $n = 2$ (quadrupole), $n = 3$ (sextupole) [1]. Arrows represent magnetic field lines. Dashed lines correspond to the mid-plane. N indicates the North Pole, S the South Pole.	10
1.3	FODO lattice composed by focusing and defocusing quadrupole magnets in turquoise and blue, respectively.	14
1.4	Beam motion in the phase space ($x - x'$ plane) describes an ellipse. The area of the ellipse is proportional to the beam emittance ϵ	17
1.5	Resonance lines: second order resonance in red, third order in black, fourth order in blue.	18
1.6	Dipole kick at location $s = s_0$	19

1.7	Example of magnetic lattice with a dipole (in gray), quadrupole (in turquoise) and sextupole (in green). Particle with reference momentum depicted in blue, while particles with negative and positive Δp are depicted in purple and orange, respectively. Momentum spread creates dispersion within the dipole (inner or outer trajectory of the off-momentum particles with respect to particle with reference momentum p_0), and chromaticity in the quadrupole, which is corrected by the subsequent sextupole.	21
1.8	Beam Position Monitors: pickup buttons [2].	22
1.9	Beam Position Monitors: pickup buttons used in the CERN LHC (left) and drawing of the LHC button pick-up assembly for dual plane measurements (right) [3].	23
1.10	Charged particles within the beam passing through two BPM electrodes. Separation of charge on the surface of the electrodes, voltage signal captured by a load resistor. . .	23
1.11	Equivalent circuit of tune measurements with standard BPM (left) and with BBQ system (right) [4].	24
1.12	Beam oscillations on the vertical plane following AC-dipole excitation on the left. Results of the FFT analysis showing the spectrum on the right.	27
1.13	3 adjacent BPMs for the computation of the β function at the location of the BPM depicted in turquoise (BPM_i). . .	27
2.1	CERN accelerator complex. [5].	30
2.2	Longitudinal view of the PS-MU [6].	31
2.3	PS-MU open (left) and closed (right) blocks [6].	32
2.4	The 4 PS-MU types [7] identified by the the position of the return yoke and the focusing/defocusing sequence with respect to the beam motion.	33

2.5	Diagram illustrating the distribution of the four Main Units types around the PS ring, forming the FOFDOD pattern.	33
2.6	Design of the hyperbolic pole of the PS-MU. [7].	34
2.7	Sketch of the PS-MU yoke profile with the three powering coils: main coil, Figure-of-Eight loop (F8L) and Pole Face Windings (PFW) [8].	35
2.8	Figure-of-Eight Loop circuit.	36
2.9	Pole Face Winding circuits plate [6]. Narrow and wide circuits 11-20, 8-10, respectively. Return conductors 1-4, 21-26 for the wide circuits, 5-7 for the narrow.	37
2.10	PFW: narrow and wide circuits [9].	38
2.11	Schematic representation of the additional circuits powering in 3C (top) and 5C (bottom) modes [9].	39
2.12	Supporting B-train coil bar.	41
2.13	MU iron blocks highlighted in blue displaying the longitudinal location of the B-train coils (red) within the MU.	41
2.14	Transverse view of B-train coils location within the MU, highlighted in skyblue [10].	42
2.15	Example of the PS supercycle in operation.	44
3.1	Measured PS-MU $B - H$ curve employed in the magnetic model. [11]	52
3.2	Boundary conditions of the MU magnetic model. Tangential field condition are superimposed on the γ_t surfaces, while normal field conditions on γ_n ones.	54
3.3	Meshing structure of the pre-existing PS-MU Opera 3D model [11].	55
3.4	Schematic representation of Sector Bending Magnet (SBEND) in MAD-X. Reference orbit entering and exiting perpendicular to the edge faces.	58

3.5	Description of the pre-existing MU optics model in MAD-X for the bare-machine configuration (strengths from F8L and PFW not included).	59
4.1	PS-MU pre-existing magnetic model. Focus on the unmatched meshing (highlighted in red) between the pole (highlighted in orange) and the main body of the iron yoke (highlighted in blue).	63
4.2	Longitudinal (on the left) and transverse (on the right) view of the MU magnetic model. Reference coordinate systems reported in gray, whose center $(0, 0, 0)$ is circled in light blue.	66
4.3	New meshing structure of the PS-MU magnetic model. Coherent mesh density within the boundary region between pole and the rest of the yoke, highlighted in purple. Highest mesh density in a half-circumference of radius $R_{ref} = 35$ mm.	67
4.4	Details of the new meshing structure. Finest mesh in the half-circumference of radius $R_{ref} = 35$ mm (a). Lower mesh density in the area below the pole (b, c, d). Coarser mesh in the area where the main coils are located.	68
4.5	Longitudinal view of PS-MU magnetic model with the new meshing structure. High mesh density in the beam region (highlighted in orange) and at the fringe fields (areas highlighted in skyblue).	70
4.6	Integrated dipolar (top), quadrupolar (middle) and sextupolar (bottom) components as a function of the longitudinal direction z at different I_{MC}	73
4.7	Field harmonics computation within a cylindrical surface of radius $R_{ref} = 35$ mm within one half-unit. Focusing and defocusing half-units illustrated in dark and light blue, respectively, main coil depicted in red.	74

4.8	Description of the new MU optics model in MAD-X.	79
5.1	Horizontal tune measurements at 10 GeV at $t = 1200ms$. . .	83
5.2	Horizontal (left) and vertical (right) chromaticities measurements at 10 GeV at $t = 1200ms$	86
5.3	Horizontal and vertical tune measurements on the flat-cycle at injection energy (2.79 GeV).	88
5.4	Horizontal and vertical first order chromaticity measurements on the flat-cycle at injection energy (2.79 GeV). . . .	89
5.5	Bare-machine power cycle with a plateau at 10.14 GeV/c in gray, beam intensity evolution throughout the cycle without excitation in purple and with excitation in orange.	90
5.6	Horizontal and vertical tune measurements on the individual bare-machine cycles in turquoise and red, respectively. .	92
5.7	Horizontal and vertical first order chromaticity measurements throughout the individual bare-machine cycles in blue and orange, respectively.	93
5.8	Comparison between tune and chromaticity measurements acquired on the steady plateaus and throughout the cycle to the 23.11 GeV/c plateau. Tune measurements are reported on the top, chromaticity on the bottom.	95
5.9	Consistent pre-cycle prior to the bare-machine cycle to the 23.11 GeV/c plateau.	98
5.10	Static beam-based measurements on the 2.79 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.	100

5.11	Static beam-based measurements on the 10.14 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.	101
5.12	Static beam-based measurements on the 23.11 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.	103
5.13	Measured horizontal (Q'_x) and vertical (Q'_y) chromaticity on the 23.11 GeV/c cycle. Light blue and light red dots represent the horizontal and vertical chromaticity measurements without MRP corrections, respectively, while dark blue and dark red indicate the corresponding measurements with MRP corrections.	105
5.14	Trim of the MRP corrections and F8L circuit on the flat-cycle at 2.79 GeV/c.	108
5.15	Horizontal and vertical tunes measurements, on top and bottom figure, respectively, with F8L circuit circuit activated at 2.79 GeV/c at various I_{F8L}	109
5.16	Averaged measured horizontal (blue) and vertical (red) tunes on the 2.79 GeV/c plateau as a function of the I_{F8L} current.	109
5.17	Horizontal and vertical chromaticities measurements in blue and orange, respectively, at 2.79 GeV/c with $I_{F8L} = 25$ A.	110
5.18	Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 2.79 GeV/c plateau as a function of the I_{F8L} current.	111

5.19	Trim of the MRP corrections and I_{F8L} current on the 10.14 GeV/c plateau: MRP corrections are inserted between 900 ms and 1100 ms, I_{F8L} current ramped-up between 1300 ms and 1350 ms.	112
5.20	Horizontal and vertical tunes measurements, on top and bottom figure, respectively, with F8L circuit activated on the 10.14 GeV/c plateau at various I_{F8L} current.	113
5.21	Averaged measured horizontal (blue) and vertical (red) tunes on the 10.14 GeV/c plateau as a function of the I_{F8L} current.	113
5.22	Horizontal and vertical chromaticities measurements in blue and orange, respectively, at 10.14 GeV/c with $I_{F8L} = 60$ A.	114
5.23	Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 10.14 GeV/c plateau as a function of the I_{F8L} current.	114
5.24	Trim of the MRP corrections and I_{F8L} current on the 18.00 GeV/c plateau.	115
5.25	Horizontal and vertical tunes measurements, on top and bottom row, respectively, with F8L circuit on at 18.00 GeV/c at various I_{F8L}	116
5.26	Averaged measured horizontal (blue) and vertical (red) tunes on the 18.00 GeV/c plateau as a function of the I_{F8L} current.	117
5.27	Horizontal and vertical chromaticities measurements in blue and green, respectively, at 18.00 GeV/c with $I_{F8L} = -80$ A.	118
5.28	Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 18.00 GeV/c plateau as a function of the I_{F8L} current.	119
5.29	Trim of the MRP corrections and I_{PFW} currents on the 2.79 GeV/c plateau.	121
5.30	Example of FFT spectrum with PFW circuits activated. In the legend, H and V refer to the horizontal and vertical planes, respectively.	122

5.31	Horizontal and vertical tunes measurements, on top and bottom row, respectively, with PFW circuit on at 2.79 GeV/c flat-cycle at various I_{PFW}	123
5.32	Averaged measured horizontal (blue) and vertical (red) tunes on the 2.79 GeV/c flat-cycle as a function of the I_{PFW} current.	124
5.33	Averaged measured horizontal (blue) and vertical (red) tunes at 10.14 GeV/c as a function of the I_{PFW} current.	124
5.34	Averaged measured horizontal (blue) and vertical (red) tunes at 18.00 GeV/c as a function of the I_{PFW} current.	124
5.35	Horizontal and vertical chromaticities measurements in blue and orange, respectively, on the 2.79 GeV/c flat-cycle with $I_{PFW} = 1$ A.	125
5.36	Horizontal and vertical chromaticities measurements in blue and orange, respectively, on the 18.00 GeV/c plateau with $I_{PFW} = 40$ A.	126
5.37	Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 2.79 GeV/c flat-cycle as a function of the I_{PFW} current.	127
5.38	Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 10.14 GeV/c plateau as a function of the I_{PFW} current.	127
5.39	Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 18.00 GeV/c plateau as a function of the I_{PFW} current.	127
5.40	Operational LHC power cycle.	129

5.41	Beam-based measurements on the bare-machine cycle to the 10.14 GeV/c plateau with MRP corrections and auxiliary circuits powered using LHC cycle settings. Top plot displays MRP measurements (purple) and corrections (orange), middle plot horizontal (turquoise) and vertical (dark red) tunes, bottom plot horizontal (light blue) and vertical (light red) first order chromaticity.	131
5.42	Horizontal and vertical spectrum in blue and red, respectively, on the 10.14 GeV at $t = 1388$ ms.	132
5.43	Beam-based measurements on the bare-machine cycle to the 18.00 GeV/c plateau with MRP corrections and auxiliary circuits powered using LHC cycle settings. Top plot displays MRP measurements (purple) and corrections (orange), middle plot horizontal (turquoise) and vertical (dark red) tunes, bottom plot horizontal (light blue) and vertical (light red) first order chromaticity.	133
6.1	Comparison between simulated and measured tunes. The left plot shows horizontal tunes, with simulated values in light blue and measured values in dark blue. The right plot presents vertical tunes, maintaining the same colors for measured and simulated points.	138
6.2	Horizontal and vertical tunes relative error between models' predictions and the beam-based measurements in blue and red, respectively.	139
6.3	On the left, simulated quadrupole strengths in the focusing and defocusing SBENDS in light blue and dark blue. On the right, simulated quadrupole strengths in the focusing and defocusing MULTIPOLES in light red and dark red, respectively.	140

6.4	PS-MU magnetic model: 2D field map at 10.14 GeV/c (left) and 18.00 GeV/c (right).	141
6.5	Simulated B_2/B_1 ratio at 2.79 GeV/c (red), 10.14 GeV/c (orange), 18.00 GeV/c (green) and 23.11 GeV/c (blue). . . .	141
6.6	Dipole field within the MU normalized to the magnetic rigidity at 2.79 GeV/c (red), 10.14 GeV/c (orange), 18.00 GeV/c (green) and 23.11 GeV/c (blue).	142
6.7	Simulated magnetic length at different energies.	144
6.8	Simulated integrated dipolar strengths at different energies.	144
6.9	Comparison between measured transfer function with the SSW system (red) and simulated points (black) [12].	146
6.10	Comparison between simulated and measured tunes. The left plot shows horizontal tunes, with simulated values in dark blue and measured values in blue. The right plot presents vertical tunes, with measured values in light red and simulated values in dark red.	150
6.11	Comparison of predicted and measured first-order chromaticities. The light dashed blue and blue curves represent the predicted and measured horizontal chromaticities, respectively, while the light dashed red and red curves represent the predicted and measured vertical chromaticities, plotted as a function of momentum	152
6.12	Simulated B_3/B_1 ratio at 2.79 GeV/c (red), 10.14 GeV/c (orange), 18.00 GeV/c (green) and 23.11 GeV/c (blue). . . .	153

6.13	Comparison between simulated and measured tunes at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with F8L activated at different currents. Horizontal measured and simulated tunes are reported on the left in light and dark blue, respectively; on the right, measured vertical tunes are depicted in light red, simulated points in dark red. Relative error between measured and simulated points in turquoise with corresponding scale on the right of each plot.	155
6.14	Comparison between simulated and measured tune=shift relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with F8L activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple.	156
6.15	Simulated and measured chromaticity at 2.79 GeV (top), 10.14 GeV (middle) and 18.00 GeV (bottom) at different I_{F8L} currents. Horizontal measured and simulated chromaticities are reported on the left in light and dark blue, respectively; on the right, measured vertical chromaticity is depicted in light red, simulated points in dark red.	159
6.16	Comparison between simulated and measured tunes at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with PFW activated at different currents. Horizontal measured and simulated tunes are reported on the left in light and dark blue, respectively; on the right, measured vertical tunes are depicted in light red, simulated points in dark red. Relative error between measured and simulated points in turquoise with corresponding scale on the right of each plot.	160

- 6.17 Comparison between simulated and measured tune-shifts relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with PFW activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple. [162](#)
- 6.18 Comparison between simulated and measured chromaticity-shifts relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with PFW activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple. [163](#)
- 6.19 Measured and simulated tunes (left) and chromaticity (right) using the LHC cycle powering settings at 10.14 GeV/c and 18.00 GeV/c. Light blue and dark blue dots represent the simulated and measured data, respectively, for the horizontal plane, while light red and dark red correspond to the simulated and measured data for the vertical plane, respectively. [164](#)
- 6.20 Comparison between simulated and measured β functions at 10.14 GeV in blue and red, respectively. Horizontal β functions are reported in the top plot, vertical in the bottom. [166](#)
- 6.21 Comparison between simulated and measured tune=shift relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV (middle plot) and 18.00 GeV (bottom plot) with F8L activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple. . [167](#)
- 6.22 Measured MRP for study of the chromatic optics shifts. . . [168](#)

6.23	Measured BPM-to-BPM phase advance. Measurements on-momentum with $r_{pos} = r_{pos,0}$ in blue, and off-momentum ($\frac{dp}{p} = 3 \times 10^{-3}$) with MRP-shift ($r_{pos} = r_{pos,0} + 10$) in green.	170
6.24	Simulated BPM-to-BPM phase advance. Data with no momentum offset in violet, data with momentum offset ($\frac{dp}{p} = 3 \times 10^{-3}$) in yellow.	170
6.25	Measured BPM-by-BPM delta-phase advance with respect to the model on the horizontal (top) and vertical plane (bottom). Measurements with $r_{pos} = r_{pos,0}$ in blue, those and with MRP-shift in green.	171
6.26	BPM-by-BPM delta simulated phase advance on the horizontal (top) and vertical plane (bottom). Reference measurements ($r_{pos} = r_{pos,0}$) and with MRP-shift ($r_{pos} = r_{pos,0} + 10$) in violet and light yellow, respectively.	171
6.27	Degraded vertical orbit measured at the BPMs for positive and negative maximum powering of the PR.DVT02 vertical orbit corrector.	173
6.28	Measured tunes (bottom) during introduction of the degraded vertical closed orbit. The PR.DVT02 vertical orbit corrector is powered on to its maximum permitted strength at $t = 500$ ms, then powered to its maximum permitted negative strength at $t = 600$ ms, before being powered off at $t = 750$ ms. No effect from the vertical orbit corrector on the MRP (top) is observed.	173

6.29	Activation of the horizontal orbit corrector $t = 500$ ms and $t = 700$ ms is shown in the top plot; the blue curve represents the amplitude used for conventional optics measurements, while the red curve corresponds to the amplitude used to create a larger closed orbit. On the bottom plot, horizontal closed orbits at $t = 300$ ms (before activation of the horizontal orbit corrector) showed in blue and at $t = 600$ ms in light green.	175
6.30	Horizontal (top) and vertical (bottom) tunes during application of the degraded horizontal orbit, at $t = 500$ ms. . . .	176
6.31	Measured BPM-to-BPM phase advance without (blue) and with (green) the degraded orbit.	177
6.32	Measured phase-beating with respect to the model predictions without (blue) and with (green) the degraded orbit. .	177
A.1	Static beam-based measurements on the 5.25 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.	186
A.2	Static beam-based measurements on the 7.00 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.	187

A.3	Static beam-based measurements on the 14.04 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.	189
A.4	Static beam-based measurements on the 18.00 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.	190

List of Tables

1.1	Expression of the horizontal (B_x) and vertical (B_y) components in a normal magnet.	9
1.2	Expression of the horizontal (B_x) and vertical (B_y) components in a skew magnet.	9
4.1	Meshing structure maximum element size in the different areas of the model.	69
4.2	Mesh sensitivity analysis for the quadrupolar component B_2 scaling down the mesh density.	75
4.3	Mesh sensitivity analysis for the quadrupolar component B_3 scaling down the mesh density.	75
4.4	Horizontal and vertical tune variation with mesh sensitivity analysis parameter k_m	76
4.5	Comparison between B-train measured field B_{meas} and B-train-like simulated field B_{sim} at different Main Coil currents I_{MC}	77
4.6	Integration length L_m in the different region of the MU model.	80
5.1	Power cycles employed for beam-based measurements. Plateau energy, measured main coil current I_{MC} and B-train field B_{meas} on each cycle's plateau.	91

5.2	Measured horizontal (q_x) and vertical (q_y) tunes averaged on the individual power cycle's plateau (p_0) with corresponding standard deviations expressed as a percentage relative to the averaged values.	92
5.3	Measured horizontal (Q'_x) and vertical (Q'_y) chromaticities averaged on the individual power cycle's plateau.	94
5.4	Averaged horizontal (Q_x) and vertical static (Q_y) tunes with MRP corrections on the individual cycle's plateau.	102
5.5	Averaged horizontal (Q'_x) and vertical static (Q'_y) chromaticities with MRP corrections on the individual cycle's plateau.	102
5.6	Averaged tunes on the individual plateaus with MRP corrections.	105
5.7	Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the flat-cycle at injection energy at various I_{F8L} currents.	111
5.8	Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 10.14 GeV/c plateau at various I_{F8L} currents.	115
5.9	Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 18.00 GeV/c plateau at various I_{F8L} currents.	118
5.10	Horizontal and vertical tune variation on energy plateau across the I_{F8L} current scan.	120
5.11	Horizontal and vertical chromaticity variation on energy plateau across the I_{F8L} current scan.	120
5.12	Tune variation on energy plateau across the I_{PFW} current scan.	128
5.13	Chromaticity variation on energy plateau across the I_{PFW} current scan.	128

5.14	Powering currents in the different MU circuits on the operational LHC-type cycle at 10.14 GeV/c and 18.00 GeV/c. . .	130
5.15	Averaged tune measurements on the 10.14 GeV/c and 18.00 GeV/c plateau with LHC-cycle powering settings.	132
5.16	Averaged chromaticity measurements on the 10.14 GeV/c and 18.00 GeV/c plateau with LHC-cycle powering settings.	133
6.1	Simulated quadrupolar strengths in the different MU regions at various energies.	137
6.2	Simulated sextupolar strengths in the different MU regions at various energies.	137
6.3	Momentum correction based on flatten k_0L with the value it has at 10.14 GeV/c.	148
6.4	Momentum correction adding model-based estimate of magnetic length into the existing calculation of programmed momentum.	149
6.5	Comparison of chromaticity measurements on the bare-machine flat-cycle with 0 MRP, and with a 10mm MRP shift corresponding to $\frac{dp}{p} = 3 \times 10^{-3}$	168
6.6	Comparison of chromaticity measurements on the bare-machine flat-cycle with and without the degraded vertical orbit. . .	174
6.7	Comparison of chromaticity measurements with the horizontal orbit corrector deactivated and activated.	175
A.1	Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 2.79 GeV/c flat-cycle at various I_{PFW} currents.	191
A.2	Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 10.14 GeV/c plateau at various I_{PFW} currents.	191

A.3	Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 18.00 GeV/c plateau at various I_{PFW} currents.	192
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List of Symbols

The following symbols are used within the thesis

α	α Twiss parameter
β	β function
ϵ	Emittance
γ	γ Twiss parameter
γ_0	Lorenz relativistic factor
$\mathcal{A}_n$	Skew multiple coefficient of order n
$\mathcal{B}_n$	Normal multiple coefficient of order n
ϕ	Phase advance
ρ	Radius of curvature
B	Magnetic Flux Density
$B\rho$	Magnetic Rigidity
c	Speed of light in vacuum
e	Electron's charge

F_L	Lorentz's force
H	Magnetic Field Strength
L	Luminosity
m_0	Particle's rest mass
n	Order of field harmonic
p	Beam momentum
Q'	First order chromaticity
Q	Tune
q	Particle's charge
r_{pos}	Beam's center of charge radial position
R_{ref}	Reference radius
v	Particle's velocity
A_n	Skew multiple coefficient of order n referred to a reference radius
B_n	Normal multiple coefficient of order n referred to a reference radius

Introduction

Particle accelerators have revolutionized our understanding of fundamental physics, driving advancements in diverse fields such as medicine, materials science, and beyond. These highly complex machines demand the seamless integration of advanced technologies across multiple disciplines, including accelerator magnet design, beam instrumentation, radio-frequency systems, particle dynamics studies, cryogenics, and power converters.

The motion of particle beams in circular accelerators, and the space they occupy within the machine, are determined by electromagnetic forces generated by magnetic units distributed along the accelerator ring. The design of these magnets must adhere to strict constraints to ensure precise beam control and stability, costs, and the safe operation of the machine.

Within this context, accurate models of the magnetic units and resulting beam-dynamics in accelerators are essential for supporting operational decisions, addressing increasingly stringent experimental requirements, and improving machine performance. None-the-less, development of truly predictive models of the magnets and beam dynamics represent a significant challenge. Historically, in many machines, the modeling of magnetic units has relied heavily on empirical approaches. For example, combining magnetic measurements or beam-based studies to address discrepancies between theoretical models and operational behavior (for example by artificially tuning magnet settings in simulation to replicate measured beam-parameters). While such simulations can indeed be effective in the sense that they may replicate specific beam parameters or conditions, they may offer limited potential to extrapolate to help inform

operational decisions. The development of predictive models of the the accelerator magnets and beam-dynamics is thus a topic of broad interest to the accelerator community.

Commissioned in 1959, the CERN Proton Synchrotron (PS) remains a cornerstone of the CERN accelerator complex. It delivers beams to a variety of experiments and serves as an injector for downstream accelerators. The PS's main magnetic units, known as Main Units (MU), are combined-function magnets that generate multipolar fields within their apertures. Unlike typical separated-function magnets, where dipole and quadrupole fields are produced by distinct magnetic units, combined-function magnets integrate multiple field components within a single unit. While this design is compact and cost-effective, it precludes independent tuning of field components, complicating the modeling and accurate prediction of field harmonics.

Over its six decades of operation, the PS's requirements have evolved significantly. Originally designed for fixed-target experiments, the PS now operates in a highly saturated regime, accommodating beams with intensities and brightness far beyond its original design parameters. Historically, PS-MU modeling relied on empirical approaches, including magnetic measurements and beam-based studies. However, these methods must be repeated whenever hardware changes occur. Despite decades of development and efforts, existing models lack predictive capabilities to support operational decision-making. For instance, the control of tune and chromaticity remains empirical, relying on response matrices obtained from beam-based studies.

This thesis aims to address these challenges by developing predictive magnetic and optics models of the PS-MU magnets, bridging the gap between theoretical modeling and operational performance. The proposed models aim to support operational decision-making, aiding in tasks such as establishing new working points, defining power cycle settings, optimizing beam extraction setups, and serving as inputs for adaptive learning approaches.

The methodology adopted in this work involves finite-element magnetic modeling of the MU to simulate field maps and compute field harmonics. These harmonics are then integrated into an optics model of the MU to predict beam parameters. The models are benchmarked against experimental

data obtained from dedicated beam-based measurement campaigns. The PS serves as a practical case study, illustrating the potential of the combined magnetic and optics modeling approach to enhance machine performance and extend operational capabilities.

In the thesis, the first two chapters delve into the theoretical background. Chapter 1 introduces foundational concepts in accelerator physics, including magnetic field descriptions, mathematical representations of beam motion, and key beam parameters. The chapter concludes with an overview of beam instrumentation and measurement techniques. Chapter 2 provides a detailed description of the CERN Proton Synchrotron, emphasizing the design and operation of its main magnetic units.

Chapter 3 examines the challenges associated with the magnetic and optics modeling of the MU magnets in the PS. The time-efficiency of the pre-existing magnetic model is analyzed, alongside the methodology of the effective optics pre-existing model. This investigation provided the motivation for the development of new, time-efficient, and predictive models, which are introduced in Chapter 4.

Chapter 5 presents an extensive beam-based measurement campaign, which includes tune and chromaticity studies conducted at progressively increasing energies to evaluate the impact of magnetic saturation on the beam dynamics. Measurements were initially performed in a bare-machine configuration, in which MU auxiliary circuits and corrector magnets around the ring are deactivated. This analysis is followed by beam-based measurements conducted with individual auxiliary circuits powered and measurements with LHC powering settings.

Chapter 6 benchmarks the developed models against experimental data. The predictive capabilities of the models are validated, demonstrating their ability to align with tune and chromaticity measurements. Additionally, magnetic model reveals significant saturation effects in the MU magnetic length, enabling corrections for momentum computations in operation, which assumes a constant magnetic length over the whole operational range of energy.

The results reported in the thesis provide a predictive powerful tools to support and inform operation. The models have already been employed to support machine development activities. These achievements were made possible by leveraging a deep understanding of magnetic modeling and par-

ticle tracking in complex accelerator environments. The original contributions of this work lie in the development of a significantly more efficient and accurate magnetic model, a systematic methodology for comparing optical and magnetic simulations, and a rigorous benchmarking framework. This approach has, for the first time in many years, enabled a deeper understanding of the complexities behind the PS accelerator.

Background concepts in accelerator physics

Particle accelerators are complex machines that rely on the intricate interplay between particle beams and electromagnetic fields. Understanding the dynamics of particle beams as they traverse an accelerator necessitates detailed mathematical modeling of beam motion and the magnetic fields generated by the main magnets. These fields define the beam's trajectory, ensure its stability, and determine key optical parameters, all of which are crucial for achieving optimal machine performance.

This chapter provides an overview of the foundational concepts in accelerator physics that underpin the work presented in this thesis. The description of magnetic fields is explored in [Section 1.1](#), with a focus on the multipolar components generated in the aperture and their influence on beam motion. [Section 1.2](#) explores the principles of beam dynamics, discussing the main beam parameters and examining the critical role magnetic fields play in shaping these parameters. [Section 1.3](#) outlines the concepts of beam instrumentation relevant for the measurements described in this thesis. Finally, [Section 1.4](#) introduces the beam-based measurement techniques employed for machine operation and beam diagnostics, with a particular focus on the linear optics measurements. Through this integrated perspective, the chapter sets the stage for the detailed investigations presented in the subsequent Chapters, highlighting the importance of combining theoretical, computational, and experimental approaches in

the study of accelerator physics.

1.1 Electromagnetic fields and particle trajectories

Before describing the motion of a particle beam within an accelerator, it is necessary to define the reference coordinate system employed.

Figure 1.1 illustrates the reference orbit of an ideal particle circulating within an accelerator, represented by the solid black line. Real particles, however, do not strictly follow this ideal orbit. Instead, they oscillate around it, as depicted by the dashed blue curve. A moving coordinate system, denoted as xyz , is introduced to describe the particle's motion relative to the ideal orbit. This system is shown in gray, where x and y represent the horizontal and vertical displacements of a particle from the ideal orbit, respectively. The z coordinate points in the direction of the particle's longitudinal motion and moves along with the particles as they travel around the accelerator ring. With this definition, the longitudinal position of the ideal particle is always $z = 0$. Real particles, that are delayed or advanced with respect to the ideal particle, have a longitudinal position $z \neq 0$. The curvilinear coordinate that defines the distance around the accelerator with respect to a reference point is denoted as s . The $x - y$ plane, perpendicular to the motion of the ideal orbit, is often referred to as the transverse plane. O and ρ represent the the center of gyration and the bending radius of the particle's curved trajectory.

Electromagnetic fields are used to guide and accelerate charged particles within accelerators by using Lorenz's force [13–15]:

$$\vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) \quad (1.1)$$

where q represent the particle's charge, $\vec{E}$ and $\vec{B}$ the applied electric and magnetic fields, respectively, and $\vec{v}$ the velocity of the particle. Particles are accelerated by electric fields aligned with their direction of motion in specific sections of the accelerator, known as Radio Frequency (RF) cavities. Details of acceleration techniques and RF cavity technology are beyond the scope of this thesis; readers are referred to [14, 16, 17] for further information. Magnetic fields, typically generated with electromag-

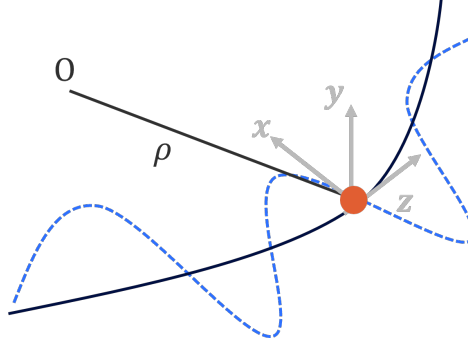


Figure 1.1. Ideal particle (red dot) motion represented by the solid black curve, real particle motion described by dashed blue curve. Reference coordinate system xyz in gray, O center of gyration. ρ is the bending radius of the particle's trajectory

netic units, are employed to guide charged particles along their trajectories. An ideal particle traveling through a region with uniform magnetic field $B = B_y$ perpendicular to its motion ($\vec{B}$ and $\vec{v}$), experiences the Lorenz force:

$$F_L = qvB \quad (1.2)$$

if the particle travels on a closed circular orbit, the centripetal force is:

$$F_c = \gamma_0 m_0 v^2 / \rho \quad (1.3)$$

where γ_0 is the Lorenz relativistic factor, defined as the ratio between the total energy of the particle E and the rest Energy $E_0 = m_0 c^2$, commonly expressed in unit of eV (being $1 \text{ eV} = 1.602176634 \times 10^{-19} \text{ J}$), m_0 is the rest mass of the particle. The rest energy for the protons is 938 MeV, and 0.511 MeV for the electrons. At equilibrium, the two forces are equal, so it is possible to equate the two right hand sides of Eq. 1.2 and Eq. 1.3:

$$qvB = \frac{\gamma_0 m_0 v^2}{\rho} \quad (1.4)$$

$$B\rho = \frac{\gamma_0 m_0 v}{q} \quad (1.5)$$

being $\gamma_0 m_0 v$ the momentum of the particle, it is possible to derive from the previous equation:

$$B\rho = \frac{p}{q} \quad (1.6)$$

where $B\rho$ is usually referred to as the magnetic rigidity, proportional to the momentum of the particle. The charge q is expressed in unit of Coulomb [C], while the momentum of the particle, in beam dynamics, it is commonly expressed in unit of GeV/c. A useful relation linking the magnetic rigidity expressed in unit of Tm and the beam momentum in GeV/c [13], is:

$$B\rho = 3.3356 \cdot p \quad (1.7)$$

The next subsection delves into the mathematical description of magnetic fields generated in particle's accelerators.

1.1.1 Magnetic field description with multipolar expansion

Transverse magnetic fields B within particle accelerators can be expressed as the sum of multiple harmonic coefficients [1, 16, 18]:

$$B = B_y + iB_x = \sum_{n=1}^{+\infty} (\mathcal{B}_n + i\mathcal{A}_n)(x + iy)^{n-1} \quad (1.8)$$

where n is the order of the harmonics ($n = 1$ indicates a dipole field, $n = 2$ a quadrupole, $n = 3$ sextupole, etc.), $\mathcal{B}_n$ and $\mathcal{A}_n$ are the normal and skew multipole coefficients, respectively, in unit of [Tm¹⁻ⁿ], defined as:

$$\mathcal{B}_n = \frac{1}{(n-1)!} \frac{\partial^{n-1} B_y}{\partial x^{n-1}} \Big|_{(0,0)} \quad (1.9)$$

$$\mathcal{A}_n = \frac{1}{(n-1)!} \frac{\partial^{n-1} B_x}{\partial x^{n-1}} \Big|_{(0,0)} \quad (1.10)$$

thus, the expression of the vertical field B_y (real part in Eq. 1.8) in a normal magnet (only $\mathcal{B}_n$ components) acting on the horizontal plane ($y = 0$) can be written as:

$$B_y = B_0 + \frac{\partial B_y}{\partial x}x + \frac{1}{2} \frac{\partial^2 B_y}{\partial x^2}x^2 + \frac{1}{6} \frac{\partial^3 B_y}{\partial x^3}x^3 \quad (1.11)$$

Tables 1.1 and 1.2 present the expressions for the normal and skew components of the vertical (B_y) and horizontal (B_x) magnetic fields, respectively, for various multipole orders up to the octupole ($n = 4$). An ideal normal magnet of order N , generates a single normal field component of that order. However, real magnets also produce skew components and lower and higher order $n \neq N$ components representing magnetic errors arising from manufacturing and/or installation imperfections.

The multipolar field decomposition of Eq. 1.8 can be also written expressing the harmonics with respect to a reference radius R_{ref} :

$$B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1} \quad (1.12)$$

Table 1.1. Expression of the horizontal (B_x) and vertical (B_y) components in a normal magnet.

Multipole order n	Normal magnet	
	B_y	B_x
1	B_1	0
2	B_2x	B_2y
3	$B_3(x^2 - y^2)$	$2B_3xy$
4	$B_4(x^3 - 3xy^2)$	$B_4(-y^3 + 3x^2y)$

Table 1.2. Expression of the horizontal (B_x) and vertical (B_y) components in a skew magnet.

Multipole order n	Skew magnet	
	B_y	B_x
1	0	A_1
2	$-A_2y$	A_2x
3	$-2A_3xy$	$A_3(x^2 - y^2)$
4	$-A_4(-y^3 + 3x^2y)$	$A_4(x^3 - 3xy^2)$

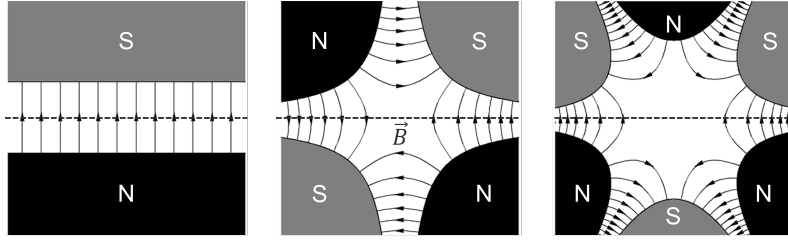


Figure 1.2. Pure normal magnets of order $n = 1$ (dipole), $n = 2$ (quadrupole), $n = 3$ (sextupole) [1]. Arrows represent magnetic field lines. Dashed lines correspond to the mid-plane. N indicates the North Pole, S the South Pole.

in which B_n and A_n represent the normal and skew multipole coefficient evaluated at the reference radius, respectively, in unit of T. The relation linking the normal multipole coefficient $\mathcal{B}_n$ and the normal multipole coefficient at a reference radius B_n is [19]:

$$\mathcal{B}_n = \frac{B_n}{R_{\text{ref}}^{n-1}} \quad (1.13)$$

A similar equation can be derived for the skew multipole components as well. Reference radius can be chosen arbitrarily as this choice, in principle, should not affect the computation of the multipole coefficients.

In most cases, accelerators are constructed using pure magnets of a specific order n , each designed to perform a particular function. Fig. 1.2 illustrates examples of pure normal magnets: a dipole magnet (left), a quadrupole magnet (center), and a sextupole magnet (right). The arrows, extending from the North (N) to South (S) poles, represent the magnetic field lines within the aperture. Normal magnets are characterized by vertical magnetic fields in the mid-plane (dashed lines). In contrast, skew magnets produce horizontal magnetic fields in the mid-plane. Dipole magnets are used to bend particles, achieving a curved trajectory around the ring. Quadrupoles and higher order magnets provide the necessary forces to control the transverse beam motion. These aspects are detailed in next sections.

Field expression in polar coordinates

To compute the harmonics, it is sometimes useful to express Eq. 1.12 in polar coordinates. The conversion from Cartesian to polar coordinates follows the following relations [1, 16, 18]:

$$\begin{cases} x = r \cos \theta \\ y = r \sin \theta \end{cases} \quad (1.14)$$

this allows to write Eq. 1.12 as:

$$B = B_y + iB_x = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{r}{R_{\text{ref}}} \right)^{n-1} e^{i(n-1)\theta} \quad (1.15)$$

and, expressing the field in multipolar components:

$$B = B_y + iB_x = B_r \sin \theta + B_\theta \cos \theta + iB_r \cos \theta - iB_\theta \sin \theta = (B_\theta + iB_r) e^{-i\theta} \quad (1.16)$$

inverting with respect to the new polar components, previous equations becomes:

$$B_\theta + iB_r = \frac{1}{e^{-i\theta}} (B_y + iB_x) \quad (1.17)$$

which, combined with Eq. 1.15 becomes:

$$B_\theta + iB_r = \frac{1}{e^{-i\theta}} \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{r}{R_{\text{ref}}} \right)^{n-1} e^{in\theta} e^{-i\theta} \quad (1.18)$$

$$B_\theta + iB_r = \sum_{n=1}^{\infty} (B_n + iA_n) \left(\frac{r}{R_{\text{ref}}} \right)^{n-1} e^{in\theta} \quad (1.19)$$

From this, it is possible to express the B_θ and B_r components as following:

$$\begin{cases} B_\theta(r, \theta) = \left(\frac{r}{R_{\text{ref}}} \right)^{n-1} \sum_{n=1}^{\infty} (B_n(r_0) \cos n\theta - A_n(r_0) \sin n\theta) \\ B_r(r, \theta) = \left(\frac{r}{R_{\text{ref}}} \right)^{n-1} \sum_{n=1}^{\infty} (B_n(r_0) \sin n\theta + A_n(r_0) \cos n\theta) \end{cases} \quad (1.20)$$

From field harmonics to magnet strengths

For beam dynamics studies and in optics simulation codes¹, it is common to normalize the multiple harmonics coefficients to the magnetic rigidity, which are called magnet strengths and are denoted as k_{n-1} [19]:

$$k_{n-1} = \frac{1}{B\rho}(n-1)!\mathcal{B}_n \quad (1.21)$$

and, considering Eq. 1.13, the previous equation becomes:

$$k_{n-1} = \frac{1}{B\rho}(n-1)!\frac{B_n}{R_{\text{ref}}^{n-1}} \quad (1.22)$$

Expressing the magnetic rigidity as in Eq. 1.7, Eq. 1.22 becomes:

$$k_{n-1} [m^{-n}] = \frac{1}{3.3356 \cdot p}(n-1)!\frac{B_n}{R_{\text{ref}}^{n-1}}. \quad (1.23)$$

in case of a normal quadrupole ($n = 2$), the strength is:

$$k_1 [m^{-2}] = \frac{1}{3.3356 \cdot p} \frac{B_2}{R_{\text{ref}}}. \quad (1.24)$$

Hamiltonian formalism

In accelerator physics, the Hamiltonian is a powerful and elegant mathematical framework used to describe the motion of particles through the magnetic elements of an accelerator [14, 20–22]. This formalism describes a system in terms of its total energy, which is the sum of kinetic and potential energies, providing a direct way to describe the interaction of particles with electromagnetic fields in terms of energy. For a charged particle in an electromagnetic field, the Hamiltonian is typically expressed as:

$$H = \sqrt{(p - qA)^2 + m^2c^4} + q\phi. \quad (1.25)$$

being A and ϕ the vector and scalar potential, respectively. The rela-

¹An optics stimulation code takes a model of the magnetic elements around the ring and considers either the kicks or transfer maps induced by those magnetic elements to track the particle trajectory around the ring and calculate specific optical parameters.

tion between the Hamiltonian and field harmonics arises when analyzing the effects of magnetic field non-linearities on particle trajectories. As shown in Eq. 1.8, magnetic fields in accelerator magnets can be expanded in terms of multipole field harmonics. Linear terms in the Hamiltonian correspond to dipole and quadrupole fields, while non-linear terms come from higher-order harmonics (sextupole, octupole, etc.). For a magnetic element of order n , the Hamiltonian can be expressed as [23, 24]:

$$H = \Re \left[\sum_{n \geq 1} (K_{n-1} + iJ_{n-1}) \frac{(x + iy)^n}{n!} \right]. \quad (1.26)$$

K_{n-1} and J_{n-1} are the normal and skew multipole strengths, respectively:

$$K_{n-1} = \frac{1}{B\rho} \frac{\partial^{n-1} B_y}{\partial x^{n-1}} \Big|_{(0,0)} \quad (1.27)$$

$$J_{n-1} = \frac{1}{B\rho} \frac{\partial^{n-1} B_x}{\partial x^{n-1}} \Big|_{(0,0)} \quad (1.28)$$

The Hamiltonian for a normal quadrupole and normal sextupole become, respectively:

$$H_2 = \frac{1}{2} K_1 (x^2 - y^2) \quad (1.29)$$

$$H_3 = \frac{1}{6} K_2 (x^3 - 3xy^2) \quad (1.30)$$

The Hamiltonian incorporates field harmonics to predict the beam dynamics, especially when non-linearities are present. These relations are used in the thesis to explain non-linear effects from measurements.

1.2 Equation of motion and optics parameters

In the previous section, the expressions of the magnetic field generated by magnets placed around an accelerator were introduced. This section focuses on describing the impact of the transverse magnetic field on the beam.

The ensemble of magnetic elements building up an accelerator is often

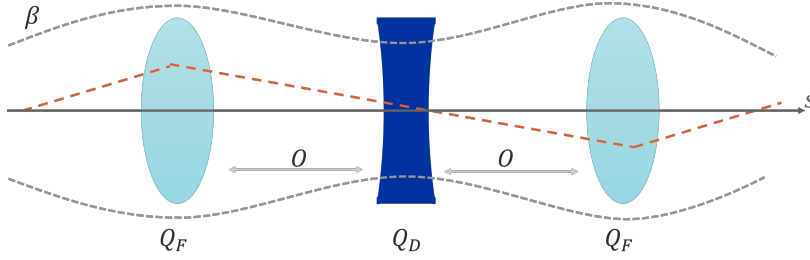


Figure 1.3. FODO lattice composed by focusing and defocusing quadrupole magnets in turquoise and blue, respectively.

called lattice. Beam optics is commonly defined as the study of single particle dynamics as it passes through magnetic elements, ignoring interactions with other particles in the machine. Linear optics, in particular, refers to the case where only linear elements, such as dipole and quadrupole magnets, are installed around the accelerator ring.

Normal dipole magnets provide a force acting on the horizontal plane, which bend the beam along curved trajectories. Particles within a beam oscillate around the ideal closed orbit due to higher order forces in the machine. Particle transverse oscillations are contained with focusing restoring forces by means of quadrupoles placed around the ring. Quadrupolar fields, acting on charged particles displaced from the ideal orbit, provide a restoring force, which is proportional to the displacement in one transverse plane. If a quadrupole focuses the beam on the horizontal plane, it simultaneously provides a divergent (defocusing) force in the vertical plane, and vice-versa. An alternating arrangement of focusing and defocusing quadrupoles allows for the confinement of transverse beam oscillations in both planes. This is referred to as alternating-gradient or strong focusing [22].

In circular accelerators, the magnetic lattice is typically composed of a periodic repetition of elementary cells. Fig. 1.3 illustrates a FODO cell, which is based on the principle of alternating-gradient focusing [13]. It consists of a sequence of a focusing quadrupole magnet (Q_F) shown in turquoise, and a defocusing quadrupole magnet (Q_D), illustrated in blue. The focusing and defocusing magnets are separated by drift spaces, where no focusing forces are present. Within this cell, particles experience alternating focusing-defocusing forces in each plane.

1.2.1 Transverse motion: Hill's equation

This subsection introduces the equation describing the beam motion in the transverse plane, often referred to as Hill's equation. The equation of motion is not derived in this thesis. Reader can go thorough its detailed and complete derivation in the references [13, 16, 25–27]. Assuming a linear lattice, Hill's equation is:

$$\begin{cases} x'' + \left(\frac{1}{\rho^2(s)} - k(s) \right) x = 0 \\ y'' + k(s)y = 0 \end{cases} \quad (1.31)$$

where x and y represent the horizontal and vertical transverse coordinates, respectively, while x'' and y'' are the corresponding second-order derivatives with respect to s ; ρ represents the bending forces from dipoles, which act exclusively in the horizontal plane, while $k(s)$ represents the restoring focusing/defocusing forces from the quadrupoles. Hill's equation is a second-order linear differential equation, similar to that of a harmonic oscillator. However, it is important to note that the restoring forces, $k(s)$, vary periodically along the accelerator. The solution of Hill's equation can be expressed as following:

$$\begin{cases} x(s) = \sqrt{\epsilon_x \beta_x(s)} \cos(\phi_x(s) - \phi_{x,0}) \\ y(s) = \sqrt{\epsilon_y \beta_y(s)} \cos(\phi_y(s) - \phi_{y,0}) \end{cases} \quad (1.32)$$

where ϵ is the emittance of the single particle, β is the β function describing the oscillations of the beam envelope around the ring, and ϕ represents the phase advance of the transverse beam motion. The beam emittance and β function together define the amplitude of the oscillations, and thus the transverse size of the beam. This, in turn, affects the aperture of the magnets and, as consequence, their cost². Although the β function is expressed in units of meters, it does not directly represent the amplitude of particle oscillations. Instead, it defines the variation of the oscillation envelope, within which the beam is confined, as shown by the dashed gray curves in Fig. 1.3. The emittance is a constant of motion at a given energy,

²Larger transverse oscillations necessitate a greater magnet aperture, leading to increased production costs. Additionally, larger magnets require more space in the accelerator tunnel, significantly impacting tunnel construction costs.

independent from s , and can be computed as:

$$\begin{cases} \epsilon_x = \gamma_x(s)x^2(s) + 2\alpha_x(s)x(s)x'(s) + \beta_x(s)x'^2(s) \\ \epsilon_y = \gamma_y(s)y^2(s) + 2\alpha_y(s)y(s)y'(s) + \beta_y(s)y'^2(s) \end{cases} \quad (1.33)$$

$x'(s)$ and $y'(s)$ describe the variation of horizontal (x) and vertical (y) positions along the longitudinal direction ($x' = \frac{dx}{ds}$, $y' = \frac{dy}{ds}$), respectively. α and γ are defined as following:

$$\alpha_{x,y}(s) = -\frac{1}{2}\beta'_{x,y}(s) \quad (1.34)$$

$$\gamma_{x,y}(s) = \frac{1 + \alpha_{x,y}^2(s)}{\beta_{x,y}(s)} \quad (1.35)$$

α , β and γ are referred to as Twiss parameters. While the emittance is an intrinsic property of the beam and cannot be altered by the magnets, α , β and γ functions are periodic in s and shaped by the focusing/defocusing properties of the lattice.

In the phase space $x, x' (y, y')$, Eq. 1.33 describes an ellipse, as shown in Fig. 1.4. According to Liouville's theorem, the area of this ellipse, $A = \pi\epsilon$, is conserved (constant of motion) under the influence of conservative forces.

1.2.2 Tune and resonance conditions

The phase advance and the β function are both functions of the longitudinal position s and have the same periodicity of the magnetic lattice. These two functions are linked by the following relation, providing the phase advance between two longitudinal locations s_0 and s :

$$\phi_{x,y}(s) = \int_{s_0}^s \frac{1}{\beta_{x,y}(s)} ds \quad (1.36)$$

this integral, computed over one revolution of the machine, provides the number of oscillations of the particles in one turn in the horizontal/vertical plane, referred to as the tune $Q_{x,y}$:

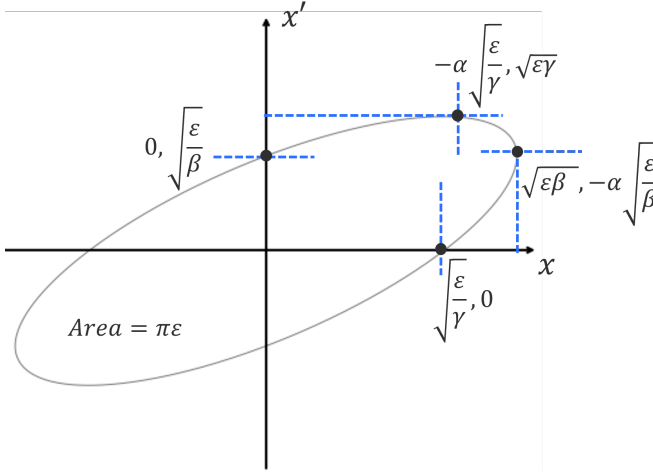


Figure 1.4. Beam motion in the phase space ($x - x'$ plane) describes an ellipse. The area of the ellipse is proportional to the beam emittance ϵ .

$$Q_{x,y} = \frac{1}{2\pi} \Delta\phi_{x,y} = \frac{1}{2\pi} \oint \frac{1}{\beta_{x,y}(s)} ds \quad (1.37)$$

To ensure a stable motion of the beam, it is essential that the tunes do not take integer, half-integer, or simple fractional values. In general, the transverse beam motion must fulfill the following condition:

$$mQ_x + nQ_y \neq N \quad (1.38)$$

where m, n and N are integers, and $m + n$ is called order of resonance. If this condition is violated, the beam can experience significant perturbations, leading to unstable motion, which could cause particle losses in the aperture, emittance growth, or tail generation [28–30]. In general, the effect of resonance diminishes with increasing resonance order, as higher-order resonances are weaker and less likely to impact beam stability. Fig. 1.5 displays the tune diagram ($Q_x - Q_y$ plane) along with resonance lines up to the 4-th order. Second order resonances are depicted in red (e.g., $Q_x + Q_y = 0$, $m + n = 2$), third order in black (e.g., $2Q_x - Q_y = 0$, $m + n = 3$), fourth order in blue (e.g., $3Q_x - Q_y = 0$, $m + n = 4$).

The importance of the above-mentioned resonance condition can be

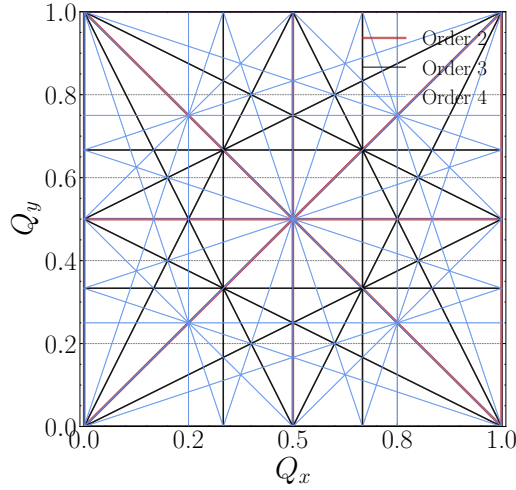


Figure 1.5. Resonance lines: second order resonance in red, third order in black, fourth order in blue.

seen in case of field imperfections in the machine. Fig. 1.6 describes the change in the closed orbit from a single dipole kick θ at the location $s = s_0$. The u coordinate represent the either x or y transverse coordinates. The closed-orbit distortion Δu at a any location around the ring, generated by a kick θ in $s = s_0$, is expressed as [31, 32]:

$$\Delta u(s) = \theta_{s_0} \frac{\sqrt{\beta(s)\beta(s_0)}}{2 \sin \pi Q} \cos(\pi Q - (\phi(s) - \phi_{s_0})) \quad (1.39)$$

showing that, in case of integer tune, the closed orbit displacement grows indefinitely in presence of dipole kick in the ring.

1.2.3 Momentum spread: dispersion and chromaticity

Up to this point, it has been assumed that all particles possess a uniform momentum. The momentum of a particle moving along the reference closed orbit is denoted as p_0 . In practice, however, particles within a beam exhibit slight deviations in momentum, expressed as $\Delta p = p - p_0$, where p is the actual momentum of a given particle.

The momentum spread within a beam has multiple consequences on its

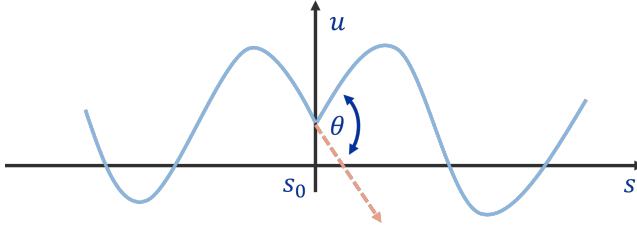


Figure 1.6. Dipole kick at location $s = s_0$.

transverse motion. Particles with a positive momentum offset with respect to the reference particle ($\Delta p/p_0 > 0$) follow a longer outer trajectory compared to the reference particle with momentum p_0 . Conversely, a particle with negative momentum offset ($\Delta p/p_0 < 0$) follows a shorter inner trajectory. It can be demonstrated that, when accounting for the momentum spread, the equation of motion (Eq.1.31) can be expressed as [31]:

$$x''(s) + \left(\frac{1}{\rho^2(s)} - k(s) \right) x(s) = \frac{1}{\rho(s)} \frac{\Delta p}{p_0} \quad (1.40)$$

which, contrary to Eq. 1.31, is not an homogeneous equation. Consequently, the solution of previous equation, describing the motion of the particles with momentum offset, is the sum of two contributions:

$$x(s) = x_\beta(s) + x_D(s) \quad (1.41)$$

where $x_\beta(s)$ is the solution of Hill's equation (without considering the momentum spread), as given in Eq. 1.32, and $x_D(s)$ represents the component that accounts for dispersion and momentum offset:

$$x_D(s) = D(s) \frac{\Delta p}{p_0} \quad (1.42)$$

where $D(s)$ is the dispersion function, providing an additional contribution to the beam orbit and, consequently, its transverse size.

Particles with a positive momentum offset passing through quadrupoles experience weaker focusing, resulting in a reduction of the tune over one revolution. Conversely, particles with a negative momentum offset experience stronger focusing, leading to an increase in the tune. This change in

tune as a function of the momentum offset is referred to as chromaticity. The Taylor expansion of the tune with respect to the momentum offset $\Delta p/p_0$ leads to the definition of chromaticity:

$$Q_{x,y} \left(\frac{\Delta p}{p_0} \right) = Q_{0,x,y} + Q'_{x,y} \left(\frac{\Delta p}{p_0} \right) + \frac{1}{2!} Q''_{x,y} \left(\frac{\Delta p}{p_0} \right)^2 + \frac{1}{3!} Q'''_{x,y} \left(\frac{\Delta p}{p_0} \right)^3 + \dots \quad (1.43)$$

with:

$$Q'_{x,y} = \frac{\partial^n Q_{x,y}}{\partial \left(\frac{\Delta p}{p_0} \right)^n} \quad (1.44)$$

Q' introduced within the quadrupoles due to the momentum dependent focusing properties is referred to as the natural chromaticity, and is always negative. Normal sextupole magnets in regions of non-zero horizontal dispersion can also generate a chromaticity, which can have either sign. The Q' generated by the combination of natural chromaticity, and chromaticity from e.g. sextupole magnets and errors, is usually referred to simply as the chromaticity. Higher order terms are non-linear chromaticity terms.

Figure 1.7 presents an example of magnetic lattice, with a dipole (in gray), a quadrupole (in turquoise) and a sextupole (in green). The particle with a negative Δp (in purple) follows a inner trajectory with respect to the particle with reference momentum (in blue), while the particle with positive Δp (in orange) has an outer trajectory: this creates dispersion in the dipole. Following, the particles with different momentum pass through a quadrupole, are focused with different strengths, creating natural chromaticity within the beam (dashed purple and orange lines), which is corrected by the subsequent sextupole magnet.

Feed-down

Feed-down refers to the effect where higher-order multipole components of a magnetic field influence lower-order multipole components due to the particle beam being displaced from the magnet's geometric center. This phenomenon occurs because the magnetic field experienced by the beam depends on its position relative to the magnet's center [16, 20]. For example, in a sextupole magnet, a beam with an offset in the horizontal plane experiences a dipole-like field and a quadrupole-like field (focusing/defo-

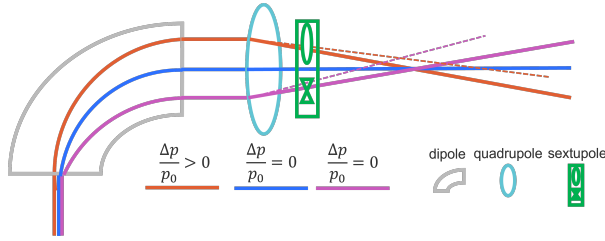


Figure 1.7. Example of magnetic lattice with a dipole (in gray), quadrupole (in turquoise) and sextupole (in green). Particle with reference momentum depicted in blue, while particles with negative and positive Δp are depicted in purple and orange, respectively. Momentum spread creates dispersion within the dipole (inner or outer trajectory of the off-momentum particles with respect to particle with reference momentum p_0), and chromaticity in the quadrupole, which is corrected by the subsequent sextupole.

cusing) in addition to the original sextupole field.

1.3 Beam instrumentation

Beam diagnostics are vital for the operation, safety and performance of any accelerator. Beam instrumentation enables real-time monitoring of beam's motion, shape, and its parameters. Without adequate beam diagnostics, it would not be possible to fulfill demands from users/experiments and machine improvements would be challenging to achieve [3, 33]. Beam instrumentation and diagnostics represent an interdisciplinary field that integrates accelerator physics with mechanical, electronic, and software engineering. The design, construction, and improvement of beam diagnostic devices pose significant challenges due to the high precision demanded by accelerator operations. In this section, devices used to measure the beam parameters relevant for this thesis are introduced. Specifically, Subsection 1.3.1 discusses the device employed for beam position monitoring, while Subsection 1.3.2 focuses on the device used for tune measurements.

1.3.1 Beam Position Monitors

Beam Position Monitor (BPM) systems are among the most common and powerful beam instrumentation devices used in particle accelerators.

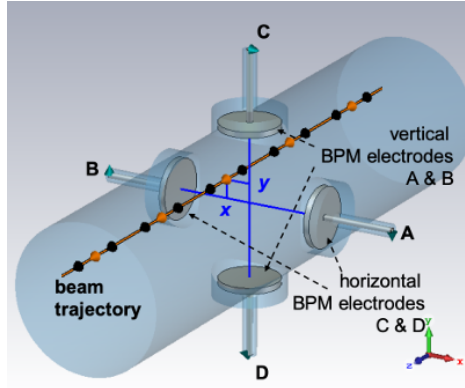


Figure 1.8. Beam Position Monitors: pickup buttons [2].

These devices measure the transverse position of the center of charge of the beam passing through them [2, 34, 35]. Each BPM system consists of BPM pickups and the read out electronics [36], used to condition and process the signals from the pickup electrodes to provide the beam position information in a digital data format to be acquired and further processed by the accelerator control system.

The most common BPM systems are based on a non-invasive, electrostatic type beam pickups, for example the button-style BPM depicted in Figs. 1.8 and 1.9. It consists of four electrodes, which are typically arranged symmetrically along the horizontal and vertical axes in a vacuum chamber. Two of these electrodes measure the horizontal displacement of the beam's center of charge with respect to the center of the vacuum chamber, while the other two capture the vertical displacement. In some cases, the accelerator is equipped with single-plane BPMs [37, 38]. For instance, a horizontal BPM with two electrodes may be followed by a single-plane vertical BPM.

Such BPM pickups design and operation are based on the principle of the image currents (or image charges). Charged particles within the beam, passing through the two electrodes, create a separation of charges within the metallic electrodes due to Coulomb interaction, creating a potential captured by a load resistor, as shown in Fig. 1.10. The signal waveforms out of the BPM electrodes are identical. However, the signal amplitude

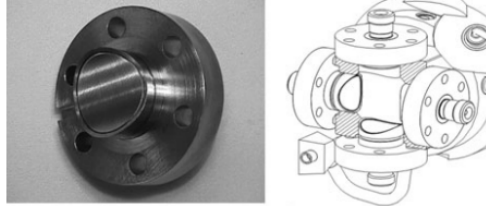


Figure 1.9. Beam Position Monitors: pickup buttons used in the CERN LHC (left) and drawing of the LHC button pick-up assembly for dual plane measurements (right) [3].

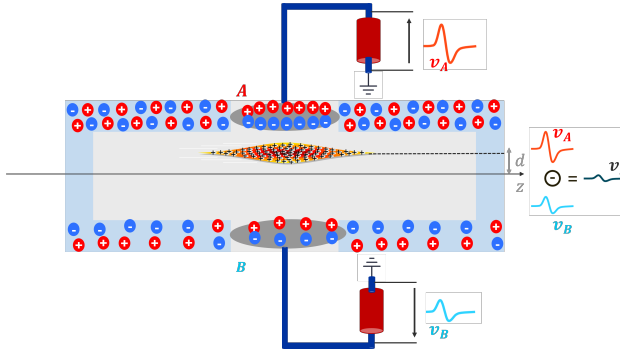


Figure 1.10. Charged particles within the beam passing through two BPM electrodes. Separation of charge on the surface of the electrodes, voltage signal captured by a load resistor.

from each electrode is proportional to the distance between that electrode and beam (d), and also to the beam intensity (i_b). Thus, to get a signal proportional to the beam position, the signal from the two BPM electrodes are subtracted [2]:

$$v_\Delta = (v_A - v_B) \propto d, i_b \quad (1.45)$$

Since the signal v_Δ remains proportional to the beam intensity, a normalization is required to extract a beam intensity independent position signal from the BPM electrodes:

$$\frac{v_\Delta}{v_\Sigma} = \frac{v_A - v_B}{v_A + v_B} \propto \frac{d}{A} \quad (1.46)$$

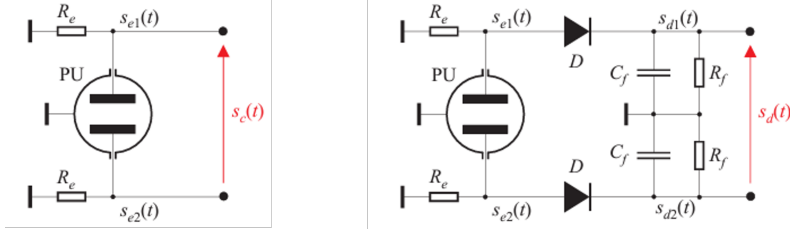


Figure 1.11. Equivalent circuit of tune measurements with standard BPM (left) and with BBQ system (right) [4].

which provides the horizontal/vertical position of the beam, once the area (A) of the electrodes and calibration factors are known. Signals from the pickups distributed around the ring are later processed by the read-out electronics.

1.3.2 Base Band Tune

Tune measurements are performed using a dedicated pickup system known as the Base-Band Tune (BBQ) system [4, 39, 40]. Originally designed at CERN for high-precision tune measurements on the LHC, the BBQ system has since been adopted in various other accelerators.

The BBQ system determines the tune by performing spectral analysis on the difference signal between opposing pickups. Incoming signals from the pickups are processed through a diode peak detector, which isolates the low-frequency (base-band) betatron modulation of the beam position from the high-frequency periodic revolution signal. This measurement technique is referred to as Direct Diode Detection [41], whose principle circuit is reported in Fig. 1.11 (circuit on the right). The time-stretched pulses conserve the betatron modulation and, as a consequence, most of the betatron energy is shifted to the baseband. This can make the betatron signal content at the detection frequency orders of magnitude larger than in classical systems [41].

The diodes D are followed by parallel $R_f C_f$ filters, forming two peak detectors, which are activated by beam pulses, charging the storage capacitor C_f to the peak voltage of each pulse. The capacitor is discharged on the R_f resistor. These $R_f C_f$ circuits are typically chosen with a time con-

stant (τ) 10 times higher than the revolution period (T) [41]. Any betatron oscillation shows up as a modulation of the peak voltage on the capacitor. The output signals are further processed by the downstream electronics to remove the DC component of the signal on the capacitor³. Isolating the betatron oscillations with a peak detector prior to spectral analysis allows the BBQ to analyze very small oscillations of the beam. This enables monitoring of the betatron tune without the need for external excitation, allowing the BBQ to operate continuously during accelerator operation.

1.4 Beam-based measurements

Beam-based measurements are a cornerstone of accelerator diagnostics, providing direct insights into the machine's behavior by analyzing the beam itself. Unlike hardware-based calibration techniques, such as magnetic measurements on active magnetic elements, beam-based measurements use the beam as a probe to evaluate and optimize key accelerator parameters, including beam emittance, transverse optics functions, longitudinal dynamics, tune, and chromaticity, as well as to assess the performance of instrumentation devices. By analyzing the beam's response to various excitations or external perturbations, these techniques enable the refinement of machine performance, the validation of theoretical models, and the improvement of the overall quality of the delivered beam.

This section focuses on the beam-based measurement techniques employed in this thesis for linear optics measurements, highlighting their methodology, implementation, and significance in achieving high-precision accelerator operation.

1.4.1 Linear optics measurements techniques

Linear optics measurements can be performed by analyzing betatron oscillations of excited beams [42], large enough to be recorded by the BPMs. AC-Dipole magnets [43] are normally used to excite the beam. These consist in fast oscillating magnets with a sinusoidally oscillating

³Typically, high- and low-pass filters are included and tailored to cut-off the signal outside the expected tune ranges, e.g. between 0.1 and 0.5 times the revolution frequency [41].

dipole field, driving forced oscillations of the beam to a frequency close to the betatron frequency, typically, for several thousands of revolutions. They can be adiabatically turned on and off [44, 45], creating coherent oscillations of the beam particles without affecting the transverse emittance. The use of an AC-dipole also introduces systematic effects on the optics measurements. The methods to correct those systematic effects are described in detail in [46, 47]. If an AC-Dipole magnet is not available in the machine, beam excitation can also be achieved using a transverse damper [48]. This device employs a stripline kicker to create an electric deflecting field and can be driven with chirp or AC-Dipole-like signals to excite the beam [49]. While AC-dipole mode induces sustained forced beam oscillations at a specific frequency distinct from the tunes, chirp pulsing sweeps excitation frequencies across the tune range [42].

BPMs measure the position of the beam on a Turn-by-Turn (TbT) basis. The TbT BPM data are cleaned via Singular Value Decomposition (SVD) method, which is a powerful numerical tool employed in variety of disciplines, including beam dynamics studies. It is a well-established technique for efficient and accurate numerical computation for large datasets [50, 51]. This cleaning process decomposes the matrix of TbT data into a series of modes, each associated with a singular value that quantifies the mode's significance. The small modes, corresponding to uncorrelated noise, are removed [52].

Following the SVD procedure, spectral analysis is conducted on the cleaned BPM data using Fast Fourier Transform (FFT) algorithms. This enables the computation of the fractional part of the tune and the reconstruction of the optics [42, 53]. The tune and BPM-to-BPM phase advance are computed by performing an interpolated FFT using the Harpy software [54], designed for the frequency analysis of betatron oscillation data. An example of forced beam oscillations with AC-dipole and FFT spectrum is provided in Fig. 1.12 on the left and right plot, respectively.

Once the phase advance is computed, the β function at the BPMs can be calculated using the three BPM Method [55, 56], which defines the β -function at the BPM location $s = s_i$ from the phase advances between adjacent BPMs $\Delta\phi_{ij}$:

$$\beta(s_i) = \frac{\cot \Delta\phi_{ij} - \cot \Delta\phi_{ik}}{\cot \Delta\phi_{ij}^m - \cot \Delta\phi_{ik}^m} \beta^m(s_i) \quad (1.47)$$

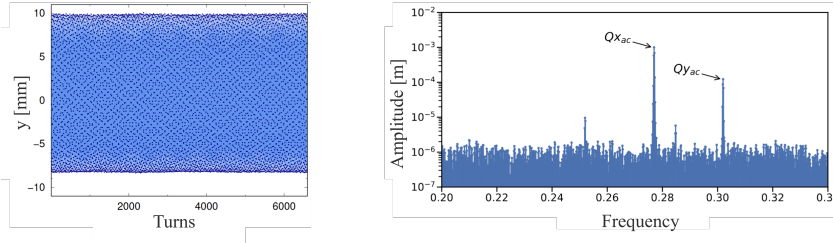


Figure 1.12. Beam oscillations on the vertical plane following AC-dipole excitation on the left. Results of the FFT analysis showing the spectrum on the right.

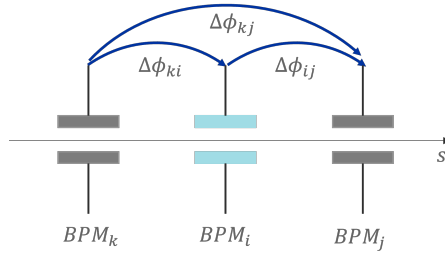


Figure 1.13. 3 adjacent BPMs for the computation of the β function at the location of the BPM depicted in turquoise (BPM_i).

where the subscript m denotes the values from the model. Fig. 1.13 illustrates three subsequent BPMs and the phase advance between them.

This method is independent of BPM calibration and transverse misalignments but is dependent on the relative positions of the BPMs. If the phase advance between two BPMs approaches $n\pi$, errors in the phase measurement are strongly amplified. As it specified later in Section 2.2, this does not affect the measurements reported in this thesis. The overall accuracy depends on the precision of the measured phase, the optics model, and the phase advances between the BPMs, which must be carefully managed to avoid critical conditions that can lead to divergences in the uncertainty calculations due to the cotangent term in Eq. 1.47 becoming undefined at these points.

Linear optics quality is typically given by the β -beating of the accelerator, defined as the relative deviation of the measured β function with

respect to what predicted from the model:

$$\frac{\Delta\beta_{x,y}(s)}{\beta_{x,y}(s)} = \frac{\beta_{x,y,meas}(s) - \beta_{x,y,model}(s)}{\beta_{x,y,model}(s)} \quad (1.48)$$

This is a very important parameter for the machine. In the LHC, for example, constraints on the maximum β -beat are set at approximately 20 % to ensure machine protection and avoid luminosity unbalance between experiments [51]. In the injectors, it is relevant for emittance growth at injection and extraction, in case of mismatch in the β functions. In addition, β -beating is relevant input for instrumentation to measure and monitor the emittance, and can also affect the response of other magnets which can influence operation control.

1.4.2 Chromaticity measurements

In the previous sections, it was seen that the dependence of the focusing force on beam momentum is generally referred to as chromaticity. This is a measurable effect which can be determined by measuring the tune shift as a function of the RF frequency [42]:

$$Q'_{x,y} = \frac{\Delta Q_{x,y}}{\frac{\Delta p}{p_0}} = - \left(\alpha_c - \frac{1}{\gamma^2} \right) \frac{\Delta Q_{x,y}}{\frac{\Delta f_{RF}}{f_{RF,0}}} \quad (1.49)$$

where γ is the Lorentz factor introduced in Section 1.1, and α_c is the momentum compaction factor, defined as the relative elongation of the mean radius corresponding to a momentum relative offset:

$$\alpha_c = \frac{\Delta r/r}{\Delta p/p_0} \quad (1.50)$$

where r is the mean radius of the beam trajectory. By varying the RF frequency, a momentum change is induced causing an orbit shift due to dispersion around the ring. This results in a change in the beam's Mean Radial Position (MRP) [57, 58]. The corresponding tune variation with momentum offset can then be analyzed to estimate the chromaticity.

The CERN Proton Synchrotron accelerator

The CERN Proton Synchrotron (PS), the first synchrotron constructed at CERN, successfully accelerated its first proton beam in 1959 [59]. Today, it plays an essential role in the injector chain for the Large Hadron Collider (LHC) [60–62], as reported in Fig. 2.1. It accelerates protons from the Proton Synchrotron Booster (PSB) [63, 64] and heavy ions from the Low Energy Ion Ring (LEIR) [64, 65]. The PS has various extraction points that direct beams to different accelerators or experiments, such as the Super Proton Synchrotron (SPS) [66], the Antiproton Decelerator (AD) [67] and the Neutron time-of-flight facility (n-TOF) [68]. Thus, the PS is capable of accelerating beams to different energy levels depending on the requirements of downstream experiments or accelerators. For example, the SPS, to properly inject beams in the LHC, requires protons at 26 GeV/c, while other facilities require beams of much lower energy. The PS’s ability to handle and deliver different kinds of beam cycles is a testament to its versatility and importance in CERN’s accelerator complex, as performance of LHC and fixed-target experiment operation depend on the quality of the beam delivered by the injectors.

Continuous challenges, driven by increasingly strict performance requirements, have led to numerous upgrades over the years. The most recent, the LHC Injectors Upgrade program (LIU) [69–73], aimed to upgrade the LHC injectors to fulfill the beam intensity and brightness requirements

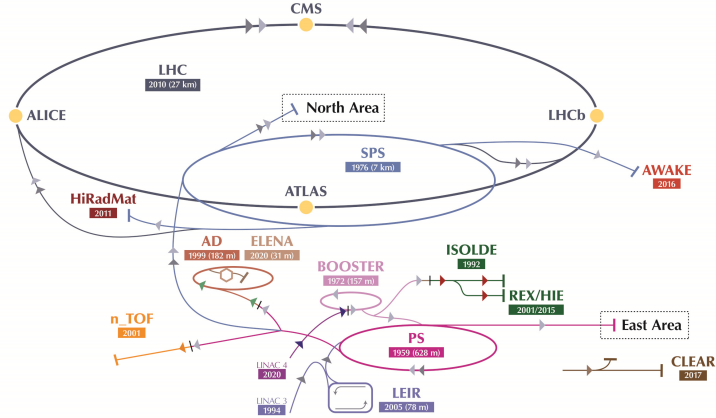


Figure 2.1. CERN accelerator complex. [5].

of the future High Luminosity LHC program (HL-LHC) [74–76], for both proton and ion beams [77, 78].

The next section introduces the main PS magnets, with particular emphasis on their geometry and powering system (Section 2.1). Section 2.2 then provides key information about the devices used within the PS for magnetic field and beam-based measurements. Lastly, Section 2.3 presents the most relevant tools used for beam control and diagnostics in the CERN Control Center (CCC) during beam-based measurements.

2.1 Main magnets

The PS, with a circumference of approximately 628 m, comprises 277 normal-conducting electromagnets, including 100 main magnets, often referred to as Main Units (MUs). These are combined-function magnets, generating a superposition of dipolar and quadrupolar fields in the aperture responsible for bending and focusing the beam. One reference MU, located outside the tunnel (MU 101) and powered in series with the other units, serves to generate reference voltages for timing, beam control, and field monitoring.

Each MU consists of 10 laminated C-shaped iron blocks, each 417 mm long: 5 consecutive focusing (F) iron blocks, referred to as F half-units, and

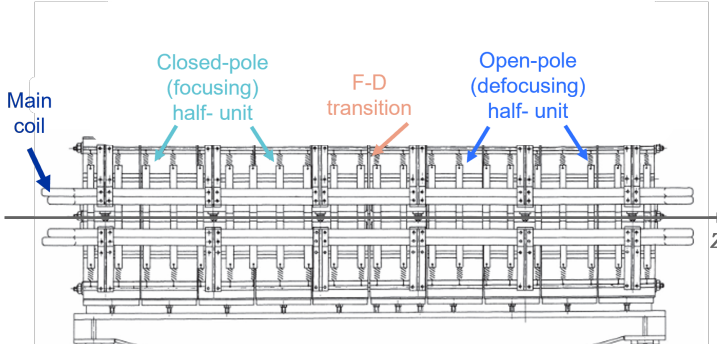


Figure 2.2. Longitudinal view of the PS-MU [6].

5 consecutive defocusing (D) iron blocks, D half-units. Two consecutive blocks are separated by air gaps, and a longer air gap separates the F and D half-units. At the equilibrium orbit, the air gaps in the F and D half-units are 7.75 mm and 9.75 mm long, respectively, while the air gap between the two half-units is 20 mm. Fig. 2.2 provides a frontal view of the MU along the longitudinal beam direction z .

This configuration creates an alternating-gradient pattern within the MU, meaning that the two half-units generate a quadrupolar component of opposite sign. As a result, the beam experiences alternating focusing and defocusing forces in each plane within the MU.

The alternating-gradient is obtained by means of two different block types, named open-pole and closed-pole blocks, which are highlighted in Fig. 2.3 in blue and turquoise, respectively.

Between consecutive MUs, there are straight sections, housing essential components such as accelerating cavities, beam diagnostic devices, injection and extraction elements, and corrector magnets that fine-tune the beam's parameters.

The overall arrangement of focusing and defocusing elements within the PS forms a periodic lattice structure commonly referred to as 'FOFDOD', reflecting the alternating sequence of focusing and defocusing elements interspersed with open drift spaces (O). In FOFDOD lattices, individual corrector elements such as quadrupoles and sextupoles can also be installed at the locations where the horizontal and vertical β -functions are different, acting more independently on the two planes [79, 80].

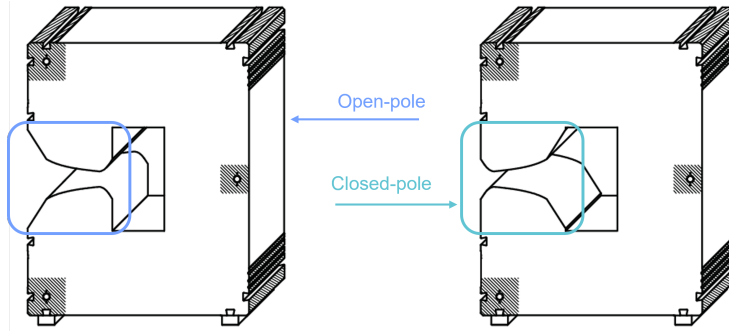


Figure 2.3. PS-MU open (left) and closed (right) blocks [6].

The focusing and defocusing half-units do not produce exactly the same gradient over the energy range of PS operation. Moreover, the positioning of the main coil terminals influences the magnetic field distribution at the ends of the MU magnets. To compensate for these effects, four different MU types, labeled R, S, T, and U, are distributed around the PS ring, and are shown in Fig. 2.4. The classification is based on the position of the return yoke either inside or outside of the beam orbit, and by the sequence F or D half-units with respect to the beam direction [10]:

- 35 MUs of type R: these have the return yoke located outside the beam orbit and follow a D–F sequence (defocusing first, followed by focusing).
- 15 MUs of type S: these also have the return yoke outside the beam orbit but follow the opposite sequence, F–D (focusing first, then defocusing).
- 35 MUs of type T: in this configuration, the return yoke is positioned inside the beam orbit, with the sequence D–F (defocusing, then focusing).
- 15 MUs of type U: these MUs have the yoke inside the beam orbit and follow the F–D sequence (focusing first, followed by defocusing).

The four MU types exert the same fundamental effect on the beam. However, their arrangement around the accelerator is specifically designed

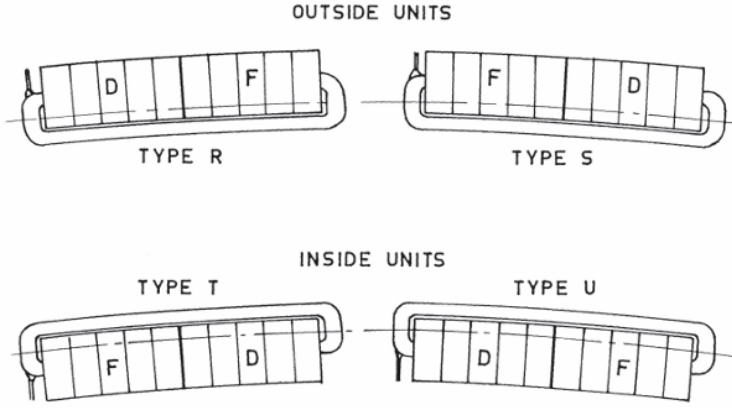


Figure 2.4. The 4 PS-MU types [7] identified by the the position of the return yoke and the focusing/defocusing sequence with respect to the beam motion.

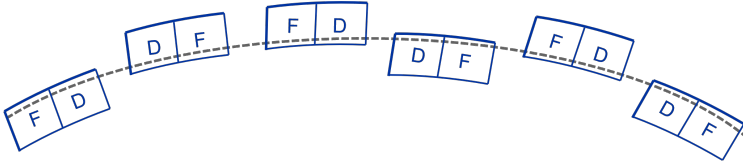


Figure 2.5. Diagram illustrating the distribution of the four Main Units types around the PS ring, forming the FOFDOD pattern.

to average out multipolar errors that arise from geometric imperfections, minimizing the impact of field distortions on the beam and enhancing overall stability. Fig 2.5 shows how the 4 MU types are placed around the ring, creating the periodic FOFDOD pattern.

The multipolar field generated by the MU is produced with a sophisticated pole profile, which consists of straight lines and hyperbolic arcs. The detailed design of the hyperbolic pole is illustrated in Fig. 2.6.

2.1.1 MU coil circuits

Each MU magnet is powered with three distinct coils: the main coil (MC) and two additional circuits, referred to as the Figure-of-Eight loop

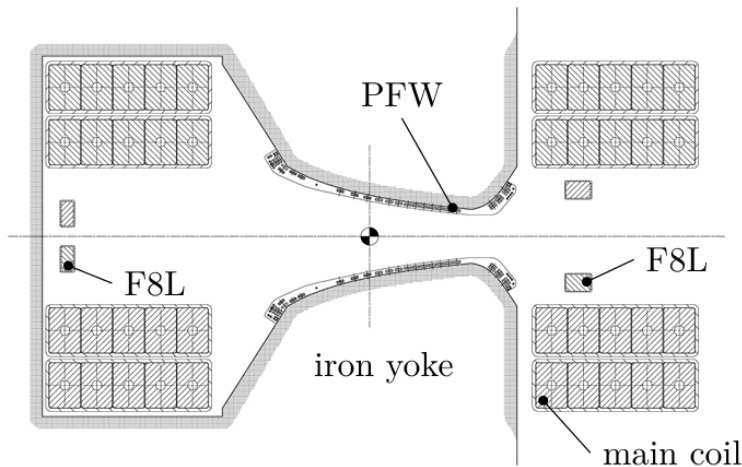


Figure 2.7. Sketch of the PS-MU yoke profile with the three powering coils: main coil, Figure-of-Eight loop (F8L) and Pole Face Windings (PFW) [8].

to cool down the conductor. The five conductor turns within each pancake are insulated with 0.5 mm mica-glass tape. The entire coil is insulated by a 4 mm mica-glass tape, and vacuum-impregnated with polyester resin. The main coils around the top poles of the 100 MU magnets are powered in series, as are those around the bottom poles. Connections between main coils in subsequent MUs are done by means of aluminum conductors, called bus-bars.

Figure-of-Eight loop

The Figure-of-Eight loop circuit, reported in Fig. 2.8, is an additional winding consisting of one single turn of rigid copper conductor, installed around both the top and bottom pole pieces of the magnet. The conductor is wound around the pole of the D half-unit in one direction and around the pole of the F half-unit in the opposite direction; thus, they cross at the central junction between the two halves, forming a figure-of-eight loop. This winding configuration allows to increase the magnetic field in the D half-unit and decreases it in the focusing half-unit, with the integrated bending field staying unchanged. Consequently, the F8L circuit allows to

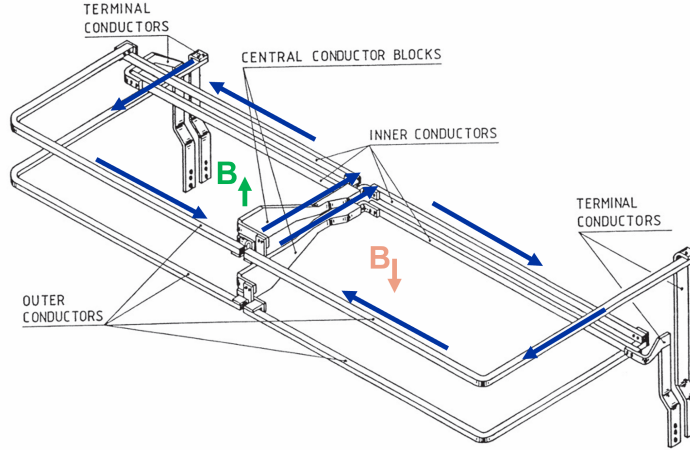


Figure 2.8. Figure-of-Eight Loop circuit.

vary the integrated field gradient in each half-unit, enabling control over the horizontal and vertical tunes of the particles.

Pole Face Windings

The Pole-Face-Windings constitute the second additional powering coil of the MUs. These conductors are placed on both the top and bottom magnet poles, positioned separately between the F and D half-units. They are arranged parallel to the surface of the hyperbolic poles, as shown in Fig. 2.9, following the longitudinal curvature of the MU.

The distribution of the conductors along the pole face generates a low-amplitude magnetic field with quadrupolar and sextupolar components. This configuration compensates for distortions in the main field and its gradient caused by saturation and leakage fields at high field levels.

The PFW are subdivided in active and passive circuits. The active circuits correct distortions in the quadrupolar and sextupolar components of the main field, while the two passive circuits compensate for harmonic distortions caused by eddy currents induced in the vacuum chamber during powering ramp-up. Thus, the passive circuits are powered by the induced voltage, and the resulting current is regulated using resistors. The active circuits are classified in narrow (N) and wide (W) circuits, as shown in

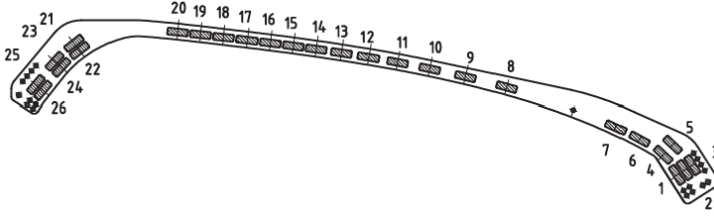


Figure 2.9. Pole Face Winding circuits plate [6]. Narrow and wide circuits 11-20, 8-10, respectively. Return conductors 1-4, 21-26 for the wide circuits, 5-7 for the narrow.

Fig. 2.10 in red and yellow, respectively. They consist of copper conductors with a cross-section of $9\text{ mm} \times 3\text{ mm}$. The narrow circuit contains ten conductor turns: six are located in the narrow part of the pole profile (top), and four surround the wide circuit (bottom), that contains only three conductor turns, located in the wide part of the pole profile.

Powering modes

There are two different modes to power the F8L and PFW circuits. The first is the so-called 3-current mode (3-CM) and was introduced in 1974 [10], where the wide and narrow circuits of a single PFW plate are connected in series. The 3-CM configuration allows the adjustment of the working point by using three distinct currents through the auxiliary circuits (I_{F8L} , $I_{PFW,F}$, and $I_{PFW,D}$). In this powering scheme, the PFW conductors primarily generate quadrupolar and sextupolar field components, influencing both the tune and chromaticity. These three distinct currents were not sufficient to fully control horizontal and vertical tunes and chromaticities (4 parameters). To fully control both tunes and chromaticities, the powering scheme of the MU auxiliary circuits was upgraded in 2007, enabling the machine to operate in the so-called 5-currents mode (5-CM) [81], which allows separate powering of the narrow and wide circuits. As a result, the control currents increased to five (I_{F8L} , $I_{PFW,F-N}$, $I_{PFW,F-W}$, $I_{PFW,D-N}$, and $I_{PFW,D-W}$). In this mode, unbalanced currents in the narrow and wide circuits generate quadrupolar, sextupolar and octupolar field components, introducing non-linear effects. The 5-CM configuration opened to the opportunity to control the horizontal and

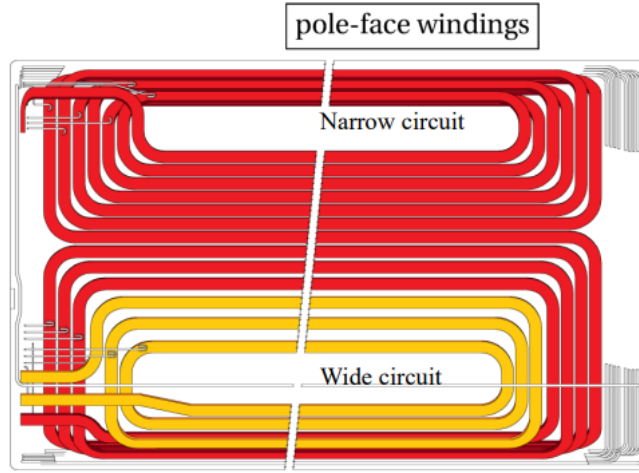


Figure 2.10. PFW: narrow and wide circuits [9].

vertical tunes and chromaticities by independently adjusting the N and W circuits of the PFW in the focusing and defocusing half-units, along with the figure-of-eight loop, leaving one physical quantity free. Fig. 2.11 presents a schematic comparison of the 3-CM and 5-CM powering modes of the PFW, shown on the top and bottom, respectively.

2.2 Field and beam-based measurements instrumentation

Particle acceleration via RF systems depends on continuous real-time monitoring of magnetic field in the machine to ensure proper synchronization between the energy of the particles and the magnetic fields guiding them. As discussed in Chapter 1, an increase in beam momentum p must be accompanied by a corresponding increase in the bending magnetic field B within the synchrotron to maintain the beam on its designed trajectory. This equilibrium is fundamental for stable operation as any deviation between the momentum of the beam and the magnetic field can lead to beam loss, instability, or inefficient acceleration.

Magnetic field measurements are, therefore, essential for ensuring that

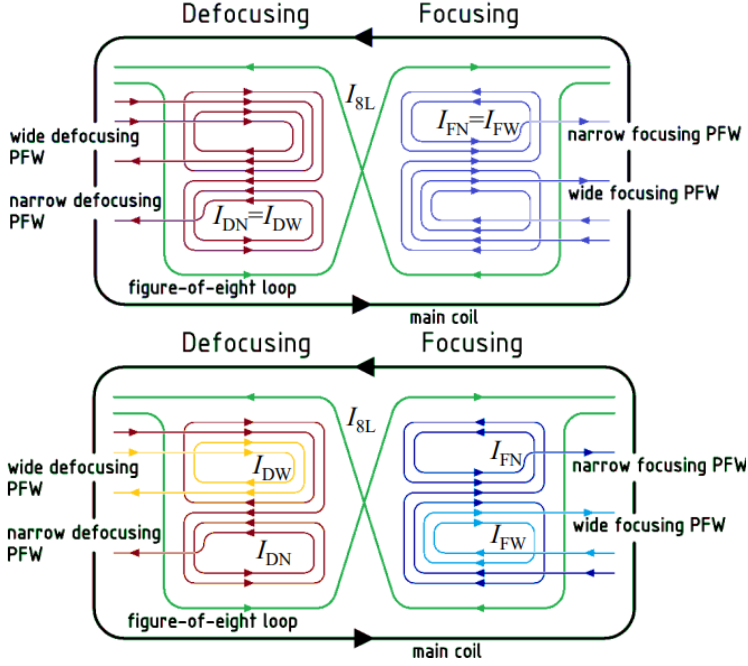


Figure 2.11. Schematic representation of the additional circuits powering in 3C (top) and 5C (bottom) modes [9].

the magnets provide the correct field at every stage of the beam cycle. Accurate magnetic measurements are especially crucial during ramping phases when both beam momentum and magnetic field must increase simultaneously and remain synchronized.

In addition to field monitoring, accelerator operation requires high precision beam-based measurements, essential for ensuring the beam's stability. These diagnostics allow for precise control of the beam's transverse and longitudinal profiles, which are critical for minimizing beam losses, ensuring uniform beam distribution. Transverse beam profile measurements provide insight into the beam size and shape in both horizontal and vertical planes, while longitudinal profile measurements give information on the energy spread and bunching of the beam as it travels along the accelerator. In order to maintain beam quality and prevent instabilities, such as transverse emittance growth or longitudinal oscillations, frequent and

accurate feedback on the beam parameters is required.

This section introduces the key elements located in the PS tunnel responsible for monitoring the magnetic field and conducting beam-based diagnostics to ensure stable and efficient operation of the machine.

2.2.1 Magnetic field measurements

As is the case for many synchrotrons at CERN, real-time magnetic field measurements in the PS are acquired via a B-train system [82–85], installed in the external MU outside of the accelerator, but powered in series with those in the machine. The B-train system consists of a set of induction coils that provide continuous measurements of the instantaneous magnetic field based on the voltage output generated by the varying magnetic flux. This allows for precise monitoring of the magnetic field during the operation of the accelerator, ensuring that the magnetic field strength is correctly synchronized with radio-frequency system.

The B-train system is also important for correcting non-linearities that arise due to magnet saturation at high field levels. These non-linear effects can distort the magnetic field, leading to beam instabilities if not properly corrected. The data from the B-train allows the machine’s control system to adjust the magnetic fields and maintain the desired beam trajectory.

In the PS, two distinct sets of B-train coils are used, with one installed in each half-unit. These provide independent measurements of the magnetic field in the focusing and defocusing sections of the MU, denoted as B_F and B_D , respectively. The total measured magnetic field B_{meas} is then calculated as the sum of the individual contributions from each half-unit, following the relation [86]:

$$B_{meas} = \frac{1}{2} \cdot B_F \cdot 1.09353 + \frac{1}{2} \cdot B_D \cdot 0.90533 \quad (2.1)$$

in which the coefficients multiplying the field contribution of the two half-units were calibrated in operation during beam commissioning to match the energy of beam.

The B-train coils are wound around insulating support bars, illustrated in Fig. 2.12, which have a longitudinal length l_b of 401 mm and width w_b of 18 mm. The B-train coil bars are positioned in the second block of each half-unit, as shown in Fig. 2.13 (blue blocks). In the transverse plane,

and frequency ranges to ensure accurate tune measurements. The pulsing strength controls the amplitude of the applied oscillation. It must be strong enough to induce a measurable oscillation in the beam, but not so strong that it distorts the spectrum by driving the beam into non-linear behavior. Selecting appropriate starting and ending frequencies is essential to ensure that the full range of beam oscillations is excited.

The same hardware used to generate chirp pulsing also enables AC-dipole excitations. This mode is not utilized for tune measurements but allows for highly accurate optics measurements, such as phase advance and β function determination. The PS is not equipped with a dedicated excitation kicker. Chirp and AC-dipole signals are generated via the transverse damper stripline kicker [48, 49].

2.3 Software architecture for machine control

After particle beams are injected from the PSB (or, in the case of ions, from LEIR) they are accelerated in the PS and subsequently delivered to a variety of experiments. Each experiment has distinct requirements, which necessitates delivering beams at different energy levels (i.e., SPS requires beam at 26 GeV/c). As a result, the acceleration process within the PS is highly dependent on the specific needs of the receiving experiments, requiring tailored control of both beam energy and timing parameters to optimize the performance of the machine.

The powering settings required to deliver a specific beam to experiments or other machines are managed through distinct power cycles. Each power cycle is tailored to a specific user or experiment, with variations in length and duration depending on the requirements of the receiving user.

PS Supercycle

The sequence of different beam cycles that the PS executes to meet the diverse needs of various users and experiments defines the concept of the PS supercycle. The supercycle is a repetitive pattern of magnetic field ramps and RF synchronization cycles that allow the PS to accelerate and extract multiple beams for different users within a single operational period, usually between 40 to 60s. It can handle different beam intensi-

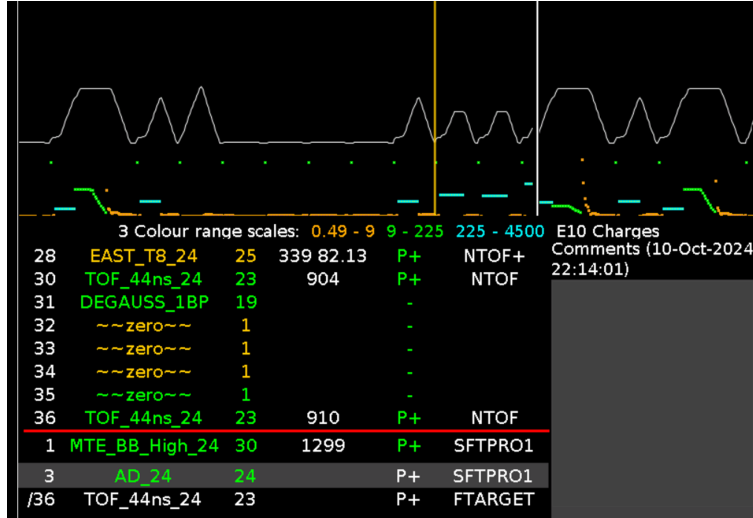


Figure 2.15. Example of the PS supercycle in operation.

ties, particle types, and energy ranges within a single operational cycle. Fig. 2.15 presents an excerpt from the PS supercycle in operation (date and time provided in the figure). The upper section depicts the sequence of power cycles, while the lower section lists the upcoming cycles (e.g., AD-24, TOF, EAST AREA), along with the particle type (e.g., p_+) and the beam's final destination.

The supercycle manages beams for various studies, such as beam optics measurements, RF studies, and beam instrumentation tests. This system enables the PS to switch rapidly between tasks, effectively fulfilling the needs of numerous users across diverse experimental setups. The flexibility of the PS supercycle allows it to serve multiple users simultaneously, optimizing the allocation of beam time and minimizing idle periods for the machine. This multi-tasking capability ensures that research and development activities can be conducted in parallel with routine operations, significantly increasing the overall efficiency of the machine.

Over multiple repetitions of the supercycle, the position of a specific power cycle in the pattern is not guaranteed to remain unchanged. This variability depends on the demands of high-priority users, such as delivering beams to the SPS for filling the LHC.

LHC Software Architecture

The software infrastructure to coordinate, control, and monitor the complex sequence of cycles executed in the PS is provided by the LHC Software Architecture (LSA) [87]. Originally developed to manage and operate the LHC, it was later extended to other accelerators at CERN. The LSA framework is responsible for managing and applying the settings required for each cycle in the supercycle, including magnetic field ramps, RF synchronization, beam energy, timing and optics settings.

The LSA framework allows for the hierarchical organization of device control, where complex devices are made up of simpler components that are controlled individually but can also be grouped together for more efficient management [88, 89]. This means that LSA can deal with systems from single powering circuits of magnets to entire sections of the machine.

The software allows operators and users to apply trims (adjustments to machine and magnet settings) to correct the beam trajectory, focusing, or other properties, enabling users to control and track changes to machine settings. In this thesis, LSA was employed to control trims, define currents in the auxiliary circuits, correct the beam's MRP, and as repository for retrieving programmed functions (field, momentum).

Q-meter

Q-meter [90] is a tool used for real-time measurements of the betatron tune and chromaticity. It provides feedback to users in the supercycle, allowing fine-tuning of machine optics and ensuring the desired tune values are maintained. With this tool, users can set the chirp frequency range and strengths. The Q-meter also allows for chromaticity measurements. In addition to the tune settings described earlier, chromaticity can be measured by adjusting the momentum deviation range dp/p through the r_{pos} shift, a trim setting in LSA which varies the RF frequency to change the MRP, allowing chromaticity measurements following the procedure described in Section 1.4. Larger r_{pos} shifts lead to larger dispersive orbit-distortions, which might result in beam losses, in turn making the tune measurement unreliable. To address this, users can set a beam intensity threshold, below which measurement points are excluded from the analysis. This ensures that data from unstable beam conditions are not included in

the chromaticity analysis, maintaining the accuracy of the measurements. The degree of the polynomial used for interpolating the measured points can be selected, depending on the chromaticity order that needs to be measured. This tool was largely used in this thesis as interface to set chirp excitation, visualize and retrieve the data from the BBQ for tune and chromaticity measurements.

Timber

Timber is a data logging and visualization system used at CERN to record and access time-series data from the accelerator complex for post-operation analysis. Timber collects data from various sources, such as beam instrumentation, magnet settings, RF systems, and environmental conditions. It records time-stamped values, allowing users to track changes in machine parameters over time, facilitating performance analysis and troubleshooting. Operators and users can monitor accelerator operations in real-time, giving them insights into beam dynamics, magnet settings, and other critical parameters. Timber has an interface that lets users graphically display the logged data. Users can generate plots and graphs for various parameters (e.g., beam intensity, magnet currents, beam orbit) to analyze trends or identify anomalies. In this thesis, Timber was used to download tune and MRP measurements.

TMS

The Trajectory Measurement System (TMS) [91] is a software tool which serves as interface with BPM data directly, allowing to control BPM settings (gain, calibration), monitoring of data quality and report key metrics, in particular beam MRP. TMS enables users to optimize these settings. For the present work, the TMS has been used for MRP measurements and monitoring, and to ensure correct BPM gain and setup during optics measurements.

Modeling of the Proton Synchrotron main magnets: state of the art

The complexity of the Proton Synchrotron Main Units (PS-MU) presents significant challenges in their accurate modeling. Nonetheless, precise modeling of these elements is desirable as the magnetic field generated by the PS-MU directly influences beam optics, stability, tune and chromaticity control, and hence machine performance within the PS and other machines in which the beam is delivered.

Over the past decades, several attempts have been made to develop digital twins of the PS-MU, each striving to capture the intricacies of their magnetic and optical behavior. Early attempts to predict the tunes of the PS during slow extraction began in the 1980s, based on harmonic predictions of 2D models of the PS-MU, but ultimately proved insufficient [92]. Later in the 1990s, 2D magnetic models were used to make qualitative predictions for the influence of shims on the PS main magnets, though little correspondence was found between beam-based measurements and the model predictions [93]. During the 1990s an alternative approach was also considered. Magnetic measurements [94] were taken as input to optics simulations [95]. It was found that tunes and chromaticities could not be well predicted, and had to be artificially matched in optics simulations.

Magnetic modelling was revisited in 2009 with the development of the

first 3D magnetic models of the PS-MU [96]. Once again, model predictions failed to offer a concrete predictive power for tune and chromaticity sufficient to support PS operation [96]. A quasi effective approach, where magnet models were artificially tuned to match B-train measurements, and optics models were artificially tuned to reproduce observed tunes and chromaticities, did allow some progress on prediction of relative optics shifts and some higher-order components [6].

In practice, while there has been significant developments in PS modelling since the 1970s, these have not had a significant impact on PS operation today. Lacking a predictive model of the PS optics, since the early 2000s effective models, based on simply matching simulations to beam-based measurements, have been developed and utilized for operation and beam dynamics studies [97, 98], while tune and chromaticity control remains based on empirically determined circuit responses measured with beam [99]. While this empirical beam-based approach represented an advancement for today's operation, however, further improvements in the magnetic and optics modeling remains a key topic of interest in the PS, for example to support operation and development of the machine [98, 99].

This chapter delves into the state of the art for the magnetic and optics modeling of the PS-MU, offering a comprehensive review of past efforts and the advancements made in recent years. The challenges and limitations in the development of reliable models for this critical component of the Proton Synchrotron and the whole CERN accelerator complex are presented in Section 3.1. Section 3.2 provides a comprehensive review of the latest pre-existing PS-MU magnetic finite-element (FE) models, detailing its core design features, the characterization of material properties, boundary conditions, and the meshing strategies employed for solving the complex field equations. Section 3.3 delves into the PS-MU optics modeling, presenting its fundamental components, and exploring the shortcomings of the current model in predicting the beam optics dependence on energy.

3.1 PS-MU Modeling: addressing challenges and key aspects

Modeling the PS-MU magnets poses a set of challenges, due to the intricate geometry of the magnets, their curvature, the complexity of the

generated multipolar field, the presence of air gaps between consecutive iron blocs, and the non-linear properties of the materials involved. This section explores the critical factors that influence the development, accuracy and reliability of PS-MU modeling, both in terms of magnetic and optics simulations.

The hyperbolic shape of the pole surfaces generates a combined-function magnetic field within the aperture. The generated multipolar field is even more complicated when the auxiliary circuits, providing higher order harmonics contributions, are included in the model.

When dealing with complex geometries and large magnet dimensions, the choice of the mesh becomes a critical aspect of finite-element modeling. A fine mesh is required to accurately capture the intricate magnetic field harmonics distribution, especially around regions with sharp gradients, such as the hyperbolic pole shapes and the transitions between air gaps and iron blocks. However, finer meshes increase computational demands, potentially leading to longer simulation times and higher resource requirements. Striking the right balance between mesh resolution and computational efficiency is an essential challenge to ensure accurate predictions while maintaining manageable simulation times. Another layer of complexity arises from the need to ensure that optics simulations remain unaffected by the meshing structure, requiring careful optimization of mesh design to avoid introducing artifacts or biases into the results. For these reasons, in this chapter, particular attention and emphasis are given to the PS-MU magnetic model meshing structure.

Furthermore, at the outset of this thesis, the extent to which harmonic distortions introduced by eddy currents and hysteresis effects influence the optics during continuous ramping was unknown, as previous studies primarily focused on static powering configurations [6, 11, 96, 100]. This gap highlights the need for a comprehensive investigation to quantify these effects and their potential impact on beam dynamics predictions and measurements.

The optics modeling of the PS-MU, crucial for predicting the machine's performance across its operational energy range, presents additional challenges beyond the complexities of the magnetic modeling. One of the primary difficulties in PS-MU optics modeling arises from the intricate non-uniform longitudinal field distribution within these magnetic units.

The air gaps between consecutive iron blocks disrupt the homogeneity of the magnetic field along the beam line, with the field strength diminishing in the regions between consecutive blocks, producing non-linear forces which impact the beam dynamics. Similarly, at the magnet extremities, the field tends to become highly non-linear. Thus, non-linear effects need to be precisely accounted for and incorporated in the optics model, as any inaccuracies in representing these fields can lead to incorrect predictions, compromising models' benchmarking with beam-based measurements.

The correlation and consistency between magnetic and optics models, as well as their respective simulation tools and codes, have often been ambiguous, complicating efforts to perform accurate beam dynamics simulations solely based on magnetic field predictions. This disconnect emphasizes the need for more integrated methodologies that harmonize magnetic and optics models, fostering a more reliable and cohesive representation of the PS-MU's behavior.

Developing predictive models capable of providing accurate and reliable inputs for accelerator operation within a reasonable timescale was a formidable challenge. This limitation has restricted the use of such models in making operational decisions, as their complexity and computational demands have hindered their applicability in time-sensitive scenarios.

3.2 Finite-element magnetic modeling of the PS main magnets

The pre-existing reference PS-MU magnetic model [11], taken as starting point for the studies reported in this thesis, is detailed in this Section. It was developed in Opera 3D [101, 102], a widely adopted commercial finite-element software known for its extensive application in accelerator magnet studies [103–105]. Opera has been a key tool in magnet design and simulation due to its versatility in handling complex designs and field configurations, making it suitable for modeling magnets like the PS-MU, which require a high degree of precision and complexity in their simulations. This model, developed between 2010 and 2020, was maintained at CERN over the years, but not largely used for operational studies, due to long simulation times.

Key features for the magnetic modeling of the PS-MU are the packing

factor (accounting for the laminated structure of the magnet), magnetic properties and hysteresis cycle of the iron (which includes the $B-H$ curve describing its magnetization), boundary conditions and symmetry planes (used to define the field conditions at the extremities of the model volume), and the design of the meshing structure. Following, these aspects, along with their impact on the magnetic model, are described in detail.

3.2.1 Packing factor

As explained in Chapter 2, each MU consists of 10 laminated iron blocks. Within each block, a thin insulation layer is inserted between consecutive laminations to minimize power loss caused by eddy currents. This introduces the concept of packing factor [106], referring to the ratio of the volume occupied by magnetic material with respect to the total volume of the structure, including both the magnetic material and any non-magnetic material, like insulation layers between laminations. This factor is critical in magnetic modeling because it affects the calculation of magnetic fields, inductance, and other electromagnetic properties of the magnet. In previous studies, the packing factor for the PS-MU has been accurately evaluated and determined to be 93.53% [6, 11]. This means that approximately 6.47% of a single block volume consists of non-magnetic material, impacting the overall magnetic field distribution and complicating the modeling process.

3.2.2 Magnetic properties and hysteresis

When modeling a magnet to simulate the field map within it, an important role is played by the magnetic permeability of its steel, which quantifies how much magnetization is induced in the material in response to an applied external magnetic field. Ferromagnetic materials are usually employed to build electromagnets due to their high magnetic permeability, allowing to reinforce and guide an applied field [107–109]. The response of these materials to a varying external field, thus its magnetic permeability, is typically non-linear. When the applied external field is periodic, the magnet undergoes a hysteresis cycle, characterized by a $B-H$ curve [110–112]. In the case of the PS-MU, the $B-H$ curve was meticulously measured [113] and integrated into the Opera pre-existing magnetic model.

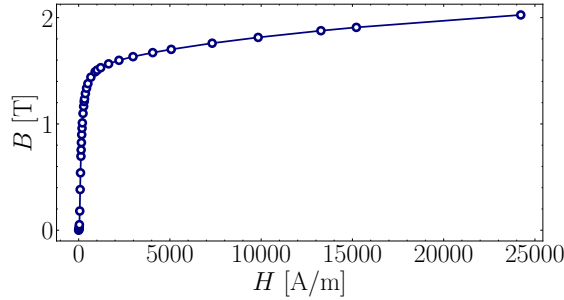


Figure 3.1. Measured PS-MU $B - H$ curve employed in the magnetic model. [11]

This $B - H$ curve, shown in Fig. 3.1, highlights the non-linear response of the PS-MU steel, particularly as it saturates above 1 Tesla. The first point on the $B - H$ curve is $(H = 0, B = 0)$, indicating that the model does not account for any remanent field, which refers to the residual magnetization present in a ferromagnetic material even after the external magnetic field has been removed. In real materials, this remanent magnetization can influence the behavior of the magnet, particularly during cycling, as it contributes to the hysteresis effect and affects the field produced by the magnet in the absence of an external current. Neglecting the remanent field in this model simplifies the magnetic response but might affect predictions at low energy.

3.2.3 Model geometry

Due to the large radius of curvature, the pre-existing MU magnetic model was simplified by approximating the magnet's geometry to a straight configuration. This approximation significantly reduces the complexity of the modeling process and facilitates the computation of the magnetic field harmonics. Despite this simplification, the model maintains a high level of accuracy in field predictions, as demonstrated through benchmarking against experimental magnetic measurements [11]. This approach strikes a balance between computational efficiency and the precision required for reliable magnet modeling. In the Opera 3D pre-existing model, the air gaps between two consecutive iron blocks in the closed (focusing) and

open (defocusing) half-units are 7.75 mm and 9.75 mm long, respectively, corresponding to the actual air gap lengths at the equilibrium orbit, as explained in Chapter 2. The main junction separating the focusing and defocusing half-units is 20 mm long.

3.2.4 Boundary conditions and symmetries

When solving magnetic field equations using a finite-element software, boundary conditions must be assigned to control the direction of the magnetic field on specific surfaces. To achieve this in the Opera MU model, the magnet is enclosed within a larger domain of air, normally referred to as the far-field area.

In Fig. 3.2, the magnet's iron structure is shown in green, while the far-field boundaries are displayed in gray. The coordinate system is indicated in black, with its origin ($x = 0$, $y = 0$, $z = 0$) marked by a blue circle. Fig. 3.2a presents a transverse view of the magnet (perpendicular to the beam longitudinal motion), in which the x and y axes represent the horizontal and vertical directions, respectively; Fig. 3.2b provides a longitudinal view, where the z axis represents the longitudinal direction, aligning with the trajectory of the circulating beam. The model boundary surfaces are designed to have no impact on the field map in the area of interest. To achieve this, they are positioned sufficiently far from the magnet, ensuring that the magnetic field strength in these regions remains below the per-mill level of the field within the magnet's aperture.

Consequently, appropriate field boundary conditions were applied to the external surfaces of the model. Specifically, a tangential field condition was imposed on the surfaces denoted as γ_t . Conversely, a normal field condition was applied to the mid-plane between the two poles at $y = 0$, as the magnetic field is designed to be purely vertical at the center of a normal magnet's aperture. This careful placement of boundary conditions ensures that the model accurately reflects the field behavior in the magnet aperture.

At the same $y = 0$ plane, a symmetry condition is also applied, which allows the modeling of only one half of the magnet (one pole), with the FE software solving also for the other half based on the imposed conditions. This approach significantly reduces computational complexity while maintaining accurate field predictions.

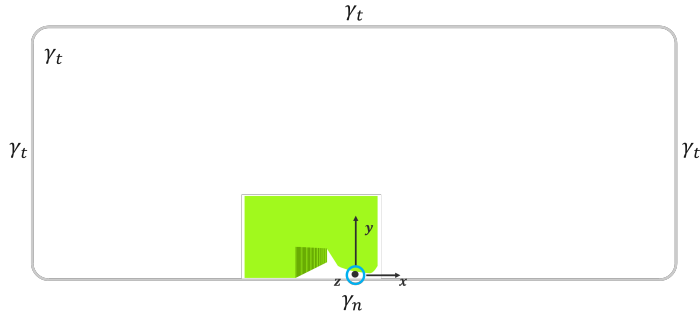
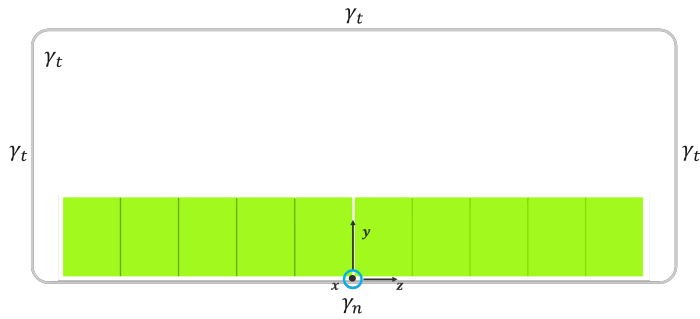
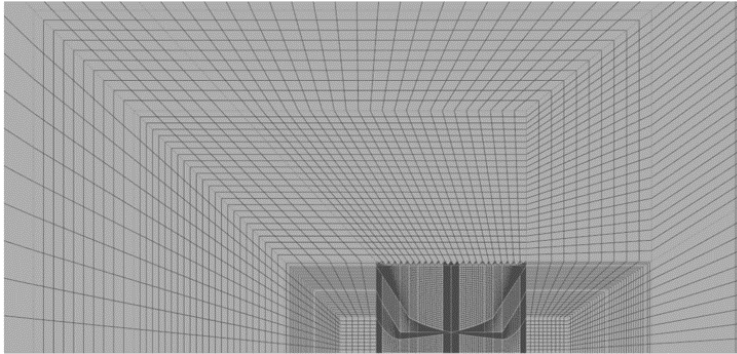
(a) Boundary conditions on the $x - y$ plane.(b) Boundary conditions on the $z - y$ plane.

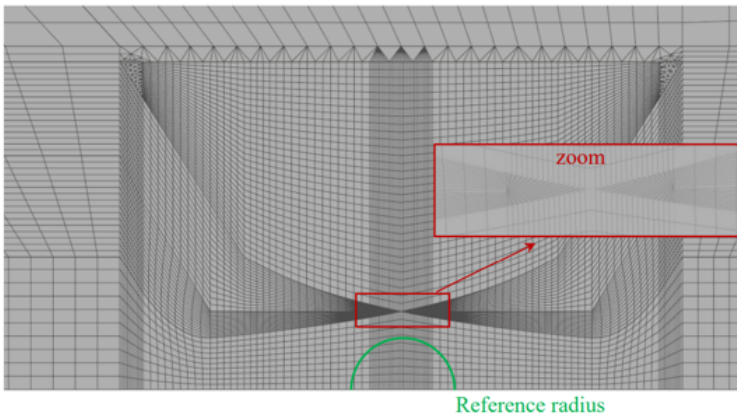
Figure 3.2. Boundary conditions of the MU magnetic model. Tangential field conditions are superimposed on the γ_t surfaces, while normal field conditions on γ_n ones.

Meshing structure

The meshing structure of the model was created using an Opera-built mosaic approach, which generates quadrilateral elements on the surfaces of the model. The pre-existing model consists of approximately 6.26×10^6 mesh domains throughout its volume. Fig. 3.3 illustrates the meshing structure in the pre-existing PS-MU model. Particularly, Fig. 3.3a shows the meshing in the yoke, the far-field region and the aperture, while Fig. 3.3b provides a more specific focus on the meshing in the pole and the aperture. The mesh was specifically designed to be finer in the center of the aperture (circled in green), where the beam passes and fine field description is needed for accurate harmonics computation, while it becomes coarser fur-



(a) Global view of the meshing structure.



(b) Detailed view of the meshing in the pole and the aperture.

Figure 3.3. Meshing structure of the pre-existing PS-MU Opera 3D model [11].

ther out. All facets of the model, including the pole profile of both open and closed half-units, are defined in the same plane, which is later swept to generate the full 3D geometry [11].

3.3 Optics modeling of the PS main magnets

The aim of magnetic modeling is to produce accurate estimates of the field harmonics generated by the magnetic units. The optics model,

by contrast, starts from estimates of the field harmonics, and uses them to produce estimates of beam parameters that are relevant for machine operation and performance.

Following the introduction on the state of the art of the PS-MU magnetic modeling in Section 3.2, this section delves into the complex optics modeling of the PS-MU. As a first step, the simulation tool employed for accelerator lattice design and beam dynamics studies is introduced in Subsection 3.3.1, highlighting its essential role in correlating magnetic field characteristics with beam behavior. Subsection 3.3.2 presents the structure of the pre-existing PS-MU optics model, detailing the empirical approach employed to define it.

3.3.1 Methodical Accelerator Design - X

Traditionally, the beam dynamics simulation tool utilized for the PS-MU optics modeling is the Methodical Accelerator Design (MAD-X) [114–117]. Originally developed for the design of the Large Hadron Collider lattice and its associated optics, MAD-X has evolved into a reference tool utilized in the field of accelerator physics for the design, optimization, and analysis of particle accelerators, ranging from synchrotrons to linear accelerators.

MAD-X has been successfully applied to a variety of projects and accelerators around the world [118, 119]. Besides the upgrade of existing facilities, it is increasingly used for the design of next-generation machines [120–123]. This widespread adoption underscores MAD-X’s versatility and reliability in simulating complex beam dynamics across various accelerator contexts.

The development of the code itself is beyond the scope of this thesis; however, several key concepts essential for understanding the MU optics model described in this chapter are briefly recapitulated.

MAD-X enables users to construct and manipulate the lattice of an accelerator, defining a sequence of elements, including bending magnets, quadrupoles, sextupoles, RF cavities, and other components. For the magnets, users can specify the locations, dimensions, and magnetic strengths of these elements to accurately model the accelerator’s configuration [124].

The software allows for the simulation of various aspects of beam dynamics, including the calculation of fundamental beam optics parameters

such as tunes, chromaticities, and Twiss parameters, assessing whether they remain within specified operational tolerances. MAD-X also enables the computation of the beam orbit at specific locations around the ring (e.g., at the BPM locations) and the prediction of the effects of perturbations, such as localized magnetic errors, on the overall beam dynamics. The matching module in MAD-X is particularly valuable for tuning the accelerator's parameters in simulation. It allows for the automatic adjustment of magnetic strengths and other parameters in the model to achieve a desired set of target optical properties.

MAD-X works seamlessly with other software and tools used in accelerator physics (such as Xsuite [125], PTC [126]). This interoperability is crucial for large-scale collaborations and projects that involve multiple teams and disciplines.

When possible, predictions made by MAD-X can be benchmarked against experimental data from beam-based measurements, allowing for continuous improvement and validation of the modeling approach.

MAD-X internal objects for optics modeling

To model a magnet in MAD-X, various internal objects and structures are available. For the optics modeling of the PS-MU, the Sector Bending Magnet (SBEND) object was selected [124], in which the planes of the edge faces are perpendicular to the reference beam trajectory, as shown in Fig. 3.4. This choice was driven by the actual structure of these magnetic units, which presents wedged gaps, with the assumption that there are no significant edge focusing effects. This object allows users to specify several key parameters, including the length of the magnet and the bending angle. Additionally, the SBEND object can incorporate quadrupolar and sextupolar components or errors that may arise within the magnets.

To account for higher-order non-linear effects stemming from multipole contributions, the MULTIPOLE element can be utilized in MAD-X. This object consists in a thin lens magnet of arbitrary order, with the deflection on the beam, imparted by magnetic normal and skew multipoles, expressed as integrated multipole strengths, denoted as $k_{N,n}L$ and $k_{S,n}L$, respectively [124]. This element assumes that multiple field components of arbitrary order are concentrated into a single infinitesimal point. In this thesis, MULTIPOLE elements were used to incorporate in the model

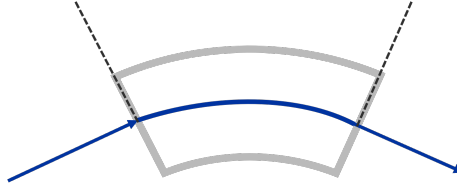


Figure 3.4. Schematic representation of Sector Bending Magnet (SBEND) in MAD-X. Reference orbit entering and exiting perpendicular to the edge faces.

higher field harmonics arising from saturation, fringe fields, field distribution in focusing-defocusing transition area.

For more detailed information on the various MAD-X objects and their specific functionalities, readers are encouraged to consult the User's Guide available for MAD-X, which provides extensive documentation and guidance on effectively utilizing this modeling tool to simulate beam dynamics in particle accelerators [124].

3.3.2 Pre-existing optics model

MAD-X has been utilized over the past decades for a variety of studies related to the PS. Among these investigations, recent researches have focused on several critical areas, including the evaluation of the feasibility of adjusting the tune working point at injection, implementing slow extraction strategies toward CERN's experimental areas, and conducting Multi-Turn Extraction (MTE) studies to supply beams for fixed-target physics at the Super Proton Synchrotron [8, 98, 100, 127].

To effectively perform beam optics studies in the PS, MAD-X simulations necessitate a reliable model of the 100 MU magnets. Given the intrinsic complexity of these magnets, developing an accurate optics model presents a significant challenge.

The reference PS-MU MAD-X optics model, employed for operational studies, is described in detail in this subsection.

MAD-X construct

The existing PS-MU bare-machine model, depicted in Fig. 3.5, comprises two SBENDs (shown in gray), which represent the two half-unit cores

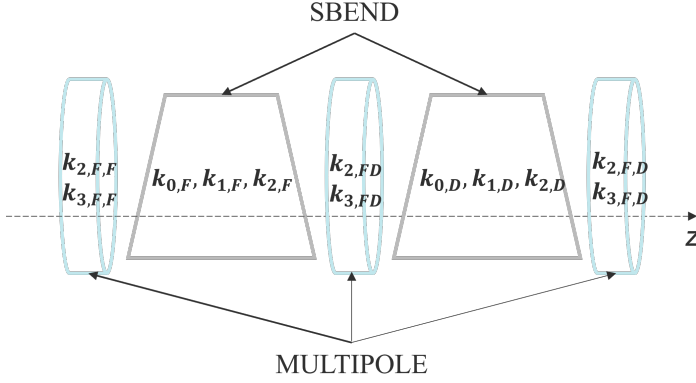


Figure 3.5. Description of the pre-existing MU optics model in MAD-X for the bare-machine configuration (strengths from F8L and PFW not included).

of the magnet. Additionally, the model incorporates three thin MULTIPOLE lenses (in light-blue) to include the non-linearities in the magnet fringes as well as in the F/D transition area air gap.

In each SBEND, several key magnetic components were defined to accurately represent the magnetic behavior of the half-unit. These include the dipolar bending fields ($k_{0,F}$ and $k_{0,D}$), which are crucial for ensuring the beam orbit to be closed. Furthermore, focusing and defocusing quadrupolar components ($k_{1,F}$ and $k_{1,D}$, respectively) are included to enable the model to focus the beam through the machine. The model also accounts for sextupolar components ($k_{2,F}$ and $k_{2,D}$), which are important for correcting chromatic effects in the beam dynamics. In case the F8L circuit is enabled, further quadrupolar components are incorporated in the focusing and defocusing SBENDs, denoted as $k_{1,F,F8L}$ and $k_{1,D,F8L}$, respectively, while the PFW circuits introduce additional quadrupolar and sextupolar components, described as $k_{1,F,PFW}$, $k_{1,D,PFW}$, $k_{2,F,PFW}$ and $k_{2,D,PFW}$.

In the two MULTIPOLE elements at the MU extremities, as well as in the F/D transition MULTIPOLE, sextupolar and octupolar kicks ($k_{2,F,F}$ - $k_{2,F,D}$ and $k_{3,F,F}$ - $k_{3,F,D}$, respectively) were defined.

An effective matched model

The PS-MU pre-existing optics model was taken from the CERN optics model repository [128], which is used as the basis for the operational models and beam dynamics studies of the PS. In that repository, PS-MU optics models corresponding to different cycles and machine configurations (bare-machine and with auxiliary circuits) can be found, described by the structure reported in Fig. 3.5.

The PS reference optics models represent an effective or matched model: the magnet strengths are not defined according to true settings applied in the machine, but rather are tuned to replicate beam-based measurements or desired beam-parameters. In the case of the PS-MU reference model, quadrupolar and sextupolar components of the SBENDs (together with higher order components in the MULTIPOLE elements) were matched via the MAD-X matching module to replicate measured tunes and chromaticities at injection in the bare machine. As the reference measurements were performed at injection, no account for the magnetic saturation of the MU is made. Assuming the strengths are constant over the operational energy range, models for different working points or use cases are then generated by replacing the desired beam parameters and using the matching module on the SBEND's quadrupolar and sextupolar strengths.

This empirical approach renders the pre-existing optics model an effective model, as it relies entirely on experimental data. However, such a model lacks predictive power, significantly limiting its application for making operational decisions. The bending angle k_0 is instead defined to curve the beam trajectory of 360° in all the SBENDs.

Combined modeling of PS main magnets

In the previous chapter, the pre-existing magnetic and optics models of the PS-MU were introduced. A detailed examination of the key elements of the magnetic model, along with the description of the MAD-X structure of the optics model, were provided. The optics model was identified as an effective model, having been derived directly from beam-based measurements.

The studies conducted in this thesis started with a thorough analysis of the pre-existing models and the evaluation of their performance. This analysis, detailed in Section 4.1, encompasses both the magnetic and optics models. To overcome limitations found in the pre-existing magnetic model, a new refined model is introduced in Section 4.2, emphasizing the accuracy, efficiency, and versatility of the new model. The validation of this model's predictions through comparisons with magnetic measurements is also presented. In Section 4.3, the advancements in the optics model are discussed, highlighting the improvements introduced to address the limitations of the previous model. While the pre-existing optics model was fully based on empirical data, studies reported in this thesis are constructed integrating the magnetic and optics models in an unified framework. By coupling the predicted field harmonics from the magnetic model directly into the optics model, it becomes possible to simulate the beam dynamics across varying energies. This aims to provide a robust predictive tool for

operational decisions-making, capable to predict the optics dependence on energy.

4.1 Assessment of pre-existing PS-MU models

The first task undertaken in the work presented in this thesis was to identify limitations in the existing MU models and assess the cause. Their effectiveness in delivering time-consistent and accurate predictions across multiple energy levels is critically evaluated. Subsection 4.1.1 analyze the pre-existing magnetic model, while Subsection 4.1.2 investigates the pre-existing MAD-X optics model.

4.1.1 Magnetic model investigation

At the outset of the work presented in this thesis, the pre-existing PS-MU magnetic model was tested for the evaluation of magnetic field maps, which were intended to be used as input data for optics model in beam dynamics studies.

However, driven by the need to perform numerous studies across multiple energy levels and machine configurations, while providing timely feedback to operation, initial simulations revealed key limitations that constrained their applicability. Primarily, during the pre- and post-processing phases, the model proved to be extremely resource-intensive. This significantly hindered efficiency and slowed down basic operations, such as mesh generation or selecting specific cells, faces, or points to assign boundary conditions. Additionally, the model's complexity made it extremely difficult to perform simulations in a reasonable time frame, with each simulation often extended to several days to complete, impacting the practicality of using the model for routine analysis, as operational assessments ideally require simulations to be completed within approximately 10 hours to allow operators to setup the machine to enable timely machine setup by the operators.

After thorough investigations, it was determined that the mesh type used in the model, along with the inconsistent mesh element densities between neighboring regions across the magnet pole, were the primary areas requiring improvement in the pre-existing model. Fig. 4.1 illustrates this

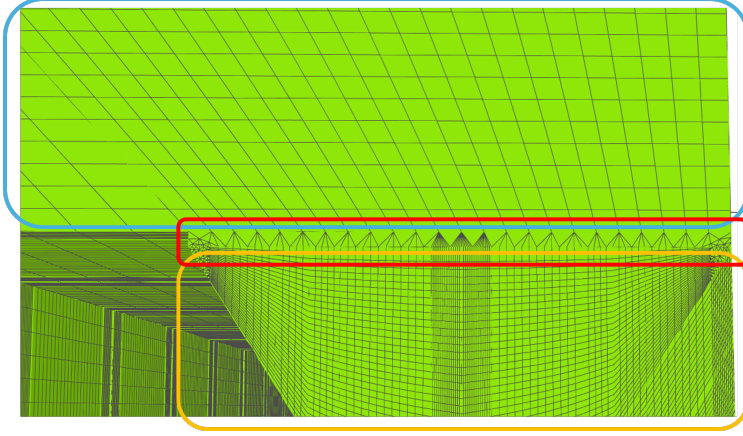


Figure 4.1. PS-MU pre-existing magnetic model. Focus on the unmatched meshing (highlighted in red) between the pole (highlighted in orange) and the main body of the iron yoke (highlighted in blue).

issue: different mesh densities between the magnet pole (highlighted in orange) and the main body of the iron yoke (highlighted in blue) resulted in a boundary region (highlighted in red) populated by unexpected triangular elements. The sharp angles formed within these triangular mesh elements significantly slowed down the finite-element software as, resolving field equations in regions with such mesh structures, required excessive computation times. This issue drastically reduced the model's time-efficiency.

Given the operational requirements for multiple simulations to assess the optics dependence on energy within the MU across various energy levels and configurations (including the bare-machine configuration and operation with auxiliary circuits activated), the magnetic model's performance became a critical bottleneck. Moreover, these mesh inconsistencies not only slowed the simulations but also raised concerns about the accuracy of the field solutions. The possibility of numerical errors in the regions where the mesh density mismatch occurred suggested that the model might not fully capture the true magnetic behavior of the PS-MU, especially in predicting the higher-order harmonics and other field characteristics.

In light of these limitations, it became evident that a more streamlined, lighter, time-efficient, and accurate model was essential to provide

feedback to operation on short timescales. These considerations drove the development of a new, improved version of the PS-MU magnetic model, which is presented later in Section 4.2.

4.1.2 Optics model investigation

The pre-existing optics model did not incorporate any quadrupolar components in the MULTIPOLE elements situated at the fringe fields nor within the F/D transition area. This means that the focusing/defocusing forces determining the beam tunes are only stored in the two SBENDs. However, field at the magnet extremities (e.i., fringe fields) can be relevant and give a further contribution to the tunes. Thus, this omission may restrict the model's capacity to accurately predict beam dynamics. These limitations are addressed with the development of a new optics model, introduced in Section 4.3.

Pre-existing models' investigation: outcomes

The pre-existing magnetic model showed mesh inefficiencies and high computational demands, while the effective optics model did not attempt to predict the evolution of the optics with energy through optics simulations, limiting its predictive capability. Despite decades of development, operation still lacked a predictive model capable of reliably informing decisions, because the pre-existing models were unable to provide predictive insights or deliver feedback on a sufficiently fast timescale. Consequently, the operation and control of the PS-MU remained entirely empirical, relying heavily on measured transfer functions.

These limitations highlighted the necessity of greater effort to provide operation with accurate models possessing predictive power. Consequently, it was decided to define multiple optics models that would no longer rely on empirical data but instead are derived directly from predictions of a new magnetic model. The integrated magnetic and optics modeling approach, supported by refined models introduced in the next chapters, aimed to deliver a powerful framework capable of influencing operational decisions and ultimately contributing to the optimization of accelerator performance.

4.2 A new magnetic model of the Proton Synchrotron main magnets

The pre-existing PS-MU magnetic model was thoroughly analyzed in the previous section, highlighting critical limitations. This assessment underscored the need for a refined magnetic model that is more manageable, computationally efficient, and time-effective. A new model, introduced in this section, was designed to overcome computational shortcomings and mitigate numerical errors caused by mismatched mesh densities across different domains. Furthermore, it aims to support the extensive simulations required for the wide range of operational conditions in the PS, delivering faster and more precise predictions.

The development of the new magnetic model started from the reference PS-MU magnetic model discussed earlier. A new meshing structure, that better accommodates the intricate geometry of the MU poles, was studied to reduce the computational load and model time-efficiency, and is presented in Subsection 4.2.1. Later, the methods employed for the harmonics computation with the new refined MU magnetic model are introduced in Subsection 4.2.2. To assess the efficiency of the new meshing structure, a mesh sensitivity analysis is presented in Subsection 4.2.3. Finally, the new magnetic model is validated against B-train magnetic measurements in Subsection 4.2.4.

Global coordinate system

The global coordinate system of the new model, denoted as $x - y - z$, is first defined, as illustrated in Fig. 4.2, which provides both a longitudinal view (on the left) and a transverse view (on the right) of the model. The x and y axes are the transverse horizontal and vertical directions, respectively, while z is referred to as the longitudinal direction, parallel to the motion of the circulating beam. The origin of the coordinate system $(0,0,0)$, circled in light blue, is located in the center of the main air gap junction between the focusing and defocusing half-units, defined as the $z = 0$ plane. From there, the open-pole half-unit (defocusing) is located on the positive semi-axis ($z > 0$), while the closed-pole (focusing) one on the negative side ($z < 0$). The $y = 0$ plane is located halfway the two

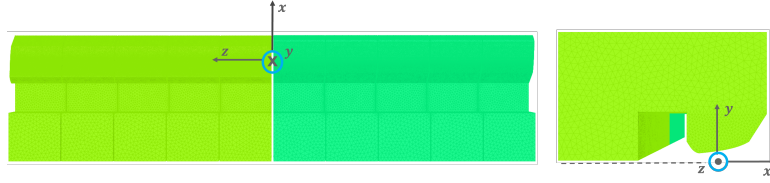


Figure 4.2. Longitudinal (on the left) and transverse (on the right) view of the MU magnetic model. Reference coordinate systems reported in gray, whose center $(0, 0, 0)$ is circled in light blue.

magnet poles, as indicated by the dashed line in Fig. 4.2. The magnet iron extends longitudinally from $z = -2.126$ m to $z = 2.134$ m, resulting in a total length of 4.26 m. In the transverse plane, the magnet boundaries span from $x = -0.76$ m to $x = 0.18$ m and from $y = 0$ to $y = 0.58$ m.

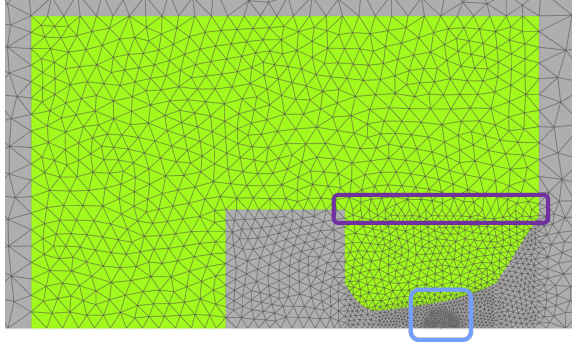
The model is enclosed within the far-field area surfaces, which define the boundaries of the model along the three axes as follows:

- Along the x -axis: $x = \pm 3.5$ m for the positive and negative x semi-axes, respectively;
- Along the y -axis: $y = 0$ m at the lower extremity and $y = 3.5$ m at the upper boundary of the vertical axis;
- Along the z -axis: $z = \pm 3.5$ m on the positive and negative z semi-axes, respectively.

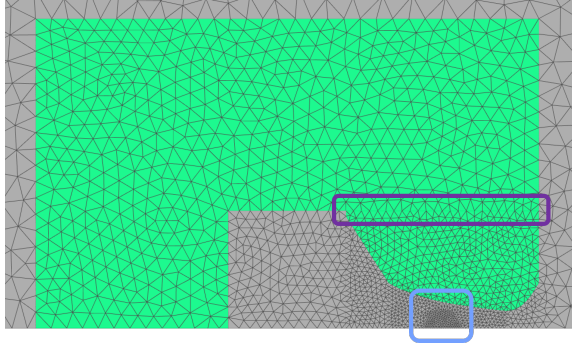
4.2.1 Meshing structure

In contrast to the quadrilateral meshing structure used in the pre-existing model, a new mesh based on tetrahedral elements is proposed. These elements perform better when dealing with multi-sided facets and surfaces [102, 129], as is the case with the PS-MU poles.

The new tetrahedral meshing structure consists of 6.27×10^6 mesh elements in the model volume, which is comparable to the number of elements in the quadrilateral mesh featuring the pre-existing magnetic model. As shown in Fig. 4.3, which presents the new meshing structure in the open-



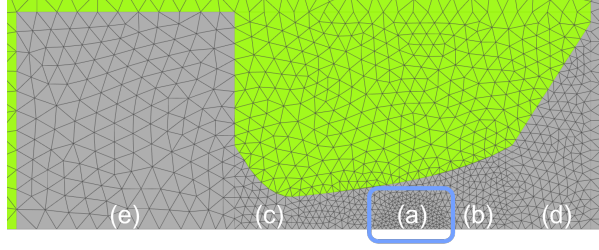
(a) Mesh in the open-pole block.



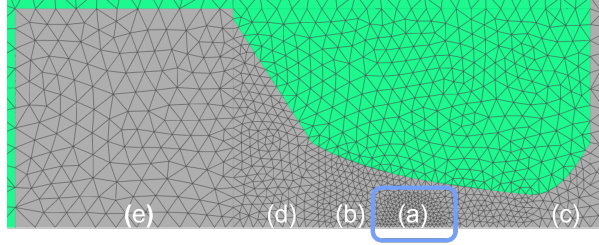
(b) Mesh in the closed-pole block.

Figure 4.3. New meshing structure of the PS-MU magnetic model. Coherent mesh density within the boundary region between pole and the rest of the yoke, highlighted in purple. Highest mesh density in a half-circumference of radius $R_{ref} = 35$ mm.

and closed-pole half-units (top and bottom, respectively), tetrahedral elements are applied to both the iron yoke and the magnet aperture. This new meshing approach offers a key advantage: it ensures a coherent connection between mesh elements in regions of the model that have different mesh densities. In particular, the interface area between the pole and the rest of the iron yoke, highlighted in purple in Fig. 4.3, is now free from the tiny-angle mesh elements that were present in the old structure, which could slow down the model's computation. By eliminating this issue, the new meshing structure increases the model's efficiency and accuracy.



(a) Mesh details in the pole and aperture in the open-pole block.



(b) Mesh details in the pole and aperture in the closed-pole block.

Figure 4.4. Details of the new meshing structure. Finest mesh in the half-circumference of radius $R_{ref} = 35$ mm (a). Lower mesh density in the area below the pole (b, c, d). Coarser mesh in the area where the main coils are located.

The proposed meshing structure is specifically optimized for harmonics computation within a reference radius (R_{ref}) of 35 mm. In fact, the highest mesh element density is concentrated in the magnet center, as highlighted in light blue in Fig. 4.3. This ensures precise harmonic calculations in the region traversed by the beam. A more detailed view of the new meshing structure within the magnet aperture is shown in Fig. 4.4. Inside the area delimited by the reference radius (a), the mesh elements are densely packed, while outside of it the mesh density decreases, maintaining good quality in the aperture (b, c, d). A coarser mesh is applied in the area where the main coil is located (e), since the field distribution in those areas do not affect heavily the harmonics computation for the optics studies in the aperture. This is demonstrated with the mesh sensitivity analysis reported in Subsection 4.2.3.

In Opera 3D, mesh density in each specific region of the model is con-

trolled by defining the Maximum Element Size¹ for that area, which governs the size of elements for surface and volume mesh generation [102]. The maximum element sizes for the different regions of the model are summarized in Table 4.1. This structured approach ensures a balance between accuracy in field prediction and computational efficiency, with finer elements where necessary for accurate field evaluation and coarser elements in less critical areas.

As discussed in the previous chapter, the pre-existing PS-MU magnetic model employed the same mesh density for both the closed and open pole faces, as illustrated in Fig. 3.3b, applied uniformly across the closed and open pole half-units. This meshing strategy resulted in unnecessary mesh domains within the model volume, contributing to increased computational demands. In contrast, the new meshing structure defines only one pole profile (either the closed or open one, depending on the half-unit). This design choice was another key factor in reducing computational load, as it significantly decreased the number of mesh domains within the model volume. In FE modeling simulations, the computational times largely depend on the number of mesh elements in the model volume. While there is no definitive formula for this dependence, it is generally accepted that simulation times scale linearly or with higher powers of the number

¹This parameter is dimensionless and serves as a scaling factor to adjust the dimensions of the mesh domains across the various cells of the model.

Table 4.1. Meshing structure maximum element size in the different areas of the model.

Magnet area	Maximum element size
Aperture - (a)	0.004
Aperture - (b)	0.007
Aperture - (c)	0.01
Aperture - (d)	0.01
Aperture - (e)	0.02
Pole	0.015
Iron yoke	0.3
Background	0.3

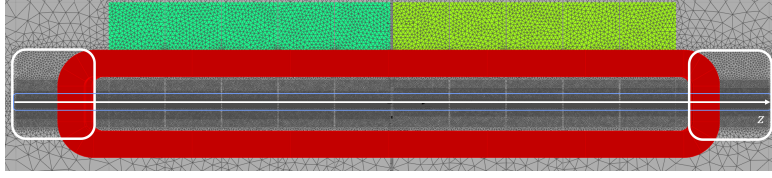


Figure 4.5. Longitudinal view of PS-MU magnetic model with the new meshing structure. High mesh density in the beam region (highlighted in orange) and at the fringe fields (areas highlighted in skyblue).

of mesh elements [130, 131]. Thus, the refined mesh is expected to notably reduce simulation times compared to the pre-existing model.

Mesh density at the fringe fields

As shown previously in Figs. 4.3 and 4.4, the new MU model incorporates a high-density mesh in the central transverse region of the magnet (highlighted in light blue). However, given the emphasis in the new optics model to the longitudinal distribution of the quadrupole field across the MU, including the fringe fields, a sufficiently dense mesh was required at the magnet extremities. As shown in Fig. 4.5, providing a longitudinal view of the new model, a fine mesh is generated outside the MU iron (regions highlighted in white) to ensure accurate computation of higher-order harmonics in the fringe fields. The longitudinal extremities of the regions used for fringe field computation are determined based on the requirement to capture fields down to the one per mill level. After examining the longitudinal evolution of the fringe fields at various current levels, it was determined that the fringe fields drop below the one per mill threshold beyond $z = \pm 2.8$ m in the two half-units.

Observations and outcome

The introduction of the new tetrahedral meshing structure adapted better to the complicated shape of the MU's pole than the meshing structure used in the pre-existing model, which was based on hexahedral elements. This change helped avoid the creation of small-angle mesh elements that could dramatically slow down the FE analysis. Additionally, the high-density mesh in the closed/open pole regions was removed where it was

unnecessary. This rendered the MU magnetic model significantly lighter, more manageable, and substantially more time-efficient. Specifically, the time required to complete a bare-machine simulation was drastically reduced to approximately 6 hours. A quantitative comparison of the simulation times for the pre-existing and the new refined magnetic model, performed both simulations under the same powering conditions, with a main coil current of approximately 2 kA, and using the same machine, revealed that the new model resulted in an eight-fold reduction in simulation time, from 55 hours with the old model to 7 hours with the new.

It is important to emphasize that this significant gain in computational efficiency was not achieved by drastically reducing the number of mesh elements. Rather, it was driven by the strategic selection of tetrahedral mesh elements and the careful placement of high-density domains only where necessary throughout the model. This approach ensured that the model maintains a high level of detail and accuracy, particularly in critical regions affecting beam dynamics, while significantly reducing the computational load.

The time efficiency of the new magnetic model represents a relevant advancement for operation, as it significantly enhances the models' predictive capability for decision-making processes (setup of new cycles, Machine Development preparation, adaptive learning applications), aiming to optimize performance of the machine [132, 133].

4.2.2 Field harmonics computation

Field harmonics were computed in Opera using two distinct approaches. The first approach involves calculating harmonics along a circumference of reference radius in the transverse $x - y$ plane at a specific location along the z -axis. This circumference is discretized into multiple points (for example, 360 points corresponds to a discretization of one point per degree) and then shifted to a different longitudinal position. This procedure enables harmonics computation at two distinct planes along the z -axis, each referenced to the same radius. By iteratively shifting the circumference along the longitudinal direction, harmonics can be tracked as they evolve along the length of the MU, providing a harmonic profile as a function of z . The harmonics computation was carried out within the range of ± 2.8 m to account for the multipolar fields present in the fringe regions.

Following this integration method, Fig. 4.6a, 4.6b and 4.6c display the integrated dipolar (B_1), quadrupolar (B_2), and sextupolar (B_3) field components, respectively, as a function of longitudinal position z at varying main coil currents I_{MC} , referred to a reference radius of 35 mm. Observing the red, orange, and green curves, which represent low to medium currents, it is evident that the dipole field remains relatively stable across the length of the MU, with the curves appearing nearly flat except at the air gap locations. In these areas, the absence of iron results in a noticeable field drop, which is more pronounced in the defocusing half-unit (positive z) than in the focusing unit (negative z), due to the larger air gap in the defocusing section. The blue curves represent the highest current used in this analysis, 4443 A, and display a noticeable variation in field harmonics within the extremity blocks compared to the core regions of the half-units. This variation arises from the more rapid saturation of iron in the fringe fields relative to the central body of the half-units. In Fig. 4.6b, the quadrupolar field changes sign at the F/D transition zone (at $z = 0$) and exhibits field drop at the air gap location and faster saturation at the magnet extremities at high currents, similar to what has been observed for the dipolar field. The sextupolar component, shown in Fig 4.6c, exhibits pronounced peaks at the fringe fields and within the F/D transition area.

Field harmonics computation for optics simulations

As it will be explained later in Section 4.3, the various regions of the MU (such as the main bodies of the half-units, fringe fields, etc.) are represented by distinct elements in the beam optics simulation tool. Each element in this model requires an assigned integrated magnet strength k_n . While the above integration method allows for the analysis of harmonic evolution at specific longitudinal positions z , it is not directly suitable as input for the optics code. This limitation arises because harmonics computed at a single z -plane do not account for longitudinal field variations. For instance, calculating harmonics in a plane situated within the iron core would ignore the field drop in the adjacent air gap.

To deliver integrated harmonics that capture field variations along the longitudinal axis, the field is integrated over a cylindrical surface with a reference radius of $R_{ref} = 35$ mm, and harmonics are presented in Tesla units. This cylindrical surface is centered in the transverse plane (at $x = 0$,

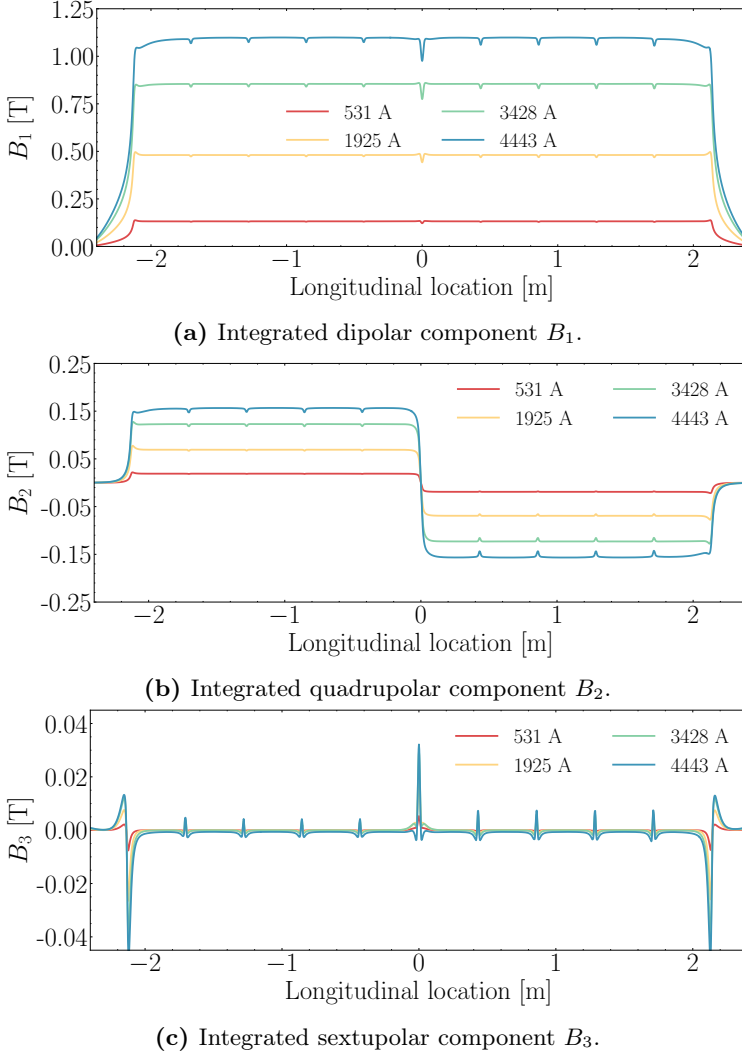


Figure 4.6. Integrated dipolar (top), quadrupolar (middle) and sextupolar (bottom) components as a function of the longitudinal direction z at different I_{MC} .

$y = 0$), while the cylinder's longitudinal boundaries, z_{beg} and z_{fin} , which defines its length, are adjusted based on the region of interest for each

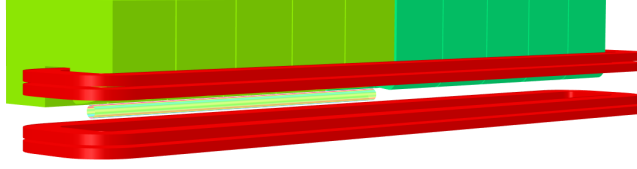


Figure 4.7. Field harmonics computation within a cylindrical surface of radius $R_{ref} = 35$ mm within one half-unit. Focusing and defocusing half-units illustrated in dark and light blue, respectively, main coil depicted in red.

integration. Fig. 4.7 illustrates the MU model, with the focusing and defocusing half-units depicted in dark and light green, respectively, and the main coil in red. It provides an example of field harmonics computation along a cylindrical surface within the defocusing half-unit.

4.2.3 Mesh sensitivity analysis

A crucial step in finite-element modeling is the assessment of the model sensitivity to the number of mesh elements. In fact, in finite-element simulations, a balance between accuracy and computational efficiency is essential, especially for models involving field harmonics computation. An overly coarse mesh may not resolve significant field gradients, causing inaccuracies, while an excessively fine mesh can increase computation time without substantial accuracy gains. If the computational load is reduced, yet the computed harmonics shift or vary significantly, it indicates that the model requires a finer mesh to reliably capture the field harmonics. Thus, the mesh sensitivity analysis allows to determine the minimum mesh density that ensures stable harmonic values, confirming that the model will provide accurate and reproducible results for beam optics calculations without unnecessary computational expense.

A mesh sensitivity analysis was conducted on the new PS-MU magnetic model to assess the accuracy of the simulation results relative to mesh granularity. To perform this analysis, a scaling parameter, k_m , was introduced to uniformly adjust the maximum element sizes specified in Table 4.1. For instance, setting $k_m = 1.1$ increases the maximum element size of each cell by 10 %, reducing the overall number of elements in the model volume and, consequently, the computational load and simulation times. To evaluate

the model sensitivity on the number of meshing elements, the analysis has been performed with a fixed main coil current of 1925 A, corresponding to a beam energy of 10.14 GeV/c. Table. 4.2 reports, for different value of k_m , the number of mesh domains in the model volume n_e , the simulation time t_s , and the integrated quadrupole in the different MU regions. Field integration was carried out, in each magnet area, along a cylindrical surface or radius 35 mm, as previously described. The table shows that, for a specific MU region, the variation in the quadrupolar component at different values of k_m is on the level of 0.3 %. This indicates that the computation of the simulated quadrupole generated by the MU is not significantly sensitive to the number of mesh elements. Similarly to Tab 4.2, Tab. 4.3 refers to the integrated sextupole in the different MU areas, ranging k_m . As observed with the quadrupole, the sextupole component also exhibits low sensitivity to the number of mesh elements in the model, with largest relative variation of the level of 0.8 %.

In the three cases presented for the mesh sensitivity analysis, the new optics model, described in detail in Section 4.3, was employed to evaluate the variation in predicted tunes with respect to the mesh. Tab. 4.4 reports

k_m	$n_e [\times 10^6]$	t_s	B_2 [mT]			
			F-core	D-core	F-Fringe	D-Fringe
1	6.27	6h 30'	6.892	-6.894	0.293	-0.302
1.1	4.98	5h 30'	6.892	-6.894	0.294	-0.303
1.2	4.00	3h 15'	6.892	-6.894	0.294	-0.302

Table 4.2. Mesh sensitivity analysis for the quadrupolar component B_2 scaling down the mesh density.

k_m	B_3 [mT]			
	F-core	D-core	F-Fringe	D-Fringe
1	-0.01938	-0.01982	0.04726	0.04796
1.1	-0.01941	-0.01983	0.04706	0.04806
1.2	-0.01941	-0.01966	0.04720	0.04796

Table 4.3. Mesh sensitivity analysis for the quadrupolar component B_3 scaling down the mesh density.

the simulated horizontal and vertical tunes corresponding to the different values of the k_m parameter. The tune variation was below the 10^{-3} level in both planes. These indicated minimal sensitivity of the predicted tunes to the number of mesh elements.

This demonstrated the robustness of the models' predictions with respect to the number of mesh domains. However, to provide the most accurate higher order field harmonic values for the optics model, the configuration with $k_m = 1$ was selected for the optics simulations².

4.2.4 Model validation against magnetic measurements

Before integrating the field harmonics from the new PS-MU magnetic model in the optics model for beam dynamics predictions, the new magnetic model has been benchmarked against magnetic field measurements. Magnetic models are generally validated through magnetic measurements to ensure that the theoretical predictions accurately reflect the real-world behavior of the magnets as simulations may involve idealized assumptions or simplifications that do not fully capture the complexities of physical magnets, such as fringe fields, minor material imperfections, or thermal effects [18]. Magnetic measurements help to identify and correct discrepancies, enhancing the model's accuracy and reliability. When the magnet design must meet strict tolerance requirements (common in high-energy

²The accuracy of the magnetic model is driven by the sensitivity of the field harmonics components on the mesh density, as reported in Tabs. 4.2 and 4.3 for the quadrupolar and sextupolar components, respectively. In the initial stages of this research, the possibility of predicting the second and higher-order chromaticity components was considered. Therefore, to adopt a conservative approach, the finest mesh configuration with $k_m = 1$ was chosen. However, if the analysis is limited to tune and first-order chromaticity predictions, coarser mesh configurations may be sufficient.

k_m	Q_x	Q_y
1	6.2557	6.2750
1.1	6.2559	6.2757
1.2	6.2562	6.2756

Table 4.4. Horizontal and vertical tune variation with mesh sensitivity analysis parameter k_m .

accelerators) validation through measurements reduces uncertainties and provides confidence that the model can support critical operations without failure. This Subsection presents the comparison between magnetic measurements and predictions from the new magnetic model.

B-train measurements vs model's predictions

During the beam-based measurements, which will be introduced and discussed extensively in Chapter 5, measured currents in the main coil I_{MC} and B-train field measurements (B_{meas}) are available for users to download, and are reported in Table 4.5. Measured currents were used as input for Opera simulations to compare the model with the measurements.

Considering the B-train coil bars dimensions and their location in the MU described in Section 2.2, field integrals have been computed in Opera on B-train-like surfaces, returning the surface integral $\oiint B dS$. Being the area of the B-train bars A_b known, the simulated B-train-like field B_{sim} in unit of T can be obtained by simple division from the surface integral as:

$$B_{sim} = \frac{\oiint B dS}{A_b} \quad (4.1)$$

B-train-like simulated fields at different values of I_{MC} are reported in Table 4.5³, alongside the difference between the measured and simu-

³Simulated data from the pre-existing PS-MU model are excluded from the analysis due to its time inefficiency, which precluded performing large number of simulations.

Table 4.5. Comparison between B-train measured field B_{meas} and B-train-like simulated field B_{sim} at different Main Coil currents I_{MC} .

I_{MC} [A]	B_{meas} [T]	B_{sim} [T]	ΔB [mT]	$\Delta B/B_{meas}$ [%]
531	0.1329	0.1320	0.9	0.67
998	0.2500	0.2487	1.3	0.52
1329	0.3332	0.3314	1.8	0.54
1925	0.4827	0.4803	2.4	0.50
2668	0.6684	0.6655	2.9	0.43
3428	0.8570	0.8537	3.3	0.39
4443	1.1000	1.0965	3.5	0.32

lated fields (ΔB) and the percentage relative difference with respect to the measurements ($\Delta B/B_{meas}$). The comparison demonstrates a strong agreement between the magnetic measurements and the model predictions, with discrepancies consistently on the order of mT throughout the entire current range, and a relative difference below 1 %. Notably, the relative error decreases as the current increases, highlighting the robustness of the model at higher operational currents. This close alignment between the simulation and experimental data underscores the reliability and accuracy of the new magnetic model.

Although minor differences exist, they fall within the accepted 1% limit. Several factors could account for these slight deviations. Firstly, the contribution of the remanent field is not accounted for in the current model, as explained in Subsection 3.2.2. To evaluate the effect of the remanent field on the MUs, dedicated magnetic measurements have been conducted [12]. These measurements indicated that the remanent field remains relatively constant along the longitudinal axis z , while showing a slight sensitivity to the transverse position. Overall, a remanent field between 1.4 mT and 3.2 mT was measured after precycling the current from 0 A to 5000 A. The measured range of remanent field aligns with the observed discrepancies ΔB between the model and the experimental data, suggesting that the remanent field may account for significant contribution on the difference. Additionally, the typical uncertainties inherent in magnetic measurements could also contribute to the residual discrepancies in this comparison. Ultimately, the magnet curvature or slight misalignments of the B-train bars from their theoretical position might also explain the slight difference between measurements and model's predictions.

4.3 New MU optics model

In Section 3.3, the analysis of the pre-existing effective optics model of the PS-MU highlighted its empirical nature. Specifically, the model relied on tuning the quadrupolar and sextupolar components in the SBENDs to match beam-based measurements (such as tune and first-order chromaticity) or specific operational working points. However, this approach did not account for predicting the dependence of beam optics on energy or other operational scenarios. This limitation highlighted the necessity for a new

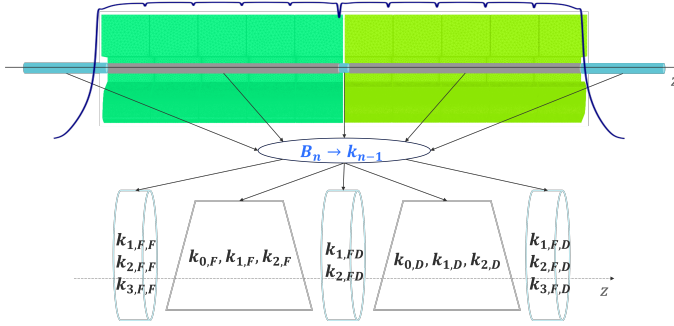


Figure 4.8. Description of the new MU optics model in MAD-X.

optics model that adopts a different approach compared to the pre-existing matched optics model of the MU.

4.3.1 From magnetic to optics model

The new optics model, used for the beam dynamics predictions reported in this thesis, rather than defining magnet strengths to align with beam-based measurements, is based on predicted harmonics derived from the new Opera model.

Figure 4.8 shows how the new magnetic and optics models are linked between themselves. Specifically, integrated field harmonics B_n evaluated at a reference radius are computed in Opera throughout cylindrical surfaces, as discussed in Subsection 4.2.2. These are later converted into magnet strengths k_{n-1} , using Eq. 1.23. Harmonics computed in the two half-units cores (gray cylinders) are incorporated in the SBENDS in MAD-X; by contrast, those computed at the fringe fields and in the F-D transition area (turquoise cylinders) are incorporated in the MULTIPOLE elements.

Thus, the structure of the MU optics model, illustrated on the bottom in Fig. 4.8, was modified with respect to the MAD-X construct of the pre-existing model, showed in Fig. 3.5. The new optics model includes quadrupolar component in the *MULTIPOLES* at the extremities of the magnets and in the F/D transition area ($k_{n,F,F}$, $k_{n,F,D}$ and $k_{n,F,D}$, respectively). While the pre-existing model concentrated the global quadrupolar component generated by the MU within the two SBENDS, the modification introduced aims to account for the longitudinal distribution of the

field, particularly in the fringe fields and the F/D transition region, to better align with the machine optics. The integration lengths in the two half-units cores are computed as following:

$$\begin{cases} L_{i,F-core} = n_b \cdot l_b + n_{air} \cdot l_{air,F} \\ L_{i,D-core} = n_b \cdot l_b + n_{air} \cdot l_{air,D} \end{cases} \quad (4.2)$$

where $n_b = 5$ and $l_b = 0.417 \text{ m}$ are the number of iron blocks per half-unit and their length, respectively, $l_{air} = 4$ is the number of air gaps between consecutive blocks within the same half-unit, and $l_{air,F}$ and $l_{air,D}$ is the length of these air gaps, specified in Section 2.1:

$$\begin{cases} L_{i,F-core} = 0.417 \cdot 5 + 0.00775 \cdot 4 = 2.116 \text{ m} \\ L_{i,D-core} = 0.417 \cdot 5 + 0.00975 \cdot 4 = 2.124 \text{ m} \end{cases} \quad (4.3)$$

As detailed previously in this chapter, the coordinate system's origin in the magnetic model is positioned at the longitudinal center of the F/D transition area's air gap, which spans 0.02 m, ranging from $z = -0.01 \text{ m}$ to $z = 0.01 \text{ m}$. This defines the integration length within the transition region. The extremities for the fringe field calculations are set at $z = \pm 2.8 \text{ m}$. Consequently, the integration lengths for the fringe fields are:

$$\begin{cases} L_{i,F-fringe} = -2.8 - (-2.116) - (-0.01) = 0.674 \text{ m} \\ L_{i,D-fringe} = 2.8 - 2.124 - 0.01 = 0.667 \text{ m} \end{cases} \quad (4.4)$$

Table 4.6 summarizes the integration length in the different MU regions.

Table 4.6. Integration length L_m in the different region of the MU model.

MU region	$L_{int} \text{ [m]}$
F core	2.116
D core	2.124
F fringe	0.674
D fringe	0.667
F/D	0.02

Beam-based measurements for models validation

The goal of this thesis is to develop predictive magnetic and optics models of the main magnetic units in the PS, including prediction of the energy dependence of the optics in the machine, to support operation and beam dynamics studies. The validity of the models is contingent upon how closely their approximations align with real-world conditions. In the previous chapter, the validation of the magnetic model against magnetic measurements was shown. However, the ultimate figure of merit is the predictions of the beam parameters in the machine through the combined optics and magnetic models of the MU. Hence, to effectively benchmark the new magnetic and optics models and validate their numerical predictions, a comprehensive series of beam-based measurements were conducted.

The validation of the models with experimental data is particularly challenging, as it relies not only on the approximations inherent in the two models but also on the accuracy of the beam-based measurements. Beam-based measurements may be influenced by time-dependent dynamic effects, such as eddy currents generated by varying magnetic fields during operation. At the outset of this work, it was unclear whether the harmonic distortions caused by eddy currents were critical for beam-based measurements, which posed a key problem to address.

Magnet hysteresis is a crucial factor in beam dynamics across the entire energy range. At low energies, remanent fields can influence the main field

within the magnet aperture, while at higher energies, iron saturation may introduce non-linear effects. These hysteresis-driven variations highlight the need for careful consideration of both low- and high-energy regimes in predictive modeling and operational tuning.

The chapter begins with a detailed description of the experimental setup and methodologies employed in conducting the beam-based measurements, reported in Section 5.1. The main optics parameters of interest for the models validation are highlighted, as well as their importance in the context of the performance of the accelerator. Section 5.2 outlines the motivation and objectives behind performing beam-based measurements in the bare-machine configuration, characterized by the deactivation of auxiliary circuits (F8L and PFW). Preliminary measurements conducted at the injection energy (2.79 GeV/c) are also presented. To address the PS operational requirements of working at higher energies (beyond 26 GeV/c), the beam momentum was progressively increased through the implementation of dedicated bare-machine power cycles. Beam losses prevented to go above 23.11 GeV/c because of tunes hitting resonances, as discussed in Section 5.3. The importance of monitoring and controlling the beam MRP to achieve accurate measurements for model benchmarking is discussed in Section 5.4.

Operationally, the F8L and PFW circuits are essential for tune and chromaticity control. Thus, to benchmark the models' response to each auxiliary circuit, F8L and PFW were powered individually (with the main coil) during the measurements to evaluate the response of beam corresponding to each circuit. The measurements with the F8L and PFW circuits are presented in Sections 5.5 and 5.6, respectively. Ultimately, the actual operational configuration of these circuits involves the complex simultaneous powering of multiple circuits. These additional complexities are examined in Section 5.7.

5.1 Measurements setup and methodology

Tune measurements presented in this Chapter were acquired with the Long BBQ system and Q-meter tool, which were introduced in Section 2.2 and Section 2.3, respectively. Accurate tune measurements and their real-time monitoring were ensured by means of carefully selected FFT settings

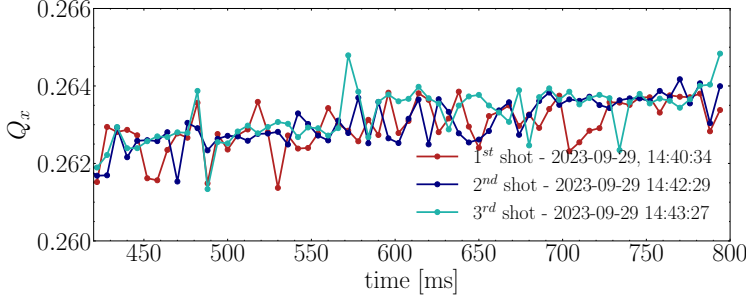


Figure 5.1. Horizontal tune measurements at 10 GeV at $t = 1200\text{ms}$.

in the Q-meter application. To obtain a clean FFT spectrum, the optimal configuration involved performing FFT analysis with a resolution of 2048 to 4096 turns, acquiring measurements every 7 ms from the beam injection.

Tune measurements were acquired over multiple shots (repetitions of the specific machine-cycle being studied) aligning with the repetition of the supercycle. Fig. 5.1 illustrates an example of three horizontal tune measurements taken at each time step at constant energy (corresponding to PS injection) and a stable machine and super-cycle configuration. These three sets of measurements correspond to three consecutive repetitions of the supercycle. A shot-to-shot tune jitter can be seen identified in Fig 5.1. Typically under stable machine conditions it was found that such variations were limited to approximately $\Delta Q \leq 3 \cdot 10^{-3}$. The upward trend in the data is attributed to MRP variations, discussed later in the chapter.

To minimize the impact of shot-to-shot jitter in the tune measurements across supercycle repetitions, a strategy involving multiple acquisitions was implemented. Specifically, it was found that collecting between 10 and 20 measurements (N) at each time step, which correspond to approximately 20 minutes of acquisitions, provided sufficient statistical averaging as taking considerably more acquisitions did not significantly change the mean and standard deviation (on the level of $10^{-3} - 10^{-4}$). The rationale behind this approach is rooted in the nature of shot-to-shot variability, which introduces fluctuations in the measured tune values due to small changes in machine conditions, such as power supply stability or environmental factors. By acquiring multiple measurements and averaging the results, the random fluctuations tend to cancel out, reducing the overall standard

deviation in the tune value, ensuring accurate and reproducible tune measurements throughout the supercycle repetitions.

When considering tune variation with cycle time, at each time step t_i , data from the shot-by-shot acquisitions were averaged to produce a globally averaged measurement $Q(t_i)$ at t_i :

$$q(t_i) = \frac{\sum_{k=1}^N Q_k(t_i)}{N} \quad (5.1)$$

where $Q_k(t_i)$ represents the measured tune value at given time t_i for each individual shot. Including the standard deviation $\sigma_q(t_i)$ which accounts for the spread in the averaged tune values over the multiple acquisitions at $t = t_i$, the measured tune at a given time can be expressed as:

$$Q(t_i) = q(t_i) \pm \sigma_q(t_i) \quad (5.2)$$

In addition to the shot-to-shot jitter, measurements can exhibit jitter and drifts in time (for example, as seen in Fig. 5.1). Under typical stable measurement conditions the magnitude of the time-jitter is generally comparable to the shot-to-shot variability ($\Delta Q \leq 3 \cdot 10^{-3}$). Since the primary purpose of this thesis is the benchmarking of the magnetic and optics models' predictions against beam-based measurements, often a single representative tune value is considered for a specific energy and machine configuration. In this case therefore, tune variation at a given energy was also averaged over time to define one measured value:

$$Q(p_0) = \frac{\sum_{t_0}^{t_f} Q(t)}{M} \pm \sigma_q(p_0) = q_{av}(p_0) \pm \sigma_q(p_0) \quad (5.3)$$

where M is the number tune samples at given momentum p_0 from $t = t_s$ to $t = t_f$. $\sigma_q(p_0)$ is the standard deviation accounting for both sources of uncertainty, the shot-by-shot jitter and the tune evolution jitter.

Chromaticity measurements: setup and data processing

In addition to the parameters defined to carry out tune measurements described earlier in this section, chromaticity measurements require additional settings that can affect the quality of the data.

Horizontal and vertical chromaticity measurements are conducted by

generating a momentum offset dp/p_0 induced via the RF system, where p_0 represents the nominal beam momentum at a given time t , and measuring the corresponding tune variations in the horizontal and vertical planes. Operationally, the Q-meter application enables to define the boundaries of the dp/p_0 scan by specifying a range of variation for the beam MRP:

$$[r_{pos_{min}}, r_{pos_{max}}] \rightarrow [-(dp/p_0)_{min}, (dp/p_0)_{max}] \quad (5.4)$$

A wider dp/p_0 variation enhances the accuracy of higher-order chromaticity estimations; however, it may induce significant tune changes or dispersive orbit shifts, potentially leading to beam losses. Significant beam-loss during the chromaticity measurement is undesirable, as it can degrade the tune measurement quality. It was determined that an r_{pos} excursion ranging from -10 mm to 10 mm relative to the initial value r_{pos_0} was sufficient to reliably capture the evolution of the first-order chromaticity while effectively minimizing beam losses in typical configurations under study. Thus:

$$r_{pos_{min}} = r_{pos_0} - 10; \quad r_{pos_{max}} = r_{pos_0} + 10; \quad (5.5)$$

This maximum r_{pos} excursion corresponded to a maximum momentum offset, relative to the nominal momentum p_0 , of approximately $\frac{\delta p}{p_0} = 3 \times 10^{-3}$.

To achieve reliable results, the number of data points acquired at each predefined momentum offset step $(dp/p_0)_i$ was evaluated. It was determined that 3 data points at 10 different momentum offset step provide sufficient accuracy for chromaticity measurements.

Upon completion of the r_{pos} (or, equivalently, dp/p_0) scan, the measured chromaticity at a given time t_i is obtained by fitting the tune measurements versus $\Delta p/p_0$. Two polynomial function of order 1 or 2 were employed for this fitting, enabling the extraction of first-order and second-order chromaticities. Fig. 5.2 depicts an example of horizontal and vertical chromaticity measurements on the left and right plots, respectively. The blue and red circles represent the measured tunes corresponding to the respective momentum offsets. These data points are interpolated using a linear function, $y = mx + q$, illustrated by the dashed turquoise curve on the left and the orange dashed curve on the right. Here, the slope m

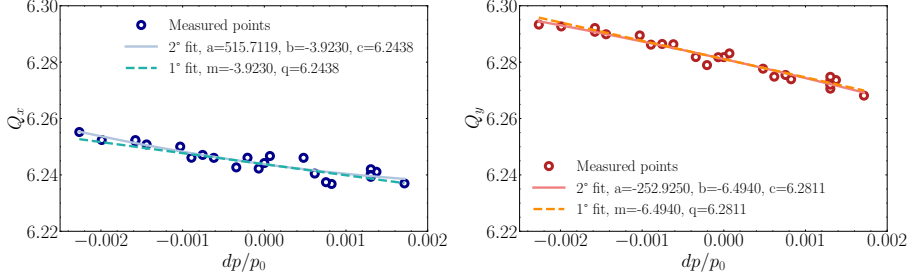


Figure 5.2. Horizontal (left) and vertical (right) chromaticities measurements at 10 GeV at $t = 1200ms$.

reflects the chromaticity $Q'(t_i)$ at a given time t_i , while the intercept q denotes the measured tune at zero momentum offset. In case of a significant second-order chromaticity a standard second-order parabolic fitting, expressed as $y = ax^2 + bx + c$, can instead be utilized to estimate the first- and second-order chromaticities, described by the parameters b and a . The parabolic fit of the measured points yields the light blue and light red curves in Fig. 5.2, showing the presence of a very slight second-order chromaticity component in both planes. While it is true that higher-order polynomial fits can artificially improve the goodness of fit by capturing random noise (i.e., overfitting), this risk is mitigated in this analysis by the fact that, in accelerator physics, second-order chromaticity can arise from non-linear magnetic fields. Therefore, the use of a second-order fit is not merely a mathematical choice but is supported by the physics of the system. Additionally, the extracted first- and second-order chromaticity values were evaluated for consistency with expectations based on the machine configuration, including the activation of additional circuits and saturation conditions. Furthermore, as shown in the example in Fig. 5.2, the linear term does not change meaningfully by introducing the second order term. These aspects reinforce the validity of the second-order fit, suggesting that the observed slight curvature is due to genuine second-order chromaticity rather than overfitting to noise.

The Q-meter application repeats this measurement process at each time step t_i throughout the power cycle under investigation, thereby providing the evolution of chromaticity along the machine cycle.

To define the chromaticity values for benchmarking, the measured chro-

maticity at a specific momentum was averaged vs time, yielding a single representative value of chromaticity $q'_{av}(p_0)$, at that energy level. A standard deviation, denoted as $\sigma_{q',av}(p_0)$, is associated to the averaged measured chromaticity $q'_{av}(p_0)$ to quantify the variability across the portion of the power cycle at momentum p_0 . The final chromaticity measurement at the energy p_0 is expressed as:

$$Q'(p_0) = q'_{av}(p_0) \pm \sigma_{q',av}(p_0) \quad (5.6)$$

5.2 Beam-based measurements in bare-machine

Following the measurement procedures outlined in the previous section, this section describes the beam-based measurements conducted on PS bare-machine cycles. The aim was to benchmark the effect of the MU in the machine and provide a consistent dataset of experimental data that can be utilized for the validation of the MU models.

The bare-machine is a particular PS configuration consisting in only powering the main coil, with no activation of the auxiliary circuits. The aim of conducting measurements on bare-machine cycles was to isolate, as much as possible, the effect of the MU on the machine optics, enabling an effective benchmarking of the MU models. As discussed in Chapter 2, the PS ring is equipped with various additional corrector magnets. In preparing the bare-machine cycles all additional corrector magnets around the ring were also deactivated during the beam-based measurements. This prevented any interference from these additional magnets, which could otherwise affect the measurements. In fact, by ensuring that the circulating beam was influenced exclusively by the MU, the models' predictions could be accurately assessed without the confounding effects of other magnets present in the ring.

Beam-based measurements were initially conducted in a bare-machine configuration on a flat cycle (without any ramp) at 2.79 GeV/c (injection energy), and are presented in Subsection 5.2.1. However, the PS consistently operates in a saturated regime up to approximately 26 GeV/c. Thus, operational requirements necessitate the consideration of higher energies beyond 2.79 GeV/c, particularly for studying the effects of saturation on the machine optics. To address this, dedicated bare-machine power

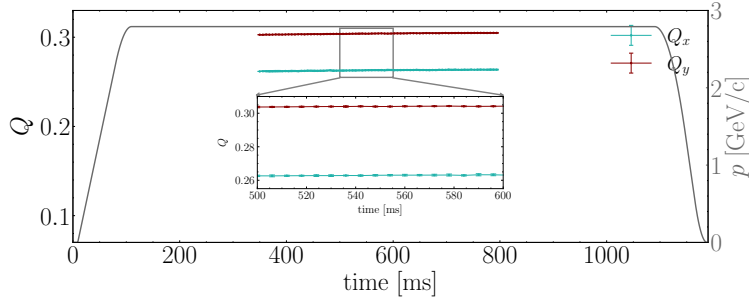


Figure 5.3. Horizontal and vertical tune measurements on the flat-cycle at injection energy (2.79 GeV).

cycles were specifically designed, enabling beam-based measurements in the bare-machine configuration at progressively higher energies. These measurements, along with the associated key challenges, are presented in Subsection 5.2.2. The bare-machine beam-based measurements were ultimately limited to 23.11 GeV/c. Beyond this energy, increased beam losses were observed due to the tunes approaching the integer resonance, as will be shown in the next section.

5.2.1 Measurements on flat-cycle at injection energy

The measured horizontal (Q_x) and vertical (Q_y) tunes throughout the bare-machine flat-cycle at injection energy are reported in Fig. 5.3 in turquoise and red, respectively. The power cycle is depicted in gray and corresponds to the scale on the right¹. Tunes were observed to be very stable, with excellent shot-to-shot reproducibility, as evidenced by the small error bars associated with each acquisition, which can be appreciated in the inset window within the plot. The maximum standard deviation from the multiple acquisition ($\sigma_{t_i, max}$), relative to the average value, was on the level of 0.2 %. Furthermore, it can be observed that, on the flat-cycle at injection energy, tune evolution is stable throughout the cycle in both planes.

¹Although the y-scale appears large for these specific measurements, it has been intentionally kept this way to maintain consistency with subsequent figures, facilitating a coherent comparison across different sets of measurements.

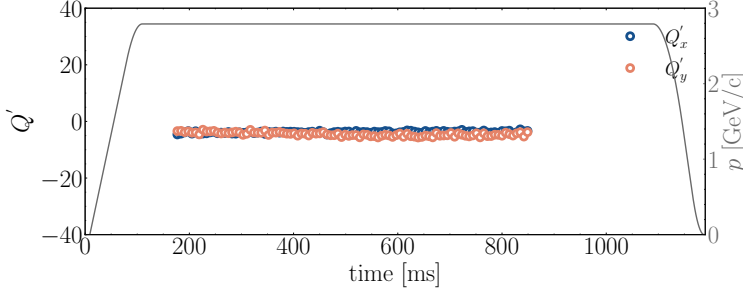


Figure 5.4. Horizontal and vertical first order chromaticity measurements on the flat-cycle at injection energy (2.79 GeV).

Figure 5.4 presents the horizontal and vertical first-order chromaticity measurements throughout the injection energy flat cycle, shown in blue and orange, respectively. The chromaticity was observed to be negative in both planes. Similar to what was observed for the tune measurements, the chromaticity exhibited excellent stability on both planes on the flat cycle, with maximum relative standard deviation below 10 %.

These results demonstrate the feasibility of conducting beam-based measurements in the bare-machine configuration. Furthermore, the measurements revealed excellent shot-to-shot reproducibility and a stable evolution throughout the flat cycle at injection energy, providing a first set of data for benchmarking the MU models' predictions.

5.2.2 Beam-based measurements at higher energies

To meet the operational need for predicting the energy dependence of the optics and investigate the effects of saturation on beam dynamics, multiple bare-machine power cycles were developed. Creating bare-machine power cycles, ensuring limited beam losses, was challenging due to the machine setup itself, as discussed earlier in the section. Thus, progressively higher energy power cycles were tested iteratively.

Figure 5.5 illustrates, as an example, the beam momentum throughout a bare-machine power cycle that includes a plateau at 10.14 GeV/c, plotted in gray as a function of time. The beam is injected at $t = 170$ ms, where the beam momentum is set to 2.79 GeV/c (indicated by the green dot). Following this, there is an initial ramp-up to a plateau at 3.90 GeV/c,

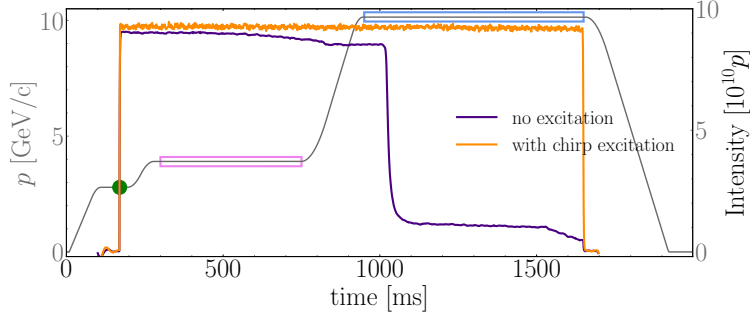


Figure 5.5. Bare-machine power cycle with a plateau at 10.14 GeV/c in gray, beam intensity evolution throughout the cycle without excitation in purple and with excitation in orange.

which is highlighted in violet. This is succeeded by a longer ramp-up to the final plateau at 10.14 GeV/c, marked in blue. Tab. 5.1 provides a summary of the bare-machine power cycles employed for beam-based measurements, aimed at benchmarking the models. For each cycle, the momentum plateau p_0 , main coil current I_{MC} , and measured field B_{meas} from the B-train are reported. The maximum momentum plateau reached in bare-machine configuration, ensuring the beam remained circulating stably, was 23.11 GeV/c. Above this value, significant beam losses were observed, due to the tunes crossing integer resonances, as it will be detailed in Section 5.3. The carefully structured power cycles were designed to allow for stable beam conditions, essential for accurate optics measurements under varying energy levels.

Addressing challenges in driving beam oscillations

Approaching higher energies, the initial optics measurements performed in the bare-machine configuration revealed a significant issue: when considering cycles above transition-energy (which occurs at 6.12 GeV) the beam failed to survive the main ramp, thereby precluding the possibility of performing measurements on the energy plateau. In addition to the beam momentum, the purple curve in Fig. 5.5 illustrates a typical example of the observed evolution of the beam intensity throughout the bare-machine cycle, showing that the beam consistently experienced loss at the end of

the ramp. To address this issue, it was found that a brief excitation at low energy (prior to the ramp), either by briefly pulsing the chirp or exciting with the AC dipole, enabled the beam to survive the ramp, as demonstrated by the orange curve. This phenomenon was consistently observed across different shots and various power cycles. This mechanism might be associated with emittance blow-up resulting from the excitation, which could help to suppress beam instability at the end of the ramp. Tune measurements on the bare-machine cycles were performed by exciting the beam with chirp signal, whose strength and frequency range were essential to identify the betatron frequency in the spectrum. The chirp parameters, including its amplitude and frequency range, were dynamically adjusted to suit the power cycle, machine configuration, and specific beam energy.

Tune measurements

Figure 5.6 illustrates examples of measured horizontal and vertical tunes in turquoise and red, respectively, across bare-machine power cycles, reported in Tab. 5.1. Tune measurements throughout the cycle with the 10.14 GeV/c plateau are reported on the left, those across the power cycle to the 18.00 GeV/c plateau on the right. Some common features were observed in the tune evolution with the different power cycles. Significant tune-shifts were observed at both the beginning and end of the ramp. This shift can be attributed to the abrupt changes in the magnetic field during

Table 5.1. Power cycles employed for beam-based measurements. Plateau energy, measured main coil current I_{MC} and B-train field B_{meas} on each cycle's plateau.

p_0 [GeV/c]	I_{MC} [A]	B_{meas} [T]
2.79	531	0.1329
5.25	998	0.2500
7.00	1329	0.3332
10.14	1925	0.4827
14.04	2668	0.6684
18.00	3428	0.8570
23.11	4443	1.1000

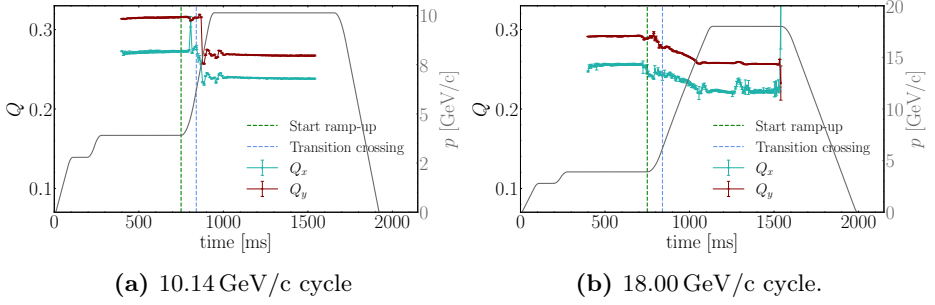


Figure 5.6. Horizontal and vertical tune measurements on the individual bare-machine cycles in turquoise and red, respectively.

the ramp, resulting in a high derivative of the magnetic field with respect to time. Such rapid changes generate transient eddy currents, which in turn induce dipolar and sextupolar field perturbations, leading to the observed shifts in orbit and tune. Additional notable tune-shifts were also observed as the transition energy was crossed, as indicated by the dashed blue lines. When the ramps end and plateaus are reached, tunes showed excellent reproducibility over multiple acquisitions and stability over the different plateaus. As the energy plateau increases, the tunes exhibited slight oscillations even during periods of steady powering conditions, as highlighted in Fig. 5.6b for the 18.00 GeV/c plateau. The measured tunes on each energy plateau p_0 were averaged, as explained in Section 5.1, and are summarized in Tab. 5.2.

Table 5.2. Measured horizontal (q_x) and vertical (q_y) tunes averaged on the individual power cycle's plateau (p_0) with corresponding standard deviations expressed as a percentage relative to the averaged values.

p_0 [GeV/c]	$q_{x,av}(p_0)$	$\sigma_{q_{x,av}}(p_0)$ [%]	$q_{y,av}(p_0)$	$\sigma_{q_{y,av}}(p_0)$ [%]
2.79	0.2629	0.27	0.3040	0.16
5.25	0.2835	0.85	0.3229	0.96
7.00	0.2300	1.09	0.2539	1.26
10.14	0.2389	0.29	0.2677	0.26
14.04	0.2257	0.89	0.2623	0.19
18.00	0.2221	2.39	0.2579	0.12

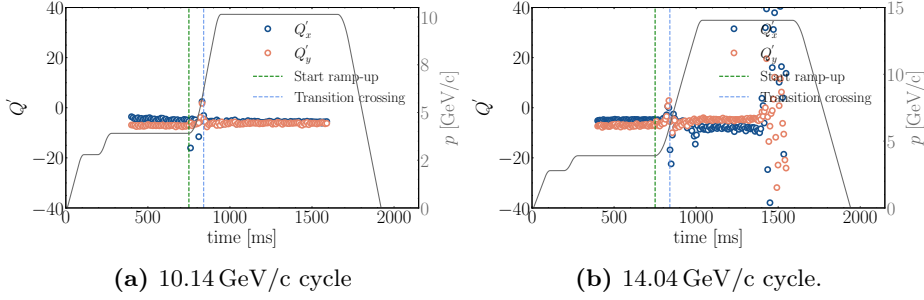


Figure 5.7. Horizontal and vertical first order chromaticity measurements throughout the individual bare-machine cycles in blue and orange, respectively.

Chromaticity measurements

Figure 5.7 shows two examples of the horizontal and vertical first-order chromaticity measurements in blue and orange, respectively, throughout the individual bare-machine cycles to 10.14 GeV/c and 14.04 GeV/c momentum plateaus (on the left and the right, respectively). In general on the various bare-machine cycles at low energy chromaticity remained stable in both planes, as seen previously detailed in Fig. 5.4. During bare-machine cycles to higher energies, chromaticity started to exhibit clear fluctuations in both planes, in particular with Q'_x decreasing and Q'_y increasing during the ramps to the various energy plateaus. Some fluctuations in the chromaticity measurements were also seen when crossing the transition energy, indicated by the dashed blue line. In general on the energy plateaus the horizontal and vertical chromaticity remained stable, with minor fluctuations primarily caused by noise in the tune detection.

The first-order horizontal and vertical chromaticity measurements, acquired on each energy plateau (static chromaticity measurements), are summarized in Tab. 5.3.

5.3 Saturation-induced effects in measurements

Ultimately, by progressively developing and testing bare-machine cycles to higher-and-higher energies it was possible to reach an ultimate momentum of 23.11 GeV/c. At this energy the effect of iron saturation in

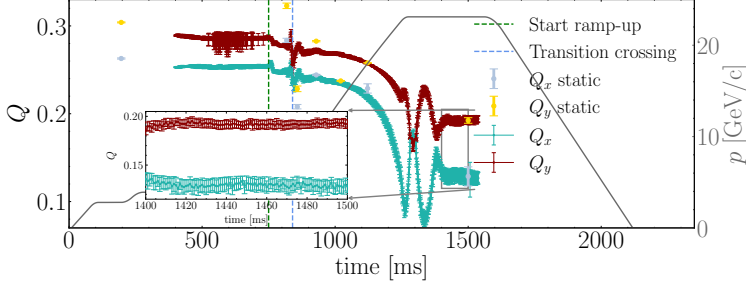
the PS MU is expected to become very pronounced, impacting the field distribution in the magnets.

Figure 5.8 presents the tune and chromaticity measurements throughout the cycle to the 23.11 GeV/c plateau on the top and bottom plot, respectively. Horizontal and vertical tunes are depicted in turquoise and red, respectively; horizontal and vertical chromaticity measurements are depicted in blue and orange, respectively. As the energy of the beam increases during the 23.11 GeV/c cycle ramp, a substantial reduction in horizontal and vertical tune is observed, together with significant increases to the magnitude of the chromaticity. Ultimately these tune shifts and chromaticities limit the extension of bare-machine cycles to even higher energies, as the beam approaches the integer resonances.

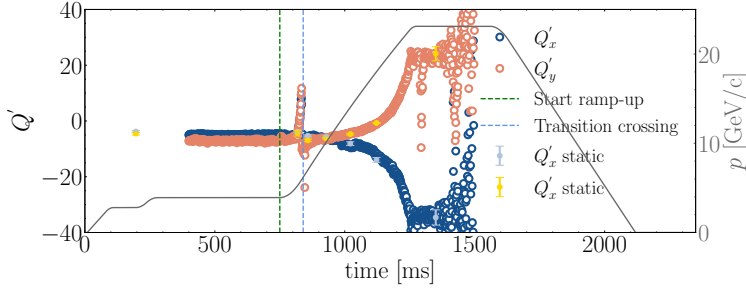
As previously observed in the lower energy cycles reported in Fig. 5.6, abrupt tune-shifts were observed at the beginning of the ramp (marked by the green dashed line) and at the transition crossing (marked by the blue dashed line). The tunes exhibited very large oscillations at the end of the ramp on the 23.11 GeV/c plateau, only stabilizing near the end of the cycle. These significant tune-shifts in both planes suggested a strong impact of harmonics distortion from eddy-currents, and those regions of the plateau were excluded from the final benchmarking analysis. An increased shot-to-shot variability is also seen at high-energy, qualitatively reflected in the larger error bars in the zoomed view compared to those observed on the lower energy plateaus shown in Fig. 5.6. Furthermore, a significant decrease in both tunes was observed above transition. This effect will be assessed through the models in Chapter 6.

Table 5.3. Measured horizontal (Q'_x) and vertical (Q'_y) chromaticities averaged on the individual power cycle's plateau.

p_0 [GeV/c]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
2.79	-3.78	8.99	-4.54	11.45
5.25	-3.83	9.40	-4.38	23.51
7.00	-5.34	6.93	-6.95	6.62
10.14	-5.71	5.60	-6.22	4.18
14.04	-8.12	8.00	-4.70	6.60
18.00	-13.98	6.09	-0.71	5.63



(a) Measured horizontal and vertical tunes on the 23 GeV/c cycle, in turquoise and red, respectively. Q_x and Q_y measurements from individual plateaus in light blue and yellow, respectively.



(b) Measured horizontal and vertical chromaticity on the 23 GeV/c cycle, in blue and orange, respectively. Q'_x and Q'_y measurements from individual plateaus in light blue and yellow, respectively.

Figure 5.8. Comparison between tune and chromaticity measurements acquired on the steady plateaus and throughout the cycle to the 23.11 GeV/c plateau. Tune measurements are reported on the top, chromaticity on the bottom.

Regarding the measured chromaticities, after oscillations across the transition energy, there is a pronounced shift to the $Q'_{x,y}$ as the energy is ramped, pointing to non-linearities generated by the iron saturation. On the 23.11 GeV/c plateau, the measured horizontal and vertical chromaticities were initially very stable. Due to the very large chromaticity on the plateau, performing the Q' measurement could cause significant beam-losses. As beam intensity reduced throughout the plateau the tune detection and chromaticity computation become very noisy. These noisy

regions are excluded from the final benchmarking of the models.

5.3.1 Benchmarking of static and dynamic measurements

The large oscillations undergone by the tunes on arriving at 23.11 GeV/c are suggestive of significant eddy current effects present at the end of the ramp, and this portion of the cycle was excluded from the benchmarking and analysis. Together with the strong decrease of the tunes across the ramp to the 23.11 GeV/c plateau, however, this raised a doubt regarding whether the MU models have a predictive power throughout the rest of the cycle and main body of the ramp, because of eddy-currents effect not included in the Opera and MAD-X models. To address this question, the measurements carried out on the individual plateaus (with static powering of the main coil), listed in Tabs. 5.2 and 5.3, were compared to those recorded continuously throughout the ramp to the 23.11 GeV/c plateau (dynamic powering of the main coil).

Thus, in addition to the continuous tune measurements throughout the cycle to the 23.11 GeV/c plateau, in Fig. 5.8 the measured tune and chromaticity from the individual lower energy plateaus are also reported. Horizontal static tune and chromaticity are shown in light blue, vertical data in yellow. The comparison of the static and dynamic tune measurements at the same momentum, shown in Fig. 5.8a, initially revealed a generally poor agreement. It can be observed that the static measurements at 5.25 GeV/c, 7 GeV/c, and 14 GeV/c deviate from the dynamic measurements acquired throughout the ramp to 23.11 GeV/c. In contrast to the poor agreement observed between dynamic and static tune measurements, a very good agreement was found between dynamic and static chromaticity measurements. This result suggests, in principle, a weak impact of dynamic effects on the chromaticity measurements.

Initially, harmonics distortion from eddy-currents was considered to explain the discrepancy between static and dynamic measurements. Eddy-currents though are normally expected to generate dipolar and sextupolar field components [134], which would affect the chromaticity (and tunes via feed-down). However, the agreement seen by comparing the static and dynamic chromaticity measurements suggested eddy-currents were not a significant contribution to explain the discrepancy observed in the tunes in the main body of the ramp.

Upon further investigation, it was found that the tune evolution, across the same power cycle, exhibited poor reproducibility over timescales exceeding one day.

A pronounced sensitivity of the beam MRP of the bare-machine cycles on the PS supercycle composition was observed. Typically it was found that changes in the supercycle regularly resulted in MRP shifts of approximately 20 mm. This super-cycle dependence of the MRP was identified as the cause of the tune variability. This was particularly marked at high energy due to chromaticity (sextupolar field) becoming very large, affecting notably the measured tunes due to the feed-down effect. These observations led to consider the uncontrolled super-cycle dependent MRP variations as the cause of tune-discrepancies (a larger MRP resulting in stronger feed-down forces acting on the beam).

This introduces an inconsistency in the models' benchmarking, as the reference orbit in MAD-X is aligned with the center of the magnets, meaning that MRP in simulation is assumed to be zero. Consequently, feed-down effects are not accounted for in the optics simulations.

In addition, the remanent field, which characterizes the hysteresis cycle in the MU, was also evaluated for its impact on the optics measurements at injection energy. This field depends on the power cycle preceding the bare-machine cycle under investigation within the PS supercycle. Unexpected variations in the remanent field can influence the reliability of the optics measurements, particularly at low energies.

5.3.2 Mitigation of MRP variability and remanent field on the measurements

To control the effect of the remanent field on the beam-based measurements, a consistent pre-cycle was introduced, within the supercycle, prior to the bare-machine cycles under investigation. Fig. 5.9 illustrates, as an example, the bare-machine cycle to the 23.11 GeV/c plateau preceded by the adopted consistent pre-cycle. With this approach, at each repetition of the supercycle, the pre-cycle magnetizes the MU's steel, providing a consistent remanent field to the bare-machine cycle. This avoids that sudden changes in the supercycle, due to PS operation and requirements from other users/experiments, perturb the optics measurements, ensuring reproducible magnetization conditions for each measurement cycle.

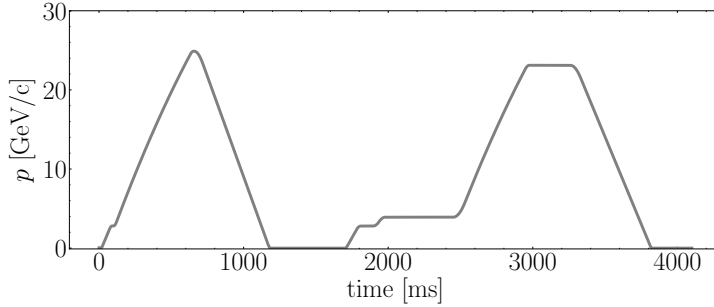


Figure 5.9. Consistent pre-cycle prior to the bare-machine cycle to the 23.11 GeV/c plateau.

After applying the pre-cycle to ensure consistent magnetization of the MU at each repetition of the bare-machine cycle within the supercycle, it was observed that the MRP variability was not mitigated by having a consistent pre-cycle in place, as it will be shown in the following section (in particular, in Figs. 5.10 and 5.11). Thus, MRP corrections were required to compensate for undesired MRP and tune shifts.

To further improve the measurements, the tune and chromaticity measurements on the bare-machine cycles were repeated, with the inclusion of dedicated MRP corrections. The MRP was monitored with the TMS application, and as with tunes and chromas the shot-to-shot and time-based variation monitored, with mean and standard deviation values being considered as figures of merit.

Corrections were applied to achieve an MRP value of zero over segments of the energy plateaus and the ramp to 23.11 GeV/c, with a precision of ± 1 mm. This was accomplished by adjusting the r_{pos} parameter in LSA. This level of precision was targeted to minimize perturbations in measured tunes and chromaticities due to changes in the supercycle composition, thereby reducing feed-down effects.

5.4 Effect of corrections on the measurements

Tune and chromaticity measurements in bare-machine were repeated across all the bare-machine power cycles, including the monitoring and corrections of the MRP and a dedicated pre-cycle included in the super-

cycle. For each bare-machine cycle, the MRP measurements, the corresponding corrections, as well as the measured tunes and chromaticities are presented in this section. Initially, measurements on the individual cycles are reported to provide accurate and reliable static tune and chromaticity estimates on each energy plateau, with corrected MRP. Following, measurements over the ramp toward the 23.11 GeV/c plateau are presented. Finally, a comparison between static and dynamic measurements with MRP corrections is provided to evaluate the influence of dynamic effects on the corrected measurements and determine which set of data to use for models' benchmarking.

Figure 5.10 presents the static measurements conducted on the flat-cycle at injection (2.79 GeV/c). The plot on the top displays the measured MRP (purple) alongside the applied corrections (orange). The plot in the middle shows the measured horizontal and vertical tunes in turquoise and dark red, respectively, while on the bottom the horizontal and vertical chromaticities are displayed in light blue and light red, respectively. The measured MRP showed no abrupt variations, demonstrating good stability throughout the flat-cycle and remaining within the ± 1 mm tolerance in the region delineated by the gray dashed lines, with an averaged value of 0.64 mm. Consequently, no corrections were necessary on the flat-cycle. The tune exhibited excellent stability in both planes, with very small error bars indicating optimal reproducibility over several acquisitions, as displayed in the zoomed plot, with standard deviations of the level of 2×10^{-3} . Similar stability was also observed in the chromaticity measurements in both planes².

The measurements throughout the cycle to the 10.14 GeV/c plateau are presented in Fig. 5.11. The MRP evolution on the ramp is characterized by a pronounced increase from -20 mm to approximately 30 mm, with significant tune-shifts occurring at the beginning of the ramp and during the transition crossing (indicated by the green and blue dashed lines, respectively). At the end of the ramp, the MRP stabilizes around 30 mm, with the tunes remaining stable. Subsequently, constant MRP corrections were applied, which corresponded with a decrease of both tunes of approxi-

²The first outlier point at injection ($t = 170$ ms) is due to tune-shifts induced during the injection process, e.g. due to orbit bumps and possible eddy currents. This results in an unreliable chromaticity evaluation, which is consequently excluded from the average.

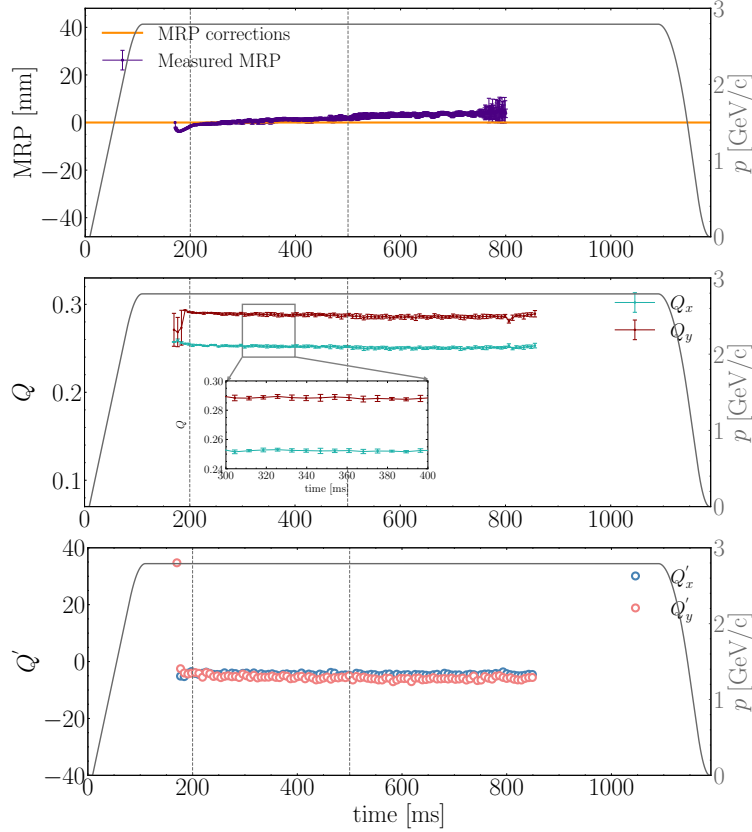


Figure 5.10. Static beam-based measurements on the 2.79 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.

mately $4 \cdot 10^{-2}$. This indicates that an MRP change of 1 mm corresponded to a tune-shift of approximately 1.3×10^{-3} . This relationship supports the decision to maintain a 0 MRP within a precision of ± 1 mm to ensure minimal perturbation of the tunes and optimize beam stability. The constant MRP corrections were sufficient to maintain stable tunes and keep the MRP within the tolerance range. MRP measurements demonstrated

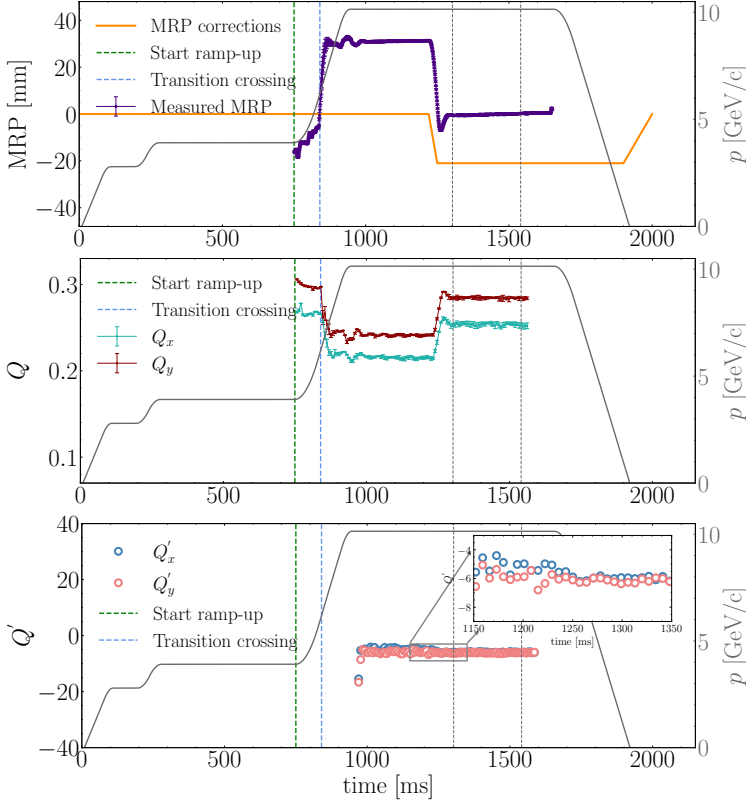


Figure 5.11. Static beam-based measurements on the 10.14 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.

excellent reproducibility over multiple acquisitions and stability across the 10.14 GeV/c plateau, with a standard deviation of approximately 0.27 mm in the region delimited by the gray dashed lines. The insertion of MRP corrections caused a slight change in the chromaticity evolution in both planes, as illustrated in the inset view of the bottom plot, while exhibiting excellent stability throughout the remaining phase of the plateau.

MRP measurements, applied corrections, and tune and chromaticity

measurements across the different bare-machine cycles were investigated and are detailed in Appendix A. The applied corrections enabled an averaged MRP within the targeted tolerance to be reached across a portion of the different energy plateaus. The static tune and chromaticity measurements with MRP corrections were averaged over the plateau regions where the MRP remained within the accepted tolerance, as indicated by the gray dashed lines in the examples reported in Figs. 5.10 and 5.11, and are reported in Tabs. 5.4 and 5.5, respectively.

Dynamic measurements throughout the cycle to the 23.11 GeV/c energy plateau

Figure 5.12 illustrates, on the top plot, the MRP measurements and corresponding corrections across the cycle to the 23.11 GeV/c plateau; the

Table 5.4. Averaged horizontal (Q_x) and vertical static (Q_y) tunes with MRP corrections on the individual cycle's plateau.

p_0 [GeV/c]	$q_{x,av}(p_0)$	$\sigma_{q_{x,av}}(p_0)$ [%]	$q_{y,av}(p_0)$	$\sigma_{q_{y,av}}(p_0)$ [%]
2.79	0.2514	0.68	0.2872	0.87
5.25	0.2584	0.46	0.2882	0.35
7.00	0.2520	0.83	0.2815	0.78
10.14	0.2539	0.95	0.2844	0.70
14.04	0.2475	0.97	0.2729	0.37
18.00	0.2302	1.39	0.2583	0.12

Table 5.5. Averaged horizontal (Q'_x) and vertical static (Q'_y) chromaticities with MRP corrections on the individual cycle's plateau.

p_0 [GeV/c]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
2.79	-4.47	7.83	-5.33	10.88
5.25	-4.41	9.70	-6.32	5.38
7.00	-5.52	2.54	-7.47	5.35
10.14	-5.93	2.19	-6.11	2.62
14.04	-7.49	2.00	-4.56	2.19
18.00	-11.64	2.49	-1.07	2.80

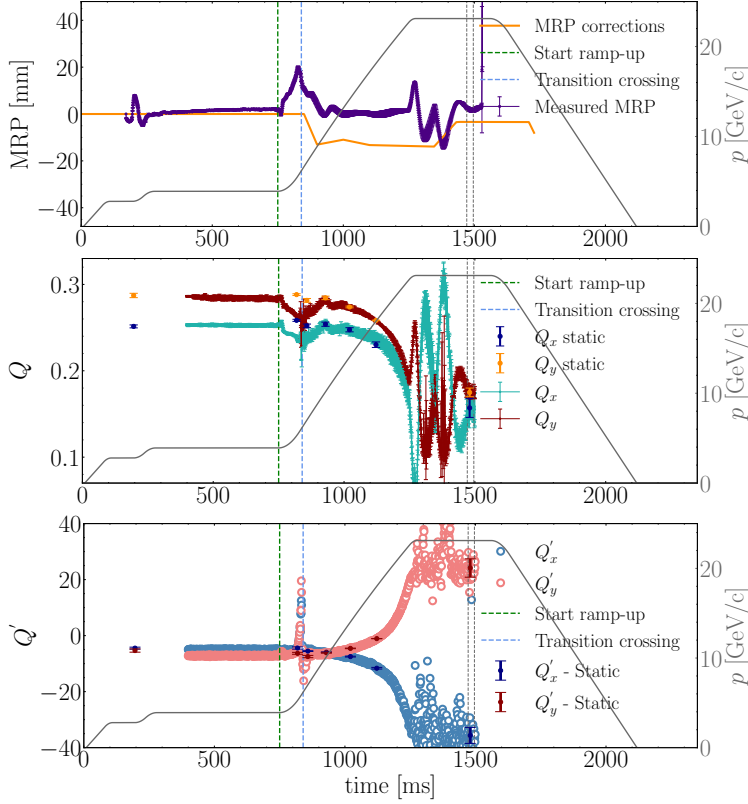


Figure 5.12. Static beam-based measurements on the 23.11 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.

tunes and chromaticity measurements are shown in the middle and bottom figures, respectively. Measurements were recorded up to approximately $t = 1500$ ms, as the beam is lost beyond this point.

Unlike the approach adopted for the lower energy cycles, the MRP was also corrected on the ramp using non-constant corrections to maintain it within the targeted tolerance during the dynamic measurements. At the end of the ramp, on the 23.11 GeV/c plateau, the MRP, and consequently

the tunes, experienced significant oscillations. The MRP was brought within tolerance in a small portion of the plateau, allowing to static tune and chromaticity measurements with corrected MRP at 23.11 GeV/c.

In addition to the tune measurements throughout the cycle to the 23.11 GeV/c plateau, Fig. 5.12 presents also the static horizontal and vertical tunes from the individual lower energy plateaus, depicted in blue and orange, respectively. The strategy of correcting the MRP on the individual bare-machine cycle's plateaus and on the ramp to 23.11 GeV/c, combined with the introduction of a consistent pre-cycle in the supercycle, resulted in excellent alignment between static and dynamic tune measurements.

The dynamic horizontal and vertical chromaticity measurements revealed a significant shift in opposite direction along the ramp. However, on the plateau, the applied corrections led to acceptable stability within the region delineated by the dashed gray lines. The static horizontal and vertical chromaticity measurements are also shown in dark blue and dark red, respectively overlaid with the dynamic measurements. Similar to the tune measurements, the two sets of chromaticity measurements exhibited excellent agreement.

The beam-based measurements showed in this section proved that, without corrections, the MRP exhibited large values on the various energy plateaus. The introduction of MRP corrections resulted in significant shifts in the tune evolution across the different cycles, highlighting the necessity of these corrections for accurate model benchmarking. The excellent agreement between static and dynamic tune measurements with MRP corrections confirms that both sets of measurements are equivalent for model validation. Furthermore, this agreement demonstrates that, aside from the transient phases at the start and end of the ramp and during transition, tune measurements are not significantly affected by dynamic or eddy-current effects throughout the main portion of the ramp. This suggests that continuous measurements taken during the 23.11 GeV ramp can be reliably used for benchmarking at various energies (excluding those specific period where MRP was not under control) without the need to establish a new bare-machine cycle each time with a specific energy plateau. Additionally, this validates the use of static Opera and MAD-X models to predict tune evolution during the main part of the ramp, despite the absence of dynamic effects in these models.

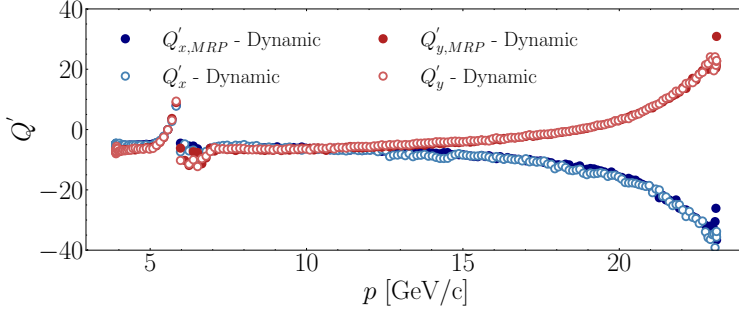


Figure 5.13. Measured horizontal (Q'_x) and vertical (Q'_y) chromaticity on the 23.11 GeV/c cycle. Light blue and light red dots represent the horizontal and vertical chromaticity measurements without MRP corrections, respectively, while dark blue and dark red indicate the corresponding measurements with MRP corrections.

An open question from operation was the long-term reproducibility of the measurements. Tab. 5.6 presents, as an example, the horizontal and vertical tune measurements at 10.14 GeV/c during the 2023 and 2024 measurements campaign. An excellent agreement was observed between the measurements taken one year apart, demonstrating the remarkable reproducibility of the tune measurements in the bare-machine configuration with MRP corrections and consistent pre-cycle in the supercycle.

Figure 5.13 displays the horizontal and vertical dynamic chromaticity measurements as a function of beam momentum. The light blue and light red dots correspond to measurements without MRP corrections, while the dark blue and dark red dots represent those taken with MRP corrections. Unlike the tune measurements, no significant variation in chromaticity was observed after applying the MRP corrections, suggesting that higher order errors were not significant in the bare-machine configuration.

Table 5.6. Averaged tunes on the individual plateaus with MRP corrections.

Year	$Q_{x,MRP}$	$Q_{y,MRP}$
2023	6.2530 ± 0.0030	6.2840 ± 0.0020
2024	6.2500 ± 0.0020	6.2810 ± 0.0010

Following these results, for the final benchmarking of the models, additional intermediate points were considered, with tunes and chromaticities derived from the dynamic measurements on the 23.11 GeV/c cycle, reported in Fig. 5.12. At higher energies, intermediate measurements were taken at 19.52 GeV/c, 20.99 GeV/c, and 21.99 GeV/c, providing crucial data between the 18.00 GeV/c and 23.11 GeV/c plateaus to assess the impact of the saturation effect at high energy in the measurements and simulations.

5.5 Impact of F8L circuit on the beam-based measurements

In the previous section, the challenges encountered in performing beam-based measurements in the bare-machine configuration up to 23.11 GeV/c were discussed. Notably, the implementation of MRP corrections was found to significantly impact the accuracy of tune measurements, although these corrections were not essential for chromaticity evaluation.

This section aims to assess the influence of the harmonics contribution from the F8L on the measured optics, evaluating how they affect tune and chromaticity evolution across different energy levels. To systematically assess the optics response to F8L harmonics, beam-based measurements were performed at three distinct beam energies (main coil currents):

- Injection energy, where measurements are affected by remanent field;
- Intermediate energy, using the plateau at 10.14, where effects from both remanent fields and iron saturation are minimal;
- High energy, using the plateau at 18.00 GeV, where iron saturation effects become prominent.

The choice of 10.14 GeV as reference energy stems from its position as an intermediate configuration, providing a baseline unaffected by lower or higher-energy magnetic phenomena. The lowest and highest energies were specifically chosen to capture conditions in which remanent field and iron saturation effects, respectively, are more pronounced.

Although performing measurements at higher energies (e.g. 23.11 GeV) was considered, beam losses resulting from tunes approaching resonance conditions made such measurements impractical.

Following the evaluation of the critical role of MRP corrections in tune measurements, beam-based measurements with the F8L circuit activated were conducted including these corrections.

Finally, on each energy plateau, the current in the additional circuit was varied across both polarities relative to the main coil current, I_{MC} , to thoroughly scan its influence on the optics. Fast ramp-up of the F8L resulted in MRP shifts. Thus, the ramp-up times were adjusted to minimize MRP fluctuations and maintain beam stability throughout the F8L activation process. Similarly to what discussed for the tune measurements in bare-machine, for each I_{F8L} current value, multiple tune measurements were acquired, later averaged at each time step t_i , providing the evolution of the tune on a specific energy plateau.

Beam excitation, injection time and FFT settings discussed in Sections 5.1 and 5.2 for the measurements in bare-machine are unchanged.

5.5.1 Effect of F8L harmonics at injection energy

This subsection reports tune and chromaticity measurements conducted on the flat-cycle at injection energy, varying I_{F8L} . MRP corrections are applied after injection and, following, the F8L circuit is activated.

Tune measurements

Figure 5.14 shows the timing of the MRP corrections and the F8L current insertions across the flat-cycle at injection energy, represented by the blue and green curves, respectively. Here, a value of 0 denotes the *OFF* state, meaning that the MRP corrections and F8L current were inactive, while a value of 1 represents the *ON* state, indicating activation. The MRP corrections were applied first, at $t = 200$ ms. Subsequently, the F8L current was activated at $t = 300$ ms reaching a stable current level at $t = 450$ ms. The ramp-down of the F8L circuit, initiated at $t = 700$ ms, provides a 250 ms interval to acquire tune measurements at constant I_{F8L} , with corrected MRP.

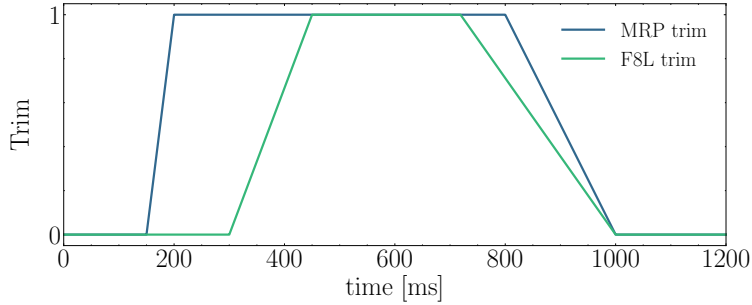


Figure 5.14. Trim of the MRP corrections and F8L circuit on the flat-cycle at 2.79 GeV/c.

Tune measurements were conducted by varying the I_{F8L} current from -35 A to 35 A. Outside of this range, the beam was lost during the plateau. Fig. 5.15 reports the horizontal and vertical tune measurements, on the top and bottom, respectively, over the 2.79 GeV/c flat-cycle at various I_{F8L} currents. At start of the I_{F8L} ramp, marked by the dashed red line at 300 ms, the horizontal and vertical tunes shift in opposite directions: for positive I_{F8L} , Q_x decreases and Q_y increases, while for negative currents, Q_x increases and Q_y decreases. At 450 ms, when the I_{F8L} ramp is terminated, the tunes stabilize and remain constant as long as the I_{F8L} current holds steady. During the subsequent ramp-down of the I_{F8L} current, both tunes return to their initial values. An overall excellent shot-by-shot reproducibility of the tune measurements was observed over the whole range of I_{F8L} current, as proved by relatively small error-bars at each I_{F8L} . As for the bare-machine, measurements with F8L and MRP corrections showed excellent reproducibility over the long term.

The opposite directional changes in the horizontal and vertical tunes are explained by the configuration design of the F8L circuit, which is engineered to increase the field in one half-unit (including the B_2 component) while decreasing it in the other half-unit, as discussed in Chapter 2.

Horizontal and vertical tune measurements with MRP corrections at various I_{F8L} currents were averaged within the plateau region delimited by the gray dashed lines in Fig. 5.15, and are displayed in Fig. 5.16, in light blue and dark red, respectively. The corresponding bandwidths were determined using a second-order polynomial fit, incorporating the covariance

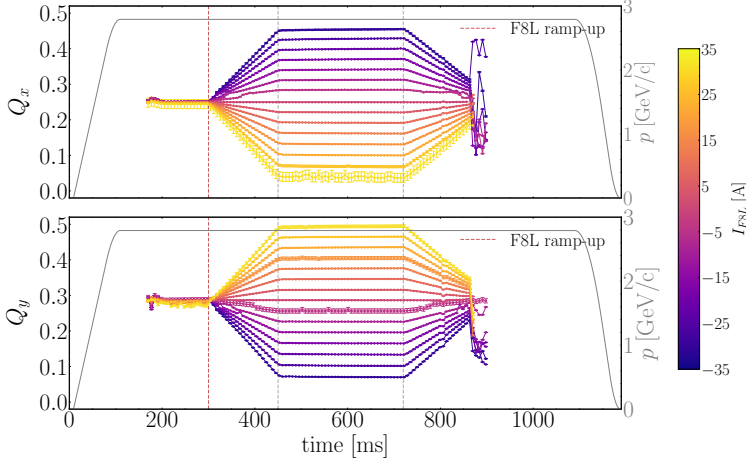


Figure 5.15. Horizontal and vertical tunes measurements, on top and bottom figure, respectively, with F8L circuit activated at 2.79 GeV/c at various I_{F8L} .

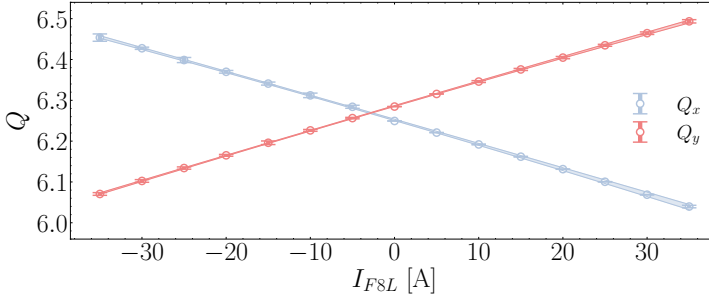


Figure 5.16. Averaged measured horizontal (blue) and vertical (red) tunes on the 2.79 GeV/c plateau as a function of the I_{F8L} current.

matrix³. A generally linear response in both the horizontal and vertical tunes at injection energy was observed as the I_{F8L} current varied. Tune-shift of approximately 6×10^{-3} with respect to I_{F8L} current increment ($\partial Q / \partial I_{F8L} [A^{-1}]$) were recorded in both planes.

³The same approach is also applied to subsequent similar figures throughout this chapter.

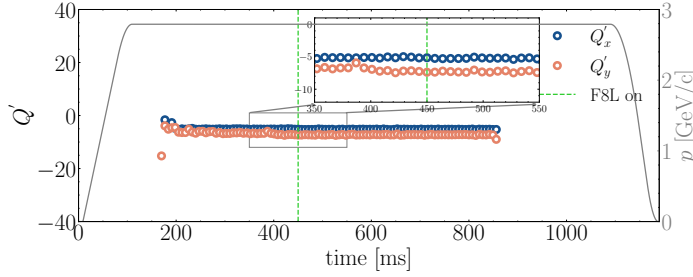


Figure 5.17. Horizontal and vertical chromaticities measurements in blue and orange, respectively, at 2.79 GeV/c with $I_{F8L} = 25$ A.

Chromaticity measurements

For chromaticity measurements on the flat-cycle, the range of I_{F8L} current was constrained to ± 30 A, as higher currents resulted in significant beam loss during the r_{pos} scan. The r_{pos} window was set to ± 20 mm relative to the initial value required for proper MRP corrections.

Figure 5.17 illustrates the horizontal and vertical chromaticity measurements on the flat cycle at $I_{F8L} = 20$ A in blue and orange, respectively. When the F8L circuit has completed the ramp at $t = 450$ ms (marked by the green dashed line), the chromaticity is stable throughout the plateau.

The chromaticity measurements at various I_{F8L} currents were averaged over the stable interval between 450 ms and 700 ms, where both MRP corrections and F8L circuit were activated. Tab. 5.7 summarizes the averaged chromaticity at injection energy varying the I_{F8L} current.

Similarly to what seen for the tunes, Fig. 5.18 displays the horizontal and vertical tune measurements as a function of the I_{F8L} . Chromaticity remained nearly unchanged when the I_{F8L} current is ranged from -30 A to 30 A, with a maximum absolute variation of 0.2 and 0.4 on the horizontal and vertical planes, respectively. Considering the measurements standard deviation, this indicated that the F8L circuit did not significantly impact the sextupolar field generated by the MU.

5.5.2 Effect of F8L harmonics on the 10.14 GeV/c plateau

This subsection presents tune and chromaticity measurements conducted with the F8L circuit on the 10.14 GeV plateau. Similarly to Fig. 5.14,

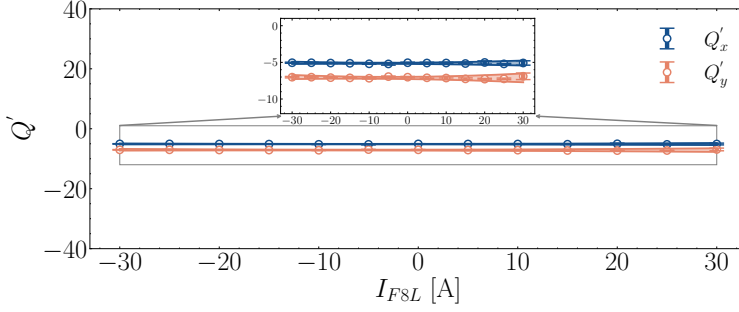


Figure 5.18. Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 2.79 GeV/c plateau as a function of the I_{F8L} current.

Fig. 5.19 illustrates the activation sequence of the MRP corrections (in blue) and the I_{F8L} current (in green) adopted for the measurements. Following, tune and chromaticity measurements ranging the I_{F8L} current are presented and analyzed.

Table 5.7. Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the flat-cycle at injection energy at various I_{F8L} currents.

I_{F8L} [A]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
-30	-5.05	1.39	-7.02	1.42
-25	-5.05	1.19	-7.02	1.42
-20	-5.09	1.18	-7.08	1.13
-15	-5.12	0.98	-7.16	0.98
-10	-5.19	1.35	-7.17	1.39
-5	-5.21	3.26	-6.95	1.15
0	-5.05	1.39	-7.02	1.42
5	-5.09	1.57	-7.10	1.83
10	-5.09	2.16	-7.14	2.10
15	-5.16	1.55	-7.25	1.79
20	-5.01	4.39	-7.29	1.51
25	-5.21	1.34	-7.25	1.52
30	-5.09	5.89	-6.90	6.52

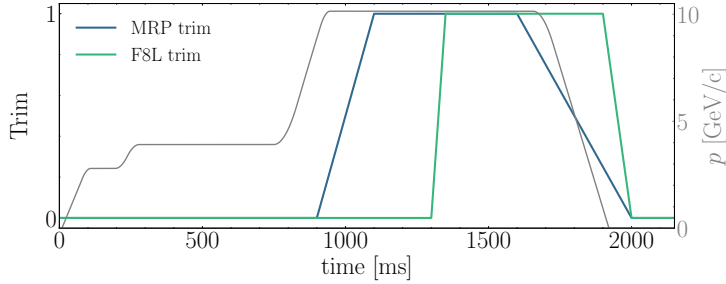


Figure 5.19. Trim of the MRP corrections and I_{F8L} current on the 10.14 GeV/c plateau: MRP corrections are inserted between 900 ms and 1100 ms, I_{F8L} current ramped-up between 1300 ms and 1350 ms.

Tune measurements

To conduct tune measurements on the 10.14 GeV/c plateau with F8L circuit activated, the I_{F8L} current was varied between -100 A and 100 A, with the activation sequence of the MRP corrections and I_{F8L} current reported in Fig 5.19. Beyond this current range, significant beam losses occurred after the F8L insertion, preventing reliable measurements.

Figure 5.20 presents the horizontal and vertical tune measurements, displayed on the top and bottom, respectively, on the 10.14 GeV/c plateau, ranging the I_{F8L} . The F8L activation at $t = 1300$ ms is marked by the red dashed line. When positive I_{F8L} currents were applied, the horizontal tune decreased while the vertical tune increased; the opposite behavior was observed for negative I_{F8L} currents. After the F8L trim, both tunes showed an excellent stability and shot-to-shot reproducibility over the full range of currents, as proved by the small error-bars.

The measured horizontal and vertical tunes were averaged in the region delimited by the vertical gray lines and are reported in Fig. 5.21 in light blue and light red, respectively, as a function of the I_{F8L} current values. A linear response of the measured tunes was observed ranging I_{F8L} , with a $\partial Q/\partial I_{F8L}$ of $1.6 \cdot 10^{-3} [A^{-1}]$.

Chromaticity Measurements

Chromaticity measurements on the 10.14 GeV/c plateau were conducted ranging the I_{F8L} current from -100 A to 100 A with a step of 20 A.

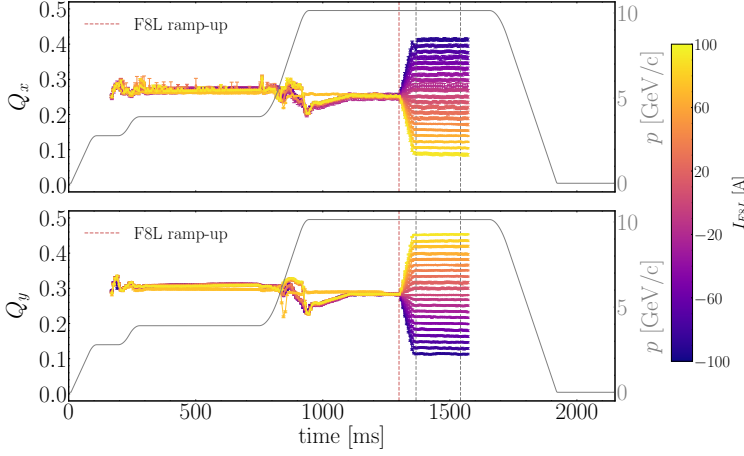


Figure 5.20. Horizontal and vertical tunes measurements, on top and bottom figure, respectively, with F8L circuit activated on the 10.14 GeV/c plateau at various I_{F8L} current.

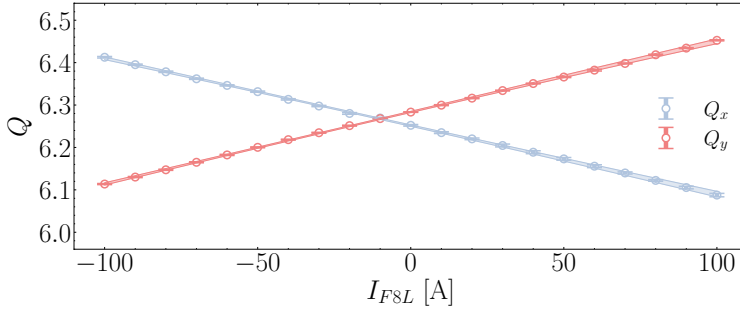


Figure 5.21. Averaged measured horizontal (blue) and vertical (red) tunes on the 10.14 GeV/c plateau as a function of the I_{F8L} current.

Figure 5.22 show, as an example, the horizontal (blue) and vertical (orange) chromaticity measurements at $I_{F8L} = 60$ A. Following the activation of the I_{F8L} current at $t = 1350$ ms (marked by the green dashed line), slight chromaticity changes were observed in both planes, remaining stable throughout the remanent part of the plateau, demonstrating good reproducibility during the r_{pos} scan.

At each I_{F8L} current, chromaticity measurements were then averaged

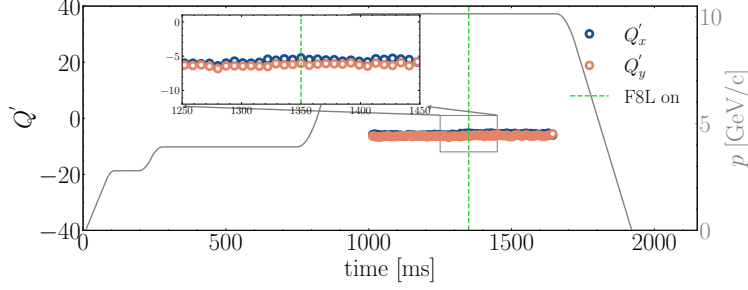


Figure 5.22. Horizontal and vertical chromaticities measurements in blue and orange, respectively, at 10.14 GeV/c with $I_{F8L} = 60$ A.

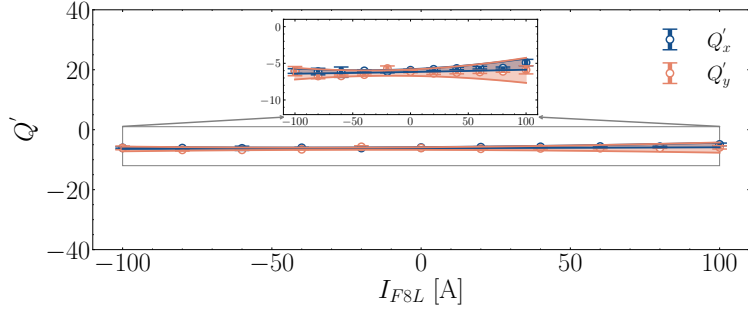


Figure 5.23. Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 10.14 GeV/c plateau as a function of the I_{F8L} current.

from $t = 1350$ ms to the end of the plateau, and are reported in Tab. 5.8. Fig. 5.23 illustrates the averaged horizontal and vertical chromaticity, shown in blue and orange, respectively, for various I_{F8L} currents. A nearly constant trend was observed across the entire range of I_{F8L} values used in the measurements, with slight variation at the level of 1 unit, comparable with maximum standard deviation. Thus, the activation of the F8L circuit at 10.14 GeV/c resulted in a maximum chromaticity variation, indicating a measurable impact on the beam's chromatic properties at this energy.

5.5.3 Effect of F8L harmonics on the 18.00 GeV/c plateau

Tune measurements in the bare-machine configuration, presented in Section 5.3, demonstrated a significant decrease beyond 10.14 GeV/c, pri-

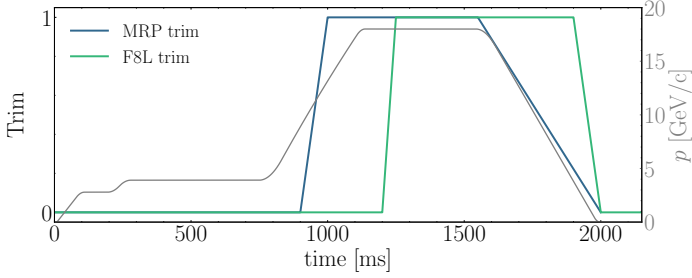


Figure 5.24. Trim of the MRP corrections and I_{F8L} current on the 18.00 GeV/c plateau.

marily attributed to the effects of iron saturation. In contrast, chromaticity measurements revealed opposing trends between the horizontal and vertical planes. To investigate the influence of higher-order harmonics generated by the F8L circuit under conditions of notable iron saturation, tune and chromaticity measurements were conducted with the F8L circuit activated on the 18.00 GeV/c plateau. MRP corrections and I_{F8L} current activation sequences are illustrated in Fig. 5.24.

Table 5.8. Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 10.14 GeV/c plateau at various I_{F8L} currents.

I_{F8L} [A]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
-100	-6.06	5.28	-6.07	10.34
-80	-6.13	7.17	-6.73	5.65
-60	-6.20	11.61	-6.72	1.93
-40	-6.04	2.32	-6.55	1.98
-20	-6.13	2.94	-5.69	6.15
0	-5.94	0.13	-6.12	0.16
20	-5.81	2.93	-6.36	2.52
40	-5.70	2.98	-6.25	3.04
60	-5.60	3.21	-6.18	3.24
80	-5.66	2.65	-6.10	2.13
100	-4.90	8.98	-5.89	9.34

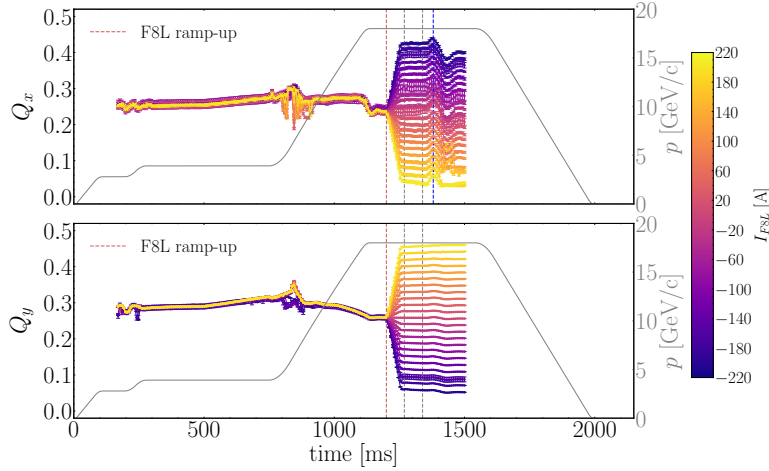


Figure 5.25. Horizontal and vertical tunes measurements, on top and bottom row, respectively, with F8L circuit on at 18.00 GeV/c at various I_{F8L} .

Tune measurements

Tune measurements on the 18.00 GeV/c plateau were conducted by ranging the I_{F8L} current from -220 A to 220 A, while keeping beam losses within acceptable limits.

Figure 5.25 illustrates the evolution of the measured horizontal (top) and vertical (bottom) tunes on the 18.00 GeV/c plateau, corresponding to different I_{F8L} current levels. When the I_{F8L} current was activated at $t = 1250$ ms, as marked by the red dashed line, tunes shifted in opposite directions. Unlike the measurements on the previous lower energy plateaus, where the tune evolution demonstrated consistent stability, as shown in Fig. 5.15 and 5.20, the 18.00 GeV/c plateau revealed a different behavior. The vertical tune remained notably stable across the plateau, while the horizontal tune experienced consistent shifts at approximately $t = 1380$ ms (marked by the blue dashed line in the top plot), attributed to variations in the MRP, because chromaticity is much higher on the horizontal plane than on the vertical at 18.00 GeV/c.

Due to this shift, the region where the measured tunes were averaged is reduced, as indicated by the gray dashed lines. The shot-to-shot reproducibility is excellent, resulting in high-precision measurements with a

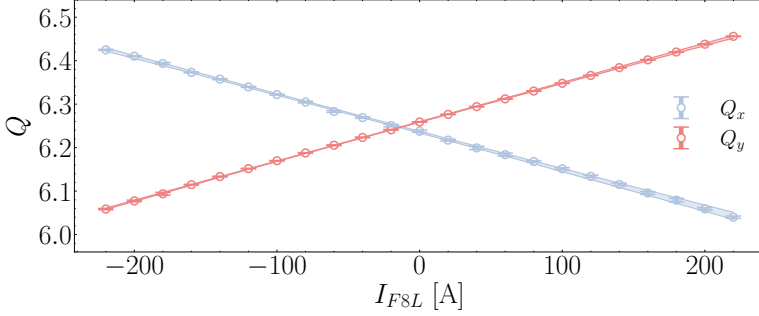


Figure 5.26. Averaged measured horizontal (blue) and vertical (red) tunes on the 18.00 GeV/c plateau as a function of the I_{F8L} current.

small standard deviation, as indicated by the minimal amplitude of the error bars. Averaged horizontal and vertical tune measurements at various I_{F8L} currents are reported in Fig. 5.26 in light blue and light red, respectively. Both tunes showed a quasi-linear response varying the I_{F8L} current with a $\partial Q / \partial I_{F8L}$ of $0.9 \cdot 10^{-3} [A^{-1}]$.

Chromaticity measurements

Using the same insertion scheme for the MRP corrections and F8L activation applied for the tune measurements and shown in Fig. 5.24, chromaticity measurements were conducted on the 18.00 GeV/c plateau at various I_{F8L} values. Unlike the range adopted for tune measurements, the I_{F8L} current was ranged from -200 A to 200 A due to persistent beam losses during the dp/p scan outside of this range.

Figure 5.27 illustrate, as an example, the horizontal (blue) and vertical (orange) chromaticities with the F8L circuit activated at $I_{F8L} = -80$ A acquired from $t = 1000$ ms to the end of the 18.00 GeV/c plateau. Following the activation of the I_{F8L} current, chromaticity remained relatively stable across the 18.00 GeV/c plateau in both planes. Measurements were averaged over the plateau region delineated by the dashed gray lines, where the MRP was kept within the accepted tolerance and are reported in Tab. 5.9.

Figure 5.28 displays the averaged horizontal and vertical chromaticity as a function of I_{F8L} current, shown in blue and orange, respectively. The vertical chromaticity exhibited minimal variation, with a maximum

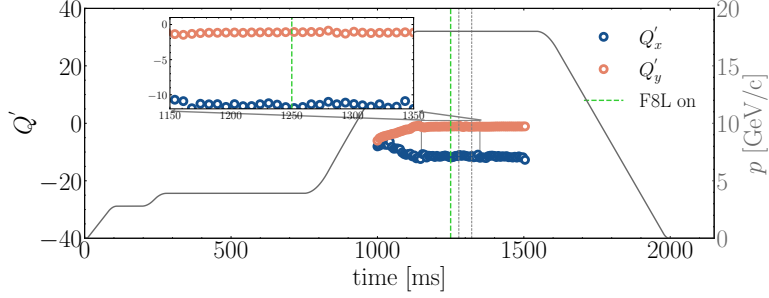


Figure 5.27. Horizontal and vertical chromaticities measurements in blue and green, respectively, at 18.00 GeV/c with $I_{F8L} = -80$ A.

absolute change of 0.4; in contrast, the horizontal chromaticity showed a larger variation, with a maximum shift of approximately 2. However, the variation in chromaticity measurements across different I_{F8L} currents remains comparable to the measurement uncertainty, suggesting that the F8L contribution had limited impact on the observed fluctuations.

Table 5.9. Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 18.00 GeV/c plateau at various I_{F8L} currents.

I_{F8L} [A]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
-200	-11.98	1.50	-1.05	24.76
-160	-11.67	9.77	-0.97	29.90
-120	-11.58	7.60	-1.37	39.42
-80	-11.32	1.94	-1.08	12.04
-40	-12.52	2.96	-1.00	9.00
0	-11.24	1.69	-1.15	4.35
40	-10.61	1.41	-1.05	4.76
80	-9.99	8.81	-1.06	10.38
120	-10.70	6.64	-1.10	17.27
160	-9.97	20.76	-1.15	29.57
200	-11.15	14.62	-1.39	68.35

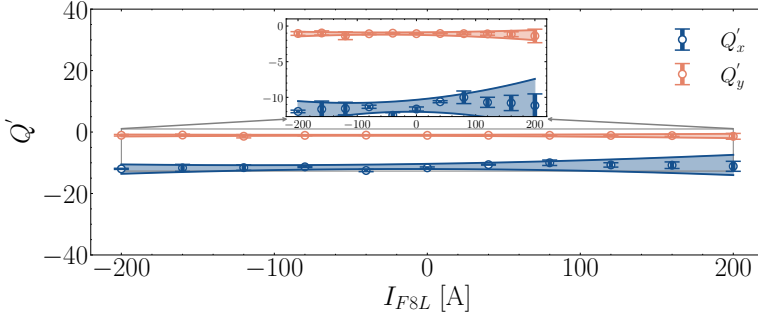


Figure 5.28. Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 18.00 GeV/c plateau as a function of the I_{F8L} current.

5.5.4 F8L harmonics effects on the measurements: outcome

Beam-based measurements conducted with MRP corrections and the F8L circuit activated were used to evaluate the impact of the harmonics generated by the F8L on the tune and first-order chromaticity across three different energy plateaus.

Tables 5.10 and 5.11 summarize the measurements across the different energy plateaus p_0 in terms of tune and chromaticity variations, respectively, per unit of I_{F8L} current. The rate of change of the measured tunes per unit of I_{F8L} current decreases with the energy in both planes, while the chromaticity measurements showed largest excursion, with respect to the bare-machine scenario, at higher energies. Tune measurements exhibited excellent shot-to-shot reproducibility and stable evolution on each energy plateau across the I_{F8L} scan. To a first approximation, the measured tune on a given plateau exhibited a linear response to variations in the I_{F8L} current. This indicates that the quadrupolar component produced by the F8L circuit behaves linearly within the investigated ranges of I_{F8L} currents. In contrast, the chromaticity exhibited a measurable yet limited variation across the I_{F8L} current scan on the different energy plateaus.

5.6 Impact of PFW circuits on the beam-based measurements

Harmonics contribution from PFW is vital in operation to provide tune and chromaticity control. This section presents the beam-based measurements performed with the PFW activated to evaluate their influence on machine optics at different energies and benchmarking the models.

Measurements in this setup face inherent challenges such as the generation of higher order non-linear field contributions and potential saturation effects at high currents, leading to non-linear effects in the beam dynamics. Unlike the F8L circuit, which showed minimal impact on chromaticity measurements at the same energy across a wide range of operating currents, the PFW activation is expected to induce substantial variations in chromaticity. The beam excitation frequency settings for the Chirp were iteratively adjusted to ensure clear detection of the peak in the FFT spectrum, accommodating the chromatic variations introduced by the PFW.

To assess the model's robustness in predicting beam optics with PFW circuits activated, beam-based measurements were conducted in a manner consistent with the measurements previously performed with the F8L circuit engaged. This included activating the PFW circuits on the three

Table 5.10. Horizontal and vertical tune variation on energy plateau across the I_{F8L} current scan.

p_0 [GeV/c]	$\partial Q_x / \partial I_{F8L}$ [1/A]	$\partial Q_y / \partial I_{F8L}$ [1/A]
2.79	-0.0060	0.0060
10.14	-0.0016	0.0017
18.00	-0.0009	0.0009

Table 5.11. Horizontal and vertical chromaticity variation on energy plateau across the I_{F8L} current scan.

p_0 [GeV/c]	$\partial Q'_x / \partial I_{F8L}$ [1/A]	$\partial Q'_y / \partial I_{F8L}$ [1/A]
2.79	0.0400	0.0600
10.14	0.2200	0.1700
18.00	0.2300	0.3600

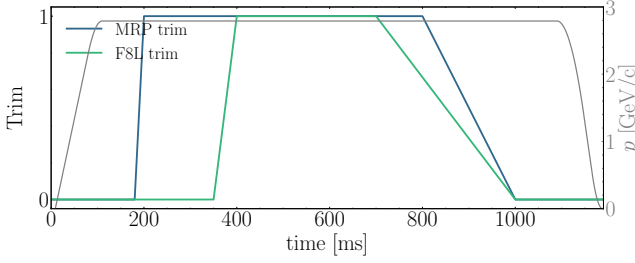


Figure 5.29. Trim of the MRP corrections and I_{PFW} currents on the 2.79 GeV/c plateau.

energy plateaus used for the F8L measurements. Such a setup enables a direct comparison of the PFW harmonics effects with those observed under F8L activation across these energy levels. Additionally, the selected plateaus provide a comprehensive perspective on the impact of the PFW circuits on beam optics, including variations in chromaticity and tune, across a consistent set of operational energies.

MRP was carefully monitored and corrected to ensure that measurements were conducted within the MRP accepted tolerance range, thereby enhancing the accuracy and consistency of the experimental data. The various PFW circuits, introduced in Section 2.1.1, were simultaneously activated and powered with a uniform current. This specific configuration, while not typically employed in standard operations, was implemented to provide a controlled setup for benchmarking the models.

Similar to the procedure described for the activation of the F8L circuit, the MRP corrections and PFW were activated sequentially to minimize abrupt MRP variations and mitigate beam losses. As an example, Fig. 5.29 illustrates the activation sequence of the MRP corrections and the I_{PFW} currents throughout the flat cycle at 2.79 GeV/c, where the IPFW currents were ranged between 6 A to -6 A as higher currents resulted in unstable beam conditions. On the 10.14 GeV/c and 18.00 GeV/c plateaus, I_{PFW} currents were ranged between ± 25 A ± 40 A, respectively.

Tune measurements

To capture the tune variations at different I_{PFW} currents while ensuring that tune detection was not influenced by coupling-driven lines in the

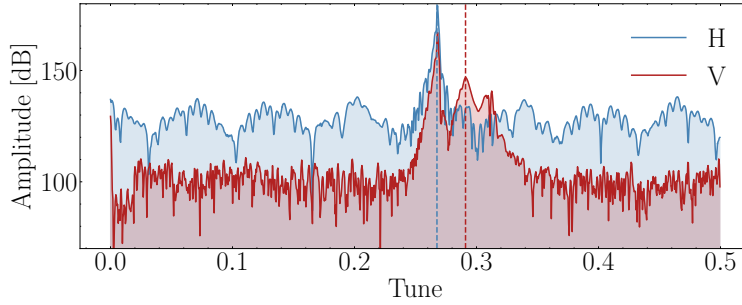


Figure 5.30. Example of FFT spectrum with PFW circuits activated. In the legend, H and V refer to the horizontal and vertical planes, respectively.

spectrum, the FFT peak detection window and excitation frequency range were iteratively adjusted. These adjustments were guided by the spectrum from previous measurement step (for example, varying the I_{PFW} current) to optimize the chirp settings. This approach ensured the highest measurement precision during the plateau phase with the PFW circuits activated, but did not track the tune evolution prior to PFW activation - an aspect not critical for this analysis. Fig. 5.30 illustrates, as an example, the FFT spectra for $I_{PFW} = 1$ A at $t = 604$ ms on the flat-cycle at injection energy. The figure highlights that, without carefully configured peak detection windows, coupling lines would interfere with the accuracy of the tune measurements.

Figure 5.31 displays, as an example, the measured horizontal (top) and vertical (bottom) tunes on the 2.79 GeV/c plateau at various I_{PFW} currents. For positive I_{F8L} currents, an increase in tune was observed in both planes, while negative currents led to a tune decrease relative to the bare-machine configuration ($I_{PFW} = 0$). Compared to the measurements taken with the F8L circuit, those conducted with the PFW circuits showed higher noise levels within the FFT spectrum, as shown in Fig. 5.30, resulting in slightly broader error bars, capturing the subtle shot-by-shot variability introduced by the higher-order harmonics. Nonetheless, the stability across the plateau remained robust in both planes, allowing for consistent monitoring of the tune evolution across the plateau. The horizontal and vertical tune measurements with PFW activated were averaged in the region of the 2.79 GeV/c plateau delimited by the dashed gray lines, and are reported in

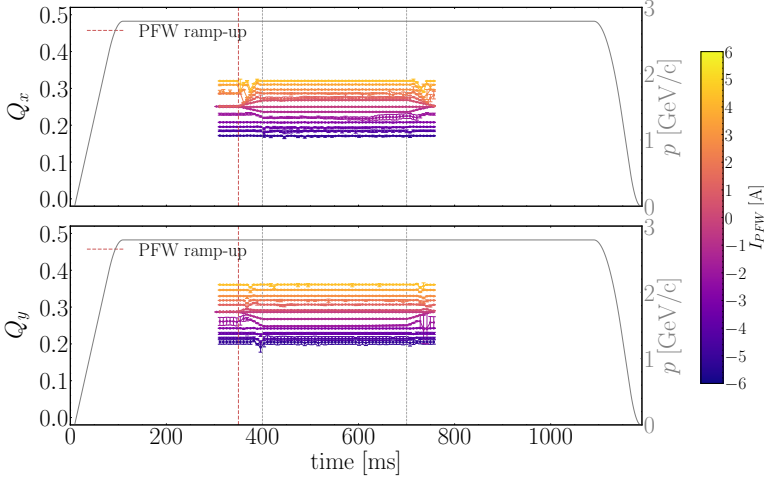


Figure 5.31. Horizontal and vertical tunes measurements, on top and bottom row, respectively, with PFW circuit on at 2.79 GeV/c flat-cycle at various I_{PFW} .

Fig. 5.32 in blue and red, respectively, across various I_{PFW} values. Comparable tune-shifts were observed in the horizontal and vertical planes. A second-order polynomial fit, along with its covariance, is included for each plane to illustrate the trend and response variability. The fit reveals a less linear response of the tunes on the I_{PFW} current compared to the behavior observed with the F8L circuit. This observation suggests a more complex interaction between the PFW-generated field harmonics and the beam optics relative to the F8L activation, confirming that the PFW contribution introduces higher complexities in predicting the beam dynamics in the machine. A consistent trend was observed in the tune measurements conducted at 10.14 GeV/c and 18.00 GeV/c, as reported in Figs. 5.33 and 5.34, respectively, illustrating the averaged tune measurements as a function of the I_{PFW} current. Additionally, a progressively less linear response of the tunes to I_{PFW} at increasing plateau energies was observed, as demonstrated by the polynomial fits.

Such complexities underline the need for accurate models to predict the PFW harmonics and capture their impact on the beam.

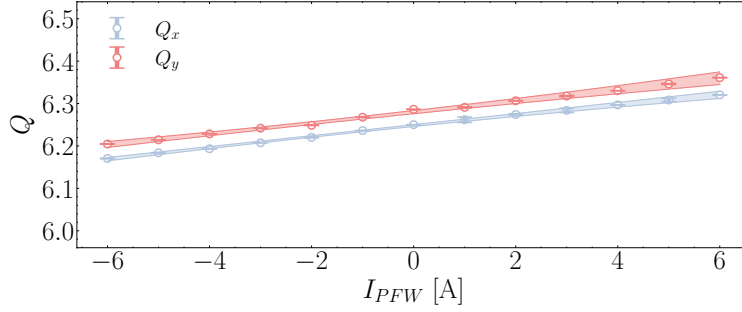


Figure 5.32. Averaged measured horizontal (blue) and vertical (red) tunes on the 2.79 GeV/c flat-cycle as a function of the I_{PFW} current.

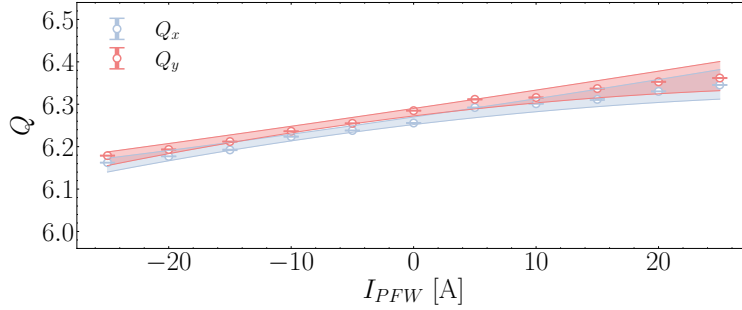


Figure 5.33. Averaged measured horizontal (blue) and vertical (red) tunes at 10.14 GeV/c as a function of the I_{PFW} current.

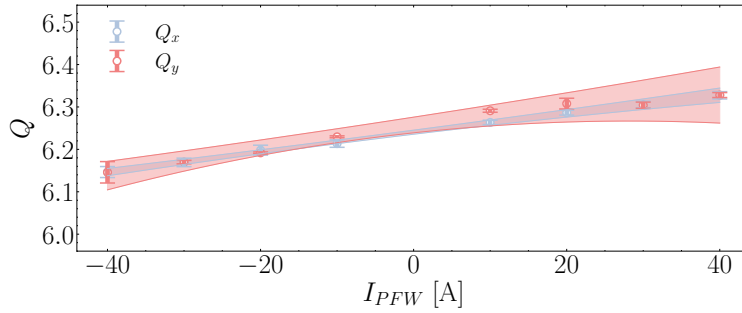


Figure 5.34. Averaged measured horizontal (blue) and vertical (red) tunes at 18.00 GeV/c as a function of the I_{PFW} current.

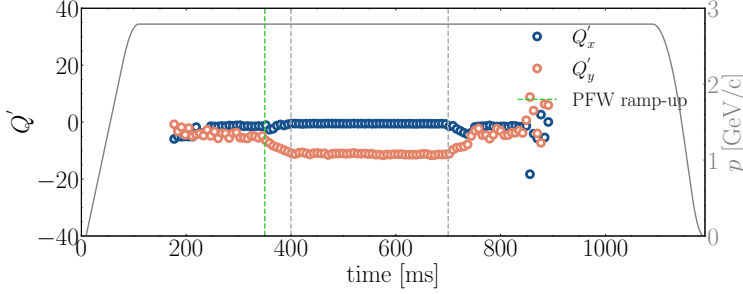


Figure 5.35. Horizontal and vertical chromaticities measurements in blue and orange, respectively, on the 2.79 GeV/c flat-cycle with $I_{PFW} = 1$ A.

Chromaticity measurements

Chromaticity measurements were conducted using the same MRP and PFW activation sequence as employed in the tune measurements, as shown in Fig. 5.29 for the flat-cycle at 2.79 GeV/c. To examine the influence of PFW harmonics on the optics, measurements were performed over a carefully selected but broad range of I_{PFW} currents. For example, on the flat-cycle at 2.79 GeV, chromaticity measurements were conducted at ± 5 A, ± 3 A, ± 2 A, and ± 1 A. The r_{pos} scan was constrained to within ± 10 mm around the target MRP value to ensure it remained within tolerance. Extending the range further led to unacceptable beam losses during the chromaticity scan.

Figure 5.35 displays the horizontal and vertical first-order chromaticity measurements across the flat-cycle at injection energy, shown in blue and orange, respectively, at $I_{PFW} = 1$ A. Significant variations in chromaticity were observed, especially on the vertical plane, when the PFW circuits were ramped-up at $t = 350$ ms, marked by the green dashed line. Once I_{PFW} currents stabilized at $t = 400$ ms, the chromaticity measurements demonstrated excellent stability across the plateau. The influence of the sextupolar field generated by the PFW was also examined at higher energies.

On the 10.14 GeV/c plateau, chromaticity measurements were conducted at I_{PFW} current settings of ± 20 A, ± 15 A, ± 10 A, and ± 5 A. Similarly, on the 18.00 GeV/c plateau, measurements were performed at ± 40 A, ± 30 A, ± 20 A, and ± 10 A. Similarly to what shown in Fig. 5.35,

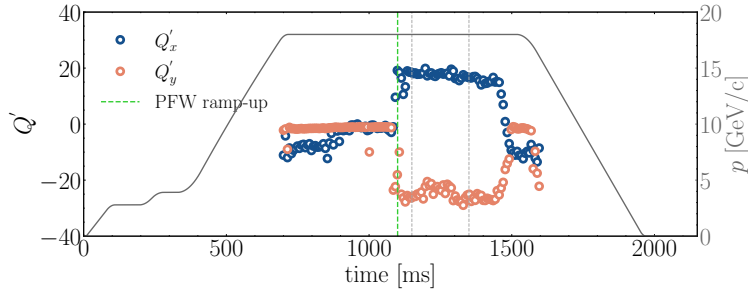


Figure 5.36. Horizontal and vertical chromaticities measurements in blue and orange, respectively, on the 18.00 GeV/c plateau with $I_{PFW} = 40$ A.

Fig. 5.36 shows the chromaticity measurements on the 18.00 GeV/c plateau at $I_{PFW} = 40$ A⁴. Following the activation of the PFW, marked by the dashed green line, a clear shift of the chromaticity in opposite direction was observed in both planes. More details on the chromaticity measurements at different energies varying the I_{PFW} current are reported in Appendix A.1.

The measurements were averaged within the stable region, delineated by the gray dashed lines, and are presented as a function of I_{PFW} currents in Figs. 5.37, 5.38, and 5.39 for 2.79 GeV/c, 10.14 GeV/c, and 18.00 GeV/c, respectively. An excursion of the chromaticity in both planes from approximately -30 to 20 was observed when varying the I_{PFW} currents across the different energy levels. Comparing these results with those including F8L reveals that the chromaticity measurements exhibit a pronounced dependence on the PFW currents, underscoring significant role of PFW in chromaticity control within the accelerator.

5.6.1 PFW effects on the measurements: outcome

Tune and chromaticity measurements were conducted on the 2.79 GeV, 10.14 GeV and 18.00 GeV energy plateaus, ranging the I_{PFW} currents. The effect of the PFW-generated field harmonics were evident in both tune and chromaticity measurements. In contrast to what was observed with the F8L, tune-shifts were observed in the same direction when varying

⁴To conduct the chromaticity measurements at 18.00 GeV/c with PFW, the plateau region in the power cycle was extended to minimize MRP shifts and beam losses during the PFW activation

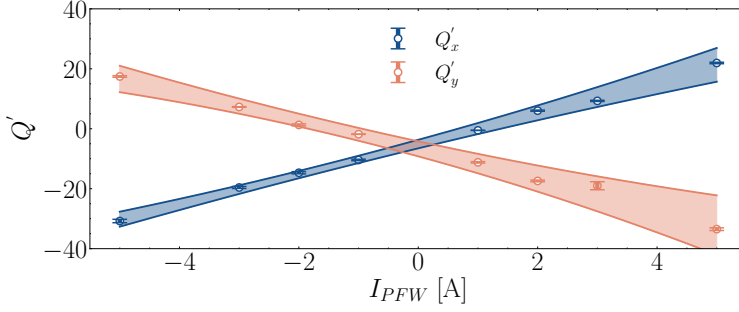


Figure 5.37. Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 2.79 GeV/c flat-cycle as a function of the I_{PFW} current.

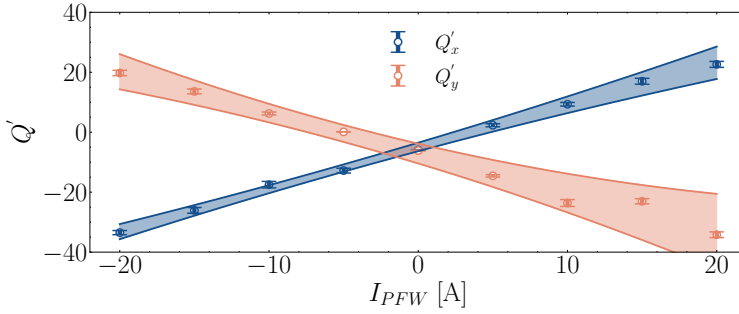


Figure 5.38. Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 10.14 GeV/c plateau as a function of the I_{PFW} current.

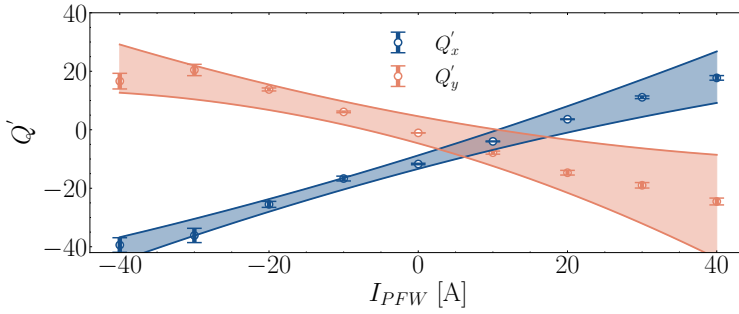


Figure 5.39. Averaged measured horizontal (blue) and vertical (orange) chromaticity on the 18.00 GeV/c plateau as a function of the I_{PFW} current.

the I_{PFW} current. The strong effect of the PFW harmonics was observed, in particular, in the chromaticity measurements, where large variations in opposite direction were observed in the horizontal and vertical planes. The variation of tune and chromaticity ($\partial Q/\partial I_{PFW}$ and $\partial Q'/\partial I_{PFW}$, respectively), at the three energy levels, is reported in Tabs. 5.12 and 5.13. A significantly higher impact of the PFW-generated harmonics on the chromaticity was observed, in contrast to the results obtained with the F8L circuit (Tab. 5.11) ⁵. These shifts in the measurements are benchmarked with the models predictions in Chapter 6.

5.7 Combined effect of F8L and PFW with LHC cycle powering settings

In previous sections, beam-based measurements were presented with either the bare-machine configuration or with uniform powering of auxiliary circuits, assessing the influence of individual circuits on the measured optics. This analysis, conducted at three distinct energies, demonstrated a significant tune dependence on the I_{F8L} current, while chromaticity showed

⁵Rate of change in tunes is higher with PFW, but the current range is reduced at a defined energy with respect to F8L

Table 5.12. Tune variation on energy plateau across the I_{PFW} current scan.

p_0 [GeV/c]	$\partial Q_x/\partial I_{PFW}$ [1/A]	$\partial Q_y/\partial I_{PFW}$ [1/A]
2.79	0.013	0.013
10.14	0.004	0.004
18.00	0.002	0.002

Table 5.13. Chromaticity variation on energy plateau across the I_{PFW} current scan.

p_0 [GeV/c]	$\partial Q'_x/\partial I_{PFW}$ [1/A]	$\partial Q'_y/\partial I_{PFW}$ [1/A]
2.79	5.15	-4.87
10.14	1.41	-1.33
18.00	0.74	-0.59

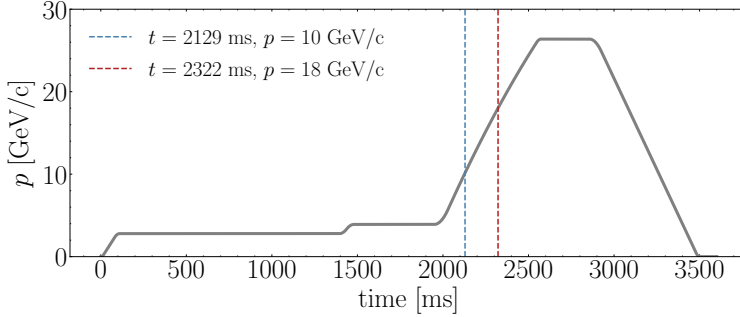


Figure 5.40. Operational LHC power cycle.

slight variations. Additionally, higher-order harmonics generated by the PFW were shown to impact tune measurements and, in particular, chromaticity due to their sextupolar component.

This section examines the cumulative response of the machine with all the circuits activated. In contrast to the previous section, where only one circuit was energized to isolate its effect, the measurements presented in this section were performed using the settings of an LHC operational cycle on the bare-machine cycles, enabling a broader assessment of the combined circuits effects on the beam. This aims to analyze a different, more complex scenario for the models benchmarking, characterized by the simultaneous powering of main coil, F8L and PFW (with different currents between wide and narrow circuits). The operational LHC cycle used for this analysis was the **LHC25#48b-BCMS-LowTail-24** cycle, depicted in Fig. 5.40.

To assess the combined influence of all MU circuits on the optics measurements, the bare-machine cycles with the 10.14 GeV/c and 18.00 GeV/c plateaus were utilized. The first enables measurements unaffected by remanent field and distortions from iron saturation. In contrast, the 18.00 GeV/c plateau enables the examination of measurements influenced by saturation distortions.

From the ramp of the LHC cycle depicted in Fig. 5.40, the 10.14 GeV energy is reached at $t = 2129$ ms, marked by the dashed blue line, while 18.00 GeV is reached at $t = 2322$ ms, marked in red. Using LSA, the powering currents of the various circuits were extracted at these specific

time steps, and are reported in Tab. 5.14. These currents, along with corrections needed to keep the MRP within the accepted tolerance, were applied on the 10.14 GeV/c and 18.00 GeV/c plateaus.

LHC operational settings on the 10.14 GeV/c cycle

MRP and tune measurements were conducted throughout the bare-machine cycle with the 10.14 GeV/c plateau, applying the LHC powering configurations to the F8L and PFW circuits reported in Tab. 5.14. Fig. 5.41 presents the beam-based measurements tracked across the entire power cycle. On the top plot, the measured MRP (in purple) with the applied corrections overlaid (in orange) are presented; in the middle plot, the corresponding horizontal and vertical tune measurements are shown in turquoise and red, respectively, while the bottom plot displays the horizontal and vertical first order chromaticity in light blue and light red, respectively.

On the 10.14 GeV/c plateau, the initial MRP was already within acceptable limits, requiring only minimal adjustment to maintain it within tolerance. Consequently, the MRP correction trim, indicated by the green dashed line in both plots, had negligible impact on the tunes, which remained stable without notable shifts. In contrast, the activation of the auxiliary circuits at $t = 1350$ ms caused a marked tune-shift. While the horizontal tune experienced a substantial variation, the vertical tune showed a comparatively weaker response. Fig. 5.42 shows the horizontal and vertical

Table 5.14. Powering currents in the different MU circuits on the operational LHC-type cycle at 10.14 GeV/c and 18.00 GeV/c.

Circuit	Current [A]	
	10.14 GeV/c	18.00 GeV/c
Main Coil	1925.30	3428.00
F8L	350.00	558.50
PFW - DN	-35.91	-54.60
PFW - DW	-47.86	-79.10
PFW - FN	23.53	42.80
PFW - FW	10.65	18.60

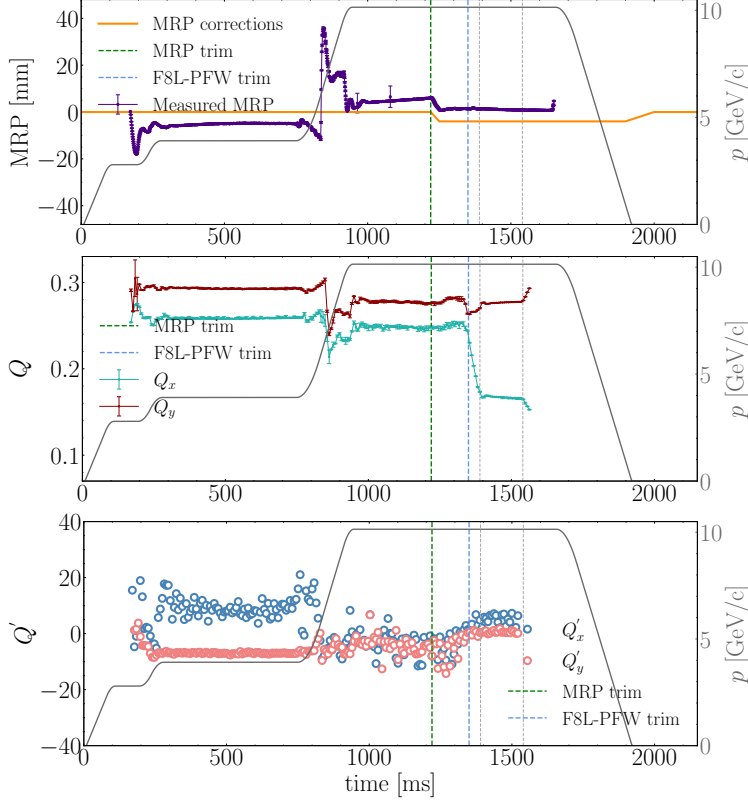


Figure 5.41. Beam-based measurements on the bare-machine cycle to the 10.14 GeV/c plateau with MRP corrections and auxiliary circuits powered using LHC cycle settings. Top plot displays MRP measurements (purple) and corrections (orange), middle plot horizontal (turquoise) and vertical (dark red) tunes, bottom plot horizontal (light blue) and vertical (light red) first order chromaticity.

spectra at $t = 1430$ ms, with both the PFW and F8L circuits activated. The peaks in the FFT spectrum in both planes are well-defined, a result of the carefully selected FFT excitation frequency and peak detection window settings, which ensured clear and precise spectral resolution.

Similarly to the tunes, the chromaticity did not exhibit a significant variation following the application of the MRP corrections. However, once the currents in the additional circuits stabilized ($t = 1350$ ms), an increase

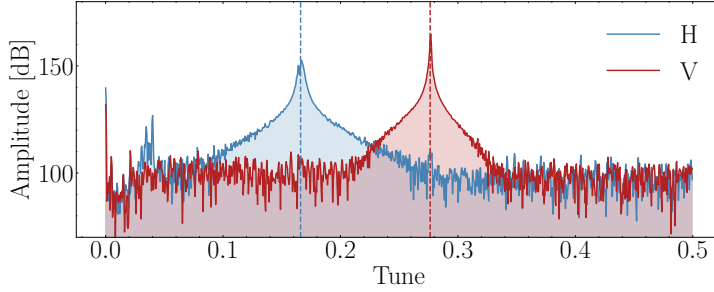


Figure 5.42. Horizontal and vertical spectrum in blue and red, respectively, on the 10.14 GeV at $t = 1388$ ms.

in chromaticity was observed in both planes. The earlier assessment of the beam optics response to the activation of individual circuits indicated that the F8L circuit had minimal impact on chromaticity. Therefore, the observed shift in chromaticity can be attributed to the higher-order harmonics generated by the PFW circuits, which play a more dominant role under these conditions.

Similarly to what seen at 10.14 GeV/c, tunes and chromaticity measurements with LHC-cycle powering settings conducted on the 18.00 GeV/c plateau are reported in Fig. 5.43. Carefully selected corrections allowed to achieve an MRP within the tolerance in the region of the plateau delimited by the dashed green lines. Following the activation of the auxiliary circuits at $t = 1100$ ms, tune and chromaticity exhibited measurable variation in both planes.

Measurements showed notable stability in the plateau region in which MRP was controlled (between the dashed gray lines) and were averaged within these regions, and reported in Tabs. 5.15 and 5.16 for tunes and chromaticity, respectively.

Table 5.15. Averaged tune measurements on the 10.14 GeV/c and 18.00 GeV/c plateau with LHC-cycle powering settings.

p_0 [GeV/c]	$q_{x,av}(p_0)$	$\sigma_{q_{x,av}}(p_0)$ [%]	$q_{y,av}(p_0)$	$\sigma_{q_{y,av}}(p_0)$ [%]
10.14	0.1670	0.60	0.2770	0.36
18.00	0.2130	0.19	0.2100	0.48

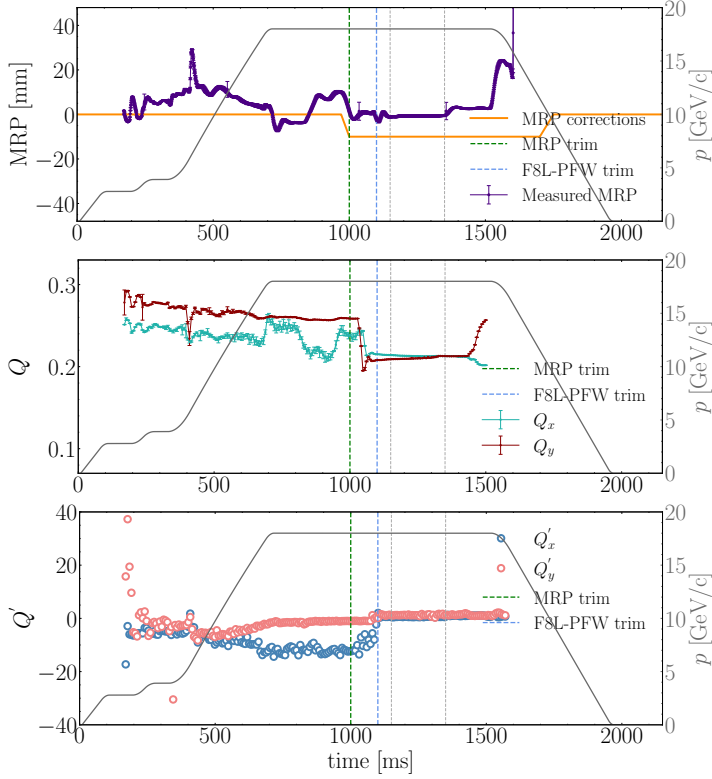


Figure 5.43. Beam-based measurements on the bare-machine cycle to the 18.00 GeV/c plateau with MRP corrections and auxiliary circuits powered using LHC cycle settings. Top plot displays MRP measurements (purple) and corrections (orange), middle plot horizontal (turquoise) and vertical (dark red) tunes, bottom plot horizontal (light blue) and vertical (light red) first order chromaticity.

Table 5.16. Averaged chromaticity measurements on the 10.14 GeV/c and 18.00 GeV/c plateau with LHC-cycle powering settings.

p_0 [GeV/c]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
10.14	4.64	11.64	0.59	59.32
18.00	0.55	14.55	1.24	24.19

5.8 Discussion and outcome

Chapter 5 presented the beam-based measurements conducted to evaluate the beam optics' response under various powering configurations.

To primarily assess the impact of the MU's individual circuits on the tune and first-order chromaticity, measurements were performed in the bare-machine configuration (with only the main coil powered) across specifically designed power cycles. These studies highlighted the significant influence of MRP variations on tune evolution throughout each cycle. MRP corrections were implemented to achieve a target value of zero within a tolerance of ± 1 mm on each energy plateau, facilitating accurate static tune measurements. The application of MRP corrections throughout the ramp to the 23.11 GeV/c plateau ensured that tune and chromaticity dynamic measurements were unaffected by MRP fluctuations. This provided the foundation for a clear comparison between static and dynamic measurements. The two sets of tune and first-order chromaticity measurements were found to be equivalent for benchmarking the models, as they did not exhibit any significant differences. This outcome demonstrated the negligible impact of transient effects on tune and first-order chromaticity in the bare-machine configuration. Consequently, the models, which do not account for dynamic effects, could be confidently employed for further analysis and benchmarking.

In operation, for tune and chromaticity control, F8L and PFW circuits are used for tune and chromaticity control. Thus, additional measurements were conducted individually powering each auxiliary circuit, including MRP corrections. These measurements were conducted at injection energy, 10.14 GeV/c and 18.00 GeV/c. A linear response of the tunes on the I_{F8L} current was seen, while chromaticity did not show strong dependence on the F8L current. Conversely, a strong dependence of the chromaticity on I_{PFW} current was seen, with a fairly linear response.

Ultimately, to investigate a more complex scenario foreseeing the simultaneous powering of all the MU's circuits, additional measurements were conducted importing the powering settings from a LHC operational cycle on the 10.14 GeV/c and 18.00 GeV/c plateau. The impact of the intricate simultaneous powering of the MU's circuits was seen in the tune and chromaticity measurements when the circuits are activated.

Chapter 6

Models' benchmarking against beam-based measurements

The measurements in Chapter 5 showed the possibility of accurately measuring tune and chromaticity throughout power cycles characterized by progressively higher energy plateaus. This was achieved by MRP monitoring and corrections carefully integrated in the measurements. The measurements showed that, once MRP corrections are included, the main body of the ramps were not significantly perturbed by dynamic effects. The beam-based measurements presented in Chapter 5 are used to benchmark the new combined magnetic and optics models, introduced in Chapter 4, aiming to assess their robustness and predictive power.

The initial assessment, presented in Section 6.1, focuses on evaluating the models' predictions under the bare-machine configuration. This analysis will allow to correct for the momentum computation employed in operation by using the predictions from the magnetic model. Subsequently, in Section 6.2 and Section 6.3 the simulated response of the beam parameters with the individual and combined powering of the auxiliary circuits are compared against the measurements. Tune and chromaticity responses represent the key figures of merit for operation, however to test in more detail the robustness of the models advanced optics studies were conducted, making more detailed measurements by looking at the local optics in the machine (rather than the global tune and chromaticity observables previously considered). These are reported in Section 6.4.

6.1 Bare-machine models' validation

The main coil currents corresponding to each energy plateau introduced in Chapter 5 and reported in Tab. 5.1 were used to simulate the field map within the MU's aperture at various energy levels with the new MU magnetic model, discussed in Section 4.2. These plateaus were further supplemented by additional points extracted from continuous measurement on the 23.11 GeV/c cycle, corresponding to 19.52 GeV/c, 20.99 GeV/c, and 21.99 GeV/c to allow a more detailed set of points for models benchmarking at energy levels where saturation effects are predominant.

Field harmonics were computed in Opera using the field equations in polar coordinates detailed in Section 1.2, and following the integration approach described in Section 4.2. To provide operation with a predictive tool to support tune and chromaticity control, quadrupolar and sextupolar field harmonics were extracted from the magnetic model and incorporated in the MAD-X optics model. These harmonics, initially expressed in Tesla and referenced to a radius of $R_{ref} = 35$ mm, were subsequently converted into magnet strengths k_n with units of $[m^{-n}]$, as described in Section 1.2, and applied to the corresponding objects of the MAD-X model, reported in Fig. 4.8. Tab. 6.1 summarizes the quadrupolar strengths for the focusing and defocusing SBENDs ($k_{1,F}$ and $k_{1,D}$, respectively), the fringe field MULTIPOLES ($k_{1,FF}$ and $k_{1,FD}$, respectively), and the focusing-defocusing transition region ($k_{1,FD}$). Similarly, Tab. 6.2 reports the sextupolar strengths in the different objects of the MAD-X model, at various energies.

To replicate the bare-machine configuration employed during the beam-based measurements, the strengths corresponding to the F8L and PFW currents were set to zero. Additionally, all corrector magnets around the ring were deactivated.

6.1.1 Predicted vs. measured tunes: a comparative analysis

The optics models at each specific energy were defined using the MU multipolar strengths defined in Tabs. 6.1 and 6.2. The output of the simulations was stored in a Twiss file.

Figure 6.1 reports the comparison between simulated and measured

tunes. The plot on the left displays the horizontal tunes, with simulated values shown in light blue and measured values in dark blue; the right plot refers, with the same colors, to measured and simulated vertical tunes. Simulations demonstrated good agreement with measurements. Models

p_0 [GeV/c]	k_1 [m^{-2}]				
	$k_{1,F}$	$k_{1,D}$	$k_{1,F,F}$	$k_{1,F,D}$	$k_{1,FD} \times 10^{-5}$
2.79	0.058071	-0.058193	0.002554	-0.002635	-8.909062
5.25	0.058192	-0.058251	0.002544	-0.002621	-6.553825
7.00	0.058201	-0.058238	0.002527	-0.002602	-5.372469
10.14	0.058214	-0.058229	0.002476	-0.002548	-1.971222
14.04	0.058209	-0.058209	0.002377	-0.002452	-4.247813
18.00	0.058110	-0.058093	0.002229	-0.002298	-1.429595
19.52	0.057955	-0.057928	0.002154	-0.002226	-0.209270
20.99	0.057772	-0.057731	0.002076	-0.002147	-0.461192
21.99	0.057535	-0.057482	0.002016	-0.002087	-0.836036
23.11	0.057173	-0.057109	0.001947	-0.002017	-1.113784

Table 6.1. Simulated quadrupolar strengths in the different MU regions at various energies.

p_0 [GeV/c]	k_2 [m^{-3}]				
	$k_{2,F}$	$k_{2,D}$	$k_{2,F,F}$	$k_{2,F,D}$	$k_{2,FD} \times 10^{-5}$
2.79	-0.009284	-0.008494	0.022810	0.023342	0.616315
5.25	-0.009051	-0.008800	0.022871	0.023360	0.612694
7.00	-0.009070	-0.009013	0.022891	0.023353	0.607090
10.14	-0.009353	-0.009565	0.022808	0.023149	0.591666
14.04	-0.010318	-0.010626	0.022482	0.022920	0.555961
18.00	-0.012432	-0.012997	0.021431	0.021963	0.505178
19.52	-0.014328	-0.015045	0.020649	0.021197	0.479131
20.99	-0.018061	-0.019023	0.019901	0.020457	0.448802
21.99	-0.022559	-0.023682	0.019327	0.019861	0.424174
23.11	-0.029352	-0.030695	0.018653	0.019133	0.393190

Table 6.2. Simulated sextupolar strengths in the different MU regions at various energies.

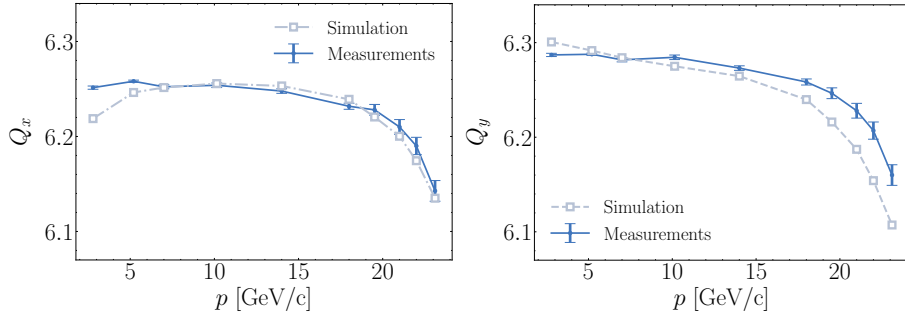


Figure 6.1. Comparison between simulated and measured tunes. The left plot shows horizontal tunes, with simulated values in light blue and measured values in dark blue. The right plot presents vertical tunes, maintaining the same colors for measured and simulated points.

correctly predict the integer part of the tunes (6). Simulated tunes closely align with the experimental data over the whole range of energy. Tune measurements in bare-machine revealed a rapid decrease at higher energies on both planes, which is well captured by the new combined magnetic and optics models. Specifically, this saturation fell within the error bars for the horizontal tunes, while a slightly more pronounced saturation compared to the measurements was seen on the vertical plane. At injection energy, a discrepancy was seen between simulations and measurements. This was expected due to the remanent field hysteresis effect, which is not included in the model, as previously mentioned in Section 3.2. Consequently, a discrepancy below $4 \cdot 10^{-2}$ was seen. Above 2.79 GeV/c, the remanent field effect diminishes and is expected to become negligible. In fact, the quality of agreement progressively improves. In particular, between 5.25 GeV/c and 14.04 GeV/c, remanent field effects are very small and saturation is not significant, resulting in an excellent agreement with discrepancy on the level of 10^{-3} .

The relative error between the tune models' predictions and the measurements is indicated with ϵ_Q and is defined as following:

$$\epsilon_Q = \frac{\Delta Q}{Q_{meas}} = \frac{Q_{meas} - Q_{sim}}{Q_{meas}} \cdot 100 \quad (6.1)$$

Figure 6.2 reports the relative error ϵ_Q for the horizontal and vertical

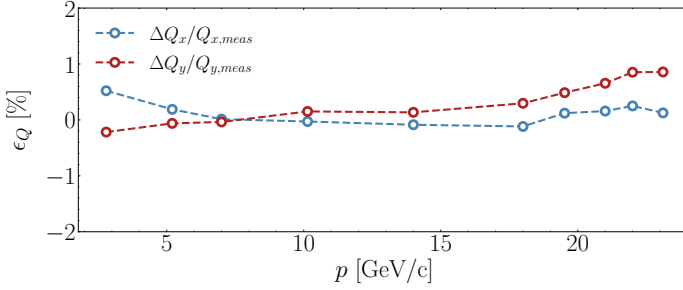


Figure 6.2. Horizontal and vertical tunes relative error between models' predictions and the beam-based measurements in blue and red, respectively.

tunes in blue and red, respectively. It shows that the tunes relative errors are below the 1 % level, with the maximum error at injection for the horizontal tunes of 0.5 % and of 0.85 % at high energy for the vertical.

6.1.2 Quadrupole saturation from magnetic model

Beam-based measurements revealed a clear, rapid decrease of both horizontal and vertical tunes above 10.14 GeV/c. Same behavior was also observed from the models. The underlying cause of this phenomenon was investigated.

MU main coil current is defined by the required magnetic field necessary to keep beam circulating at higher energies on a constant circumference. The tune decrease suggested a more rapid saturation of the quadrupolar component generated by the MU with respect to the saturation of the dipolar component ¹. This is supported by the predictions from the magnetic model. In this context, Fig. 6.3 presents the simulated quadrupolar strengths derived from Opera, which served as input for the optics simulations. The left plot illustrates the quadrupolar strengths of the SBENDs in the focusing and defocusing half-units, shown in light blue and dark blue, respectively. In the right plot, the quadrupolar strengths associated with the focusing and defocusing MULTIPOLES, which incorporate the contributions from fringe fields, are similarly represented in light red and dark red. Initially, it was suspected that saturation of the fringe fields was

¹If dipolar and quadrupolar component would saturate at same rate, tunes would stay constant at increasing energy.

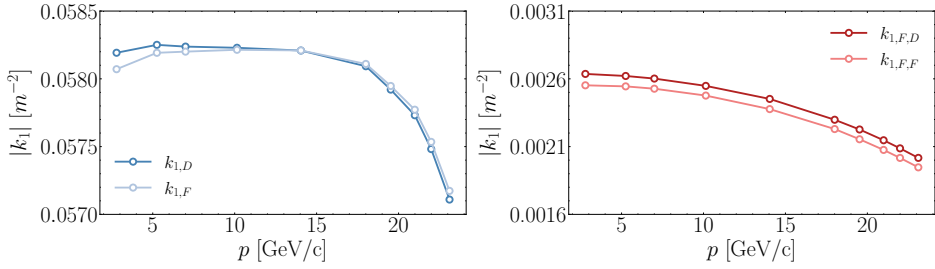


Figure 6.3. On the left, simulated quadrupole strengths in the focusing and defocusing SBENDS in light blue and dark blue. On the right, simulated quadrupole strengths in the focusing and defocusing MULTIPOLES in light red and dark red, respectively.

the primary cause of the quadrupole drop at increasing energy. By breaking down the harmonics in the half-units cores and fringe fields, the faster saturation of the quadrupolar field is associated to the half-units cores. Indeed, the model reveals that the quadrupole generated within the main body of the half-units exhibits corresponding pattern of rapid saturation as the tunes at high energies, consistent with the tune drop seen from the measurements.

Thus, the saturation of the quadrupolar strengths generated by the MU is attributed to the onset of iron saturation effects within the magnetic cores. These effects directly influence the field harmonics, thereby altering the machine's tune responses. This phenomenon is qualitatively illustrated in Fig. 6.4, which depicts the 2D field maps generated by the magnetic model at 10.14 GeV and 18.00 GeV on the left and on the right, respectively. The field maps reveal that the hyperbolic pole, characteristic of an ideal quadrupole, begins to saturate at its edges as energy increases. This localized saturation reduces the effectiveness of the quadrupole field generation relative to the dipole field. Consequently, as the energy surpasses approximately 14 GeV/c, the increase in quadrupole strength does not scale proportionally with the increase in dipole strength. This imbalance leads to the observed reductions in tune, highlighting the significant role of iron saturation in shaping the beam dynamics at higher energies.

This behavior is corroborated by the B_2/B_1 at different energies, shown in Fig. 6.5. This ratio demonstrates a clear collapse at higher energies,

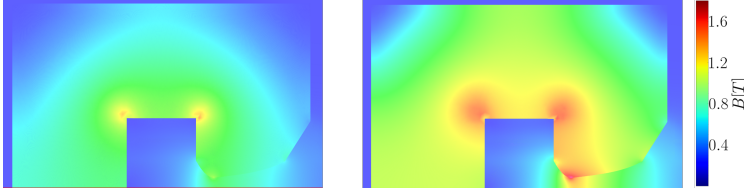


Figure 6.4. PS-MU magnetic model: 2D field map at 10.14 GeV/c (left) and 18.00 GeV/c (right).

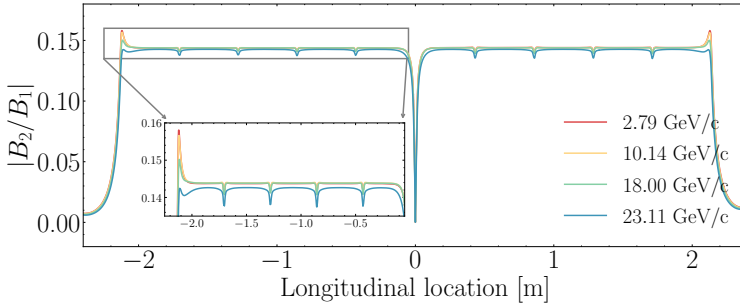


Figure 6.5. Simulated B_2/B_1 ratio at 2.79 GeV/c (red), 10.14 GeV/c (orange), 18.00 GeV/c (green) and 23.11 GeV/c (blue).

indicating the diminishing influence of quadrupolar component relative to the dipole field. This effect occurs at lower energies primary at the magnet extremities and it is pronounced in the half-unit cores at increasing energy, as highlighted in the zoomed inset. This observed reduction in the quadrupole generated by the MU relative to the dipole field provides a compelling explanation for the tune drops at elevated energies, where iron saturation effects become increasingly dominant.

6.1.3 Model improvement driven by magnetic length saturation predictions

The tune comparison between models' predictions and beam-based measurements revealed an agreement within the error-bars on the horizontal plane in the saturation region, while a larger discrepancy was observed on the vertical plane. If true, this would imply that saturation is modeled more precisely in one half-unit with respect to the other. This seems im-

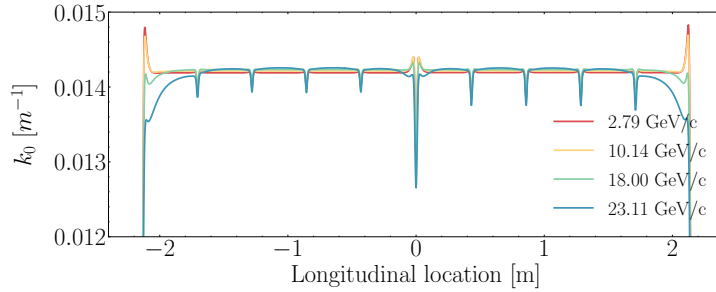


Figure 6.6. Dipole field within the MU normalized to the magnetic rigidity at 2.79 GeV/c (red), 10.14 GeV/c (orange), 18.00 GeV/c (green) and 23.11 GeV/c (blue).

plausible as they are characterized by the same material construction, and hence would expect to be described by the same hysteresis curve in the magnetic model.

The increasing discrepancy of Q_y at higher energies was also unexpected in light of the comparison between the predicted field from the magnetic model and the B-train measurements, showed in Section 4.2. This comparison highlighted the convergence of the model predictions to the B-train measurements for higher energies. This pointed to something missing in the models, which was not captured by the B-train comparison.

Hence, saturation-driven effects in the fringe fields, which are not captured by the B-train due to their position in the MU (detailed in Section 2.2), could be an explanation for the different discrepancy observed between the horizontal and vertical tunes. Fig. 6.6 shows the dipole field from the magnetic model, at four different energies, as a function of the longitudinal location in the MU, normalized to the magnetic rigidity ($k_0 [m^{-1}]$). The more rapid saturation of the dipole field at the fringe fields at higher energies is visible in the blue curve, illustrating the dipole field at 23.11 GeV/c. In light of this observation, it was decided to assess the magnetic length predicted by the model.

Magnetic length

The MAD-X optics simulations rely on the estimate of the beam momentum to convert the field harmonics computed in Opera (B_n) into mag-

net strengths (k_{n-1}). The beam momentum, accessible through LSA, is derived from the magnetic rigidity, following Eq. 1.7. In the previous sections, the field from the magnetic model was normalized using the programmed momentum of the specific cycle from LSA. This designed momentum is regulated based on the B-train measurements, which ensure that the designed and the actual field in the machine matches. The nominal calculation used in the design of PS cycles assumes a constant magnetic length across the entire energy range, from injection to extraction, equal to the theoretical nominal magnetic length of the machine:

$$L_{m,nom} = \frac{C - L_{LS}n_{LS} - L_{SS}n_{SS}}{100} \quad (6.2)$$

being C the circumference of the machine equal to $2 \cdot \pi \cdot 100$, n_{LS} and L_{LS} the number of straight long sections (20) and their length (3 m), while n_{SS} and L_{SS} refers to the 80 short straight sections 1.6 m each. This relation returns a magnetic length of 4.403 m.

Using the magnetic model, the magnetic length was simulated at various energies, as shown in Fig. 6.7. At injection, the simulated magnetic length closely matches the theoretical value, with an error below the per-mill level. The figure clearly illustrates that the magnetic length decreases with increasing energy due to iron saturation. By 23.11 GeV/c, the magnetic length is reduced by approximately 0.8% compared to its value at injection.

This reduction is attributed to the onset of iron saturation, which impacts the effective field distribution. As the saturation of the dipole component is concentrated at the magnet extremities it not captured by the B-train regulation, and since the PS operation assumes both the magnetic length and the bending radius remain constant, the effect of magnetic length saturation is not accounted for in the programmed beam momentum evaluation.

This introduces a subtle yet important discrepancy in the magnetic strengths computation used in the optics model. The same effect is also evident from the simulation of the integrated dipole strengths k_0L , which are reported in Fig. 6.8. This also illustrates the problem with the programmed momentum computation because, with the machine circumference fixed and MRP forced to be constant, the k_0L should be constant.

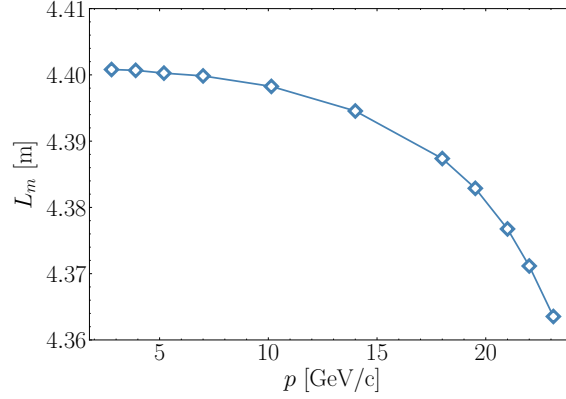


Figure 6.7. Simulated magnetic length at different energies.

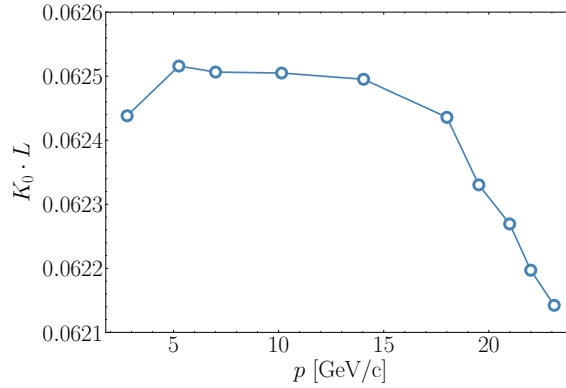


Figure 6.8. Simulated integrated dipolar strengths at different energies.

Overcoming B-train limitations via Single Stretched Wire measurements

Due to their longitudinal positioning within the MU, as carefully described in Section 2.2, the B-train coils do not capture the more rapid saturation of the iron at the magnet extremities compared to the main body of the half-units. To address this limitation and test Opera predictions of the magnetic length, magnetic measurements of the integrated field across the entire MU were performed by specialized a team at CERN [12], using the Single Stretched Wire (SSW) method [135–137]. This technique is used

for precision magnetic field measurements, especially in large magnets like those in particle accelerators. This method involves placing a thin, tensioned conductive wire along the longitudinal axis of the magnetic field to measure the integrated magnetic field along that path. A current is passed through the wire, creating a magnetic field around the wire that interacts with the magnetic field of the magnet being measured. This interaction produces a force on the wire (Lorentz force), which is proportional to the strength and direction of the magnetic field along the wire's path. The resulting force displaces the wire slightly. Sensitive detectors, such as position sensors or voltage probes, measure this displacement or the induced voltage along the wire. By measuring the displacement or voltage along the wire's path, the integrated magnetic field (field strength over distance) is calculated along the length of the wire. This is essential in regions where magnetic fields may vary, especially near the magnet extremities.

A straight wire was extended from one extremity of the MU to the other, with additional margin to account for fringe fields. The measured transfer function T_F obtained using the SSW system, defined as the ratio of the integrated field along the MU to the current I_{MC} , was calculated in units of Tm/kA [86] and is reported in Fig. 6.9 in red. It shows clearly that the B-train measurements, shown in green, due to its location, is not able to fully capture the dipole saturation at the magnet extremities. The OPERA model was used to make predictions of the simulated transfer function, which are depicted in black in Fig. 6.9. The SSW measured transfer function and the simulations confirm a rapid saturation of the dipole field at increasing energies, revealing a strong agreement between the two transfer functions at medium to high currents, where the saturation of the iron is significant.

6.1.4 Corrections for momentum computation

The potential for correcting in beam momentum computation caused by the saturation of the magnetic length was investigated through two distinct approaches.

The first approach adopted a theoretical framework based on physical principles. By definition, the integrated dipolar strength should remain constant across the energy range to ensure the circumference does not change (and since MRP is forced to be constant). By ensuring that the

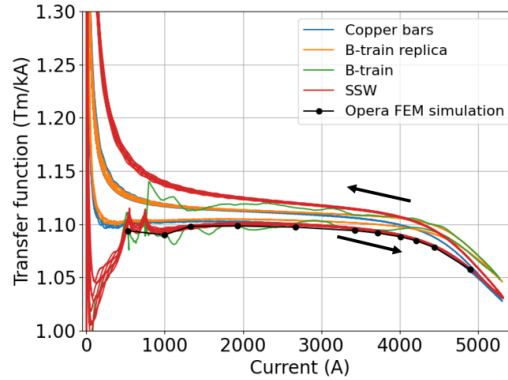


Figure 6.9. Comparison between measured transfer function with the SSW system (red) and simulated points (black) [12].

dipolar field integral remains flat, this method seeks to refine the momentum calculation while adhering to the expected physical behavior of the magnet. The second approach involved a direct momentum correction by incorporating the model-based magnetic length into the programmed momentum computation. Both approaches aimed to provide a more accurate evaluation of the beam momentum, ultimately enhancing the precision of the optics simulations and improving the agreement between modeled and measured machine behavior. The motivation for having these two distinct approaches is to provide a more accurate evaluation of the beam momentum, enhance the precision of optics simulations and improve the agreement with the measurements.

Corrected momenta computation by flattening k_0L

To correct for the error in the programmed beam momentum calculation due to saturation of the magnetic length/bending radius, a constant integrated dipolar strength was assumed over the entire momentum range. This strength was taken as its value at 10.14 GeV/c, denoted as $k_0(10.14 \text{ GeV/c})$, which remains approximately constant between 7.00 GeV/c and 14.04 GeV/c, as shown in Fig. 6.8. This intermediate point was selected as it minimizes the influence of both remanent fields and iron saturation effects. The dipolar strength k_0 at 10.14 GeV/c is computed as:

$$k_0(10.14 \text{ GeV}/c) = \frac{1}{3.3356p} B_{1,i}(10.14 \text{ GeV}/c) = 0.01116 \text{ [m}^{-1}] \quad (6.3)$$

where $B_{1,i}$ is the integrated dipole field across the MU, divided by the integration length and expressed in Tesla. Using this as the reference value, the corrected momenta p_{corr} can be computed by inverting the relation:

$$p_{corr} = \frac{B_{1,i}(p)}{3.3356 \cdot k_0(10.14 \text{ GeV}/c)} \quad (6.4)$$

This method ensures that the beam momentum is accurately adjusted to counteract the evolving magnetic properties of the machine as energy increases, which are not accounted for in the operational beam momentum computation.

Table 6.3 presents the operational beam momentum p_0 extracted from LSA, alongside the corrected beam momenta obtained by flattening k_0 at 10.14 GeV/c. This comparison highlights the impact of accounting for the saturation of the magnetic length on the beam momentum calculation. The table also includes the relative error between the operational and corrected momenta, expressed as a percentage. At 5.25 GeV/c and 7.00 GeV/c, the simulated dipole strengths exceed the reference dipole strength at 10.14 GeV/c, as shown in Fig. 6.8, which is used for momentum correction. This results in a negative relative error, as shown in the third column of Tab. 6.3.

Corrected momentum computation via magnetic length predictions from the model

The second approach involved computing the corrected beam momentum by integrating the predicted magnetic lengths from the model into the pre-existing calculation of the programmed momentum. This aims to correct the B-train-based estimate of the momentum by adding an extra input from the Opera magnetic model.

The magnetic length is related to the circumference bending radius via the following relation:

$$L_m = \frac{2\pi\rho}{N} \quad (6.5)$$

being $N = 100$ the number of MU distributed around the ring, which can be expressed as:

$$\rho = \frac{NL_m}{2\pi} \quad (6.6)$$

Substituting this into the definition of magnetic rigidity (Eq. 1.7), it is possible to write:

$$B\rho = B \frac{NL_m}{2\pi} = 3.3356 \cdot p \quad (6.7)$$

and so express the momentum as:

$$p = \frac{1}{2\pi} \frac{1}{3.3356} BNL_m \quad (6.8)$$

In operation, the nominal the momentum computation is based on the nominal magnetic length:

$$B\rho = B \frac{NL_m}{2\pi} = 3.3356 \cdot p \quad (6.9)$$

p_0 [GeV/c]	p_{corr} [GeV/c]	$\Delta p/p_0$ [%]
2.791	2.788	0.107
5.252	5.253	-0.017
7.000	7.000	-0.002
10.141	10.141	0.000
14.043	14.040	0.016
18.005	17.985	0.111
19.524	19.469	0.279
20.991	20.912	0.377
21.993	21.885	0.492
23.110	22.976	0.580

Table 6.3. Momentum correction based on flatten k_0L with the value it has at 10.14 GeV/c.

and so express the momentum as:

$$p = \frac{1}{2\pi} \frac{1}{3.3356} BN L_{m,nom} \quad (6.10)$$

conversely, the model-driven estimate of the magnetic length ($L_{m,model}$) is integrated into the existing calculation of the programmed momentum:

$$p = \frac{1}{2\pi} \frac{1}{3.3356} BN L_{m,model} \quad (6.11)$$

where B is the B-train measured field, reported in Tab. 4.5. Following this approach, momentum corrections obtained adding model-based estimate of magnetic length into the existing calculation of programmed momentum are presented in Tab. 6.4.

6.1.5 Simulated effect of momentum corrections

The magnetic length values obtained from the magnetic model at various energies were used to dynamically adjust the beam momentum calculation, thereby accounting for the gradual reduction in magnetic length due to iron saturation effects. These corrections aim to enhance the precision of optics simulations and align the beam momentum calculation with the

p_0 [GeV/c]	p_{corr} [GeV/c]	$\Delta p/p_0$ [%]
2.791	2.791	0.023
5.252	5.249	0.056
7.000	6.997	0.062
10.141	10.134	0.075
14.043	14.032	0.075
18.005	17.970	0.195
19.524	19.456	0.348
20.991	20.896	0.453
21.993	21.863	0.593
23.110	22.942	0.726

Table 6.4. Momentum correction adding model-based estimate of magnetic length into the existing calculation of programmed momentum.

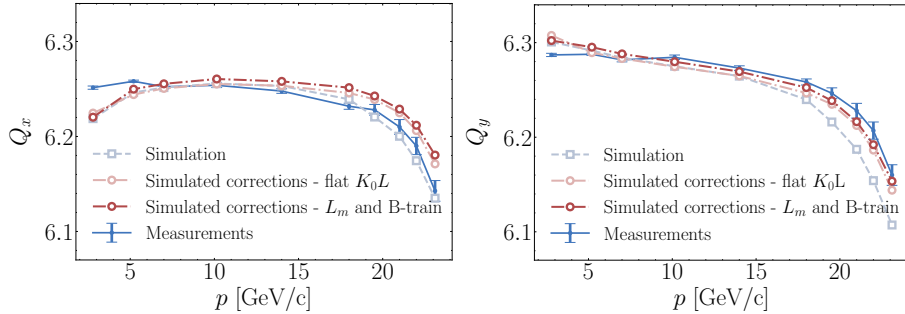


Figure 6.10. Comparison between simulated and measured tunes. The left plot shows horizontal tunes, with simulated values in dark blue and measured values in blue. The right plot presents vertical tunes, with measured values in light red and simulated values in dark red.

actual machine conditions. Using the corrected momenta with the two different approaches, quadrupolar strengths were computed again to account for these corrections in the optics simulations.

Figure 6.10 displays the measured and simulated tunes from Fig. 6.1, along with the simulated tunes incorporating momentum corrections to account for magnetic length saturation. Tunes corrected by flattening the k_0L are shown in light red, while those corrected using the simulated magnetic length and B-train measurements are shown in dark red. The two correction methods demonstrated good consistency. These momentum corrections resulted in an increase in tunes in both planes. The horizontal simulated tune exhibited a slight over-correction, but still within the measured standard deviation, while, with these corrections, the vertical predicted tunes fall within the measurement error bars across the entire energy range. The comparable saturation and agreement seen on the horizontal and vertical plane is consistent with physical considerations reported earlier in the section.

These results highlight the significant impact of applying momentum corrections to account for the saturation of the magnetic length. Both correction methods, flattening the k_0L and integration of the simulated magnetic into the programmed momentum computation, demonstrated consistency, with only minor differences between the predicted tunes, providing confidence on the momentum corrections. In both planes, the new

model showed a good predictive power for the tunes, with agreement with experimental data of the level below $1 \cdot 10^{-2}$. This outcome not only validates the robustness of the magnetic model but also offers a promising pathway for operational improvements. Incorporating these corrections into the PS operation to improve momentum/rigidity calculation could improve strength calibration not only of the MU but for all the machine and circuits in the ring, and the PS operation team is now planning to incorporate the OPERA-based corrections for the predicted magnetic length into the LSA control system.

6.1.6 Predicted vs measured chromaticity

Figure 6.11 shows the comparison between the predicted and measured first-order horizontal chromaticities, represented by the light blue (predicted) and blue (measured) curves, respectively, and the vertical chromaticities, shown in light dashed red (predicted) and red (measured), as a function of momentum, respectively. A very good agreement was observed over the entire energy range, with slight discrepancies at low energies attributed to the effects of remanent fields. The predicted chromaticities remained relatively constant up to 10.14 GeV, aligning well with the experimental observations. Beyond 10 GeV, the model accurately captured the saturation of the horizontal and vertical chromaticities, which shift in opposite directions, consistent with the measured data, although the simulated values exhibited a slightly faster variation compared to the experimental data. Nevertheless, the discrepancy remained within the error-bars up to 22 GeV/c, which is a very good result. This demonstrates the model's capability to predict chromaticity evolution even in the presence of nonlinear effects such as iron saturation. On this scale, the models provide a predictive tool to be useful for operation predictions on chromaticity. Since chromaticity is unchanged by iron saturation up to approximately 14 GeV/c, the magnetic-optics model has been used to fill gaps in dedicated measurements. The understanding achieved by the improved models with respect to the sextupole saturation has motivated the re-design of EAST-T9 and T10 cycles. In particular, the slow extraction on these cycles was changed to 15 GeV/c based on the models' predictions in order to allow the PFW to be deactivated during slow-extraction, simplifying operation of those cycles. The better understanding of the bare-machine coming

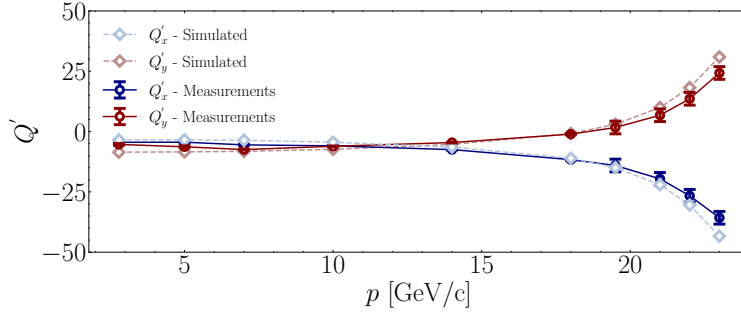


Figure 6.11. Comparison of predicted and measured first-order chromaticities. The light dashed blue and blue curves represent the predicted and measured horizontal chromaticities, respectively, while the light dashed red and red curves represent the predicted and measured vertical chromaticities, plotted as a function of momentum

from the models has allowed operation to precisely decide the maximum energy to operate without chromaticity corrections. This provided input to operation without a dedicated measurement campaign.

Drastic chromaticity variations were observed in simulations and measurements above 14.04 GeV/c, occurring in opposite directions. This is due to iron saturation, which generates a non-linear dependence of B_y on the horizontal axis x , creating sextupolar component at higher energies. Fig. 6.12 illustrates the B_3/B_1 ratio at various energy levels. Below 18.00 GeV/c, the sextupole component produced by the MU cores is nearly zero, consistent with the chromaticity remaining almost flat in this energy range. Above this threshold, the B_3/B_1 ratio increases due to the saturation-induced sextupole, resulting in enhanced chromaticity shifts, as depicted in Fig. 6.11. While the B_3/B_1 ratio in the MU half-unit core increases, a decrease is observed at the fringes.

6.2 Predictions from auxiliary circuits

In the previous section, the benchmarking of bare-machine models was introduced, showing the relevant advancement of the models in providing accurate tune and chromaticity predictions in this machine configuration. To support practical operation of the machine which relies on the auxiliary

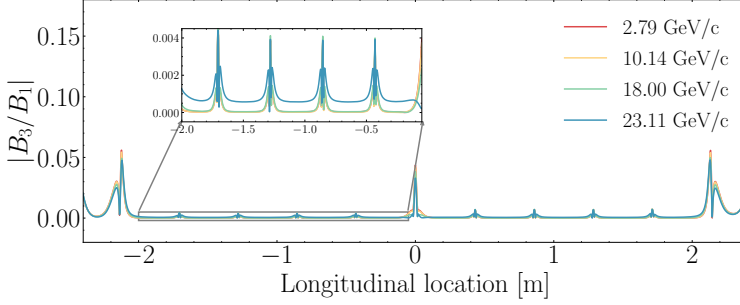


Figure 6.12. Simulated B_3/B_1 ratio at 2.79 GeV/c (red), 10.14 GeV/c (orange), 18.00 GeV/c (green) and 23.11 GeV/c (blue).

circuits for tune and chromaticity control, it is essential to benchmark the models including the harmonics contribution from the F8L and PFW.

In this section, the beam-based studies presented in Sections 5.5 and 5.6 are used to benchmark the tune and chromaticity response from the model under the individual powering of the auxiliary circuits. Subsection 6.2.1 provides the benchmarking of tune and first-order chromaticity predictions, incorporating the F8L circuit at various current levels. Subsection 6.2.2 addresses the validation of the model with the PFW circuit powered.

To replicate the beam-based measurement setup, the MU magnetic model retains the characteristics and properties outlined in Chapter 3, with the auxiliary circuits individually integrated into the MU magnetic model and powered with the same currents used during the measurements. The simulated quadrupolar and sextupolar harmonics, resulting from the combined powering of the main coil and a single auxiliary circuit, were converted into strengths and provided as input to MAD-X for optics simulations, as described in Section 1.2.

6.2.1 Validation of tune and chromaticity predictions with F8L circuit

The beam-based measurements involving the F8L circuit, detailed in Section 5.5, were conducted at injection energy, 10.14 GeV, and 18.00 GeV. On each energy plateau, the F8L current (I_{F8L}) was varied to assess the response of the tunes and first-order chromaticities to the changing field

harmonics generated by the F8L circuit. This analysis showed a linear response of the tunes in both planes to the I_{F8L} current, indicating a predictable relationship between the applied current and tune variation, while the chromaticity influence was consistent with zero.

To evaluate the accuracy of the predicted tune and chromaticity responses against the experimentally observed data, magnetic and optics simulations were carried out at pre-selected F8L current levels within the I_{F8L} range used during the measurements.

Comparison between measured and simulated tunes

Figure 6.13 presents the comparison between measured tunes and model predictions with the F8L circuit activated on the flat-cycle at injection energy (top panel), at the 10.14 GeV/c plateau (middle panel), and at the 18.00 GeV/c plateau (bottom panel), as a function of the I_{F8L} current. The relative error between measured and simulated tunes, expressed as a percentage, is also shown in turquoise, with the corresponding scale on the right. Outside the remanent field region (above injection energy), tune response at various I_{F8L} currents at 10.14 GeV/c exhibited excellent agreement with the measurements on both planes. Similar agreement was also observed at 18.00 GeV/c, where saturation plays a key role. The overall agreement is within the 1 %, both in the remanent field and saturation region.

Given the slight discrepancies observed between the experimental data and simulations in the bare-machine configuration, it is useful to evaluate the predicted and measured tune shifts, $\delta Q_{x/y}$, relative to the bare-machine values $Q_{x/y,0}$, as a function of the I_{F8L} current:

$$\delta Q = Q_0 - Q(I_{F8L}). \quad (6.12)$$

With regard to tune control in the PS, a particularly meaningful assessment can also be made by considering instead the tune-shifts in response to I_{F8L} currents normalized to the magnetic rigidity. The measured and simulated tune-shifts (δQ) values are shown in Fig. 6.14 for the horizontal (left) and vertical (right) tunes on the flat cycle at 2.79 GeV/c (top plot), the 10.14 GeV/c plateau (middle plot), and 18.00 GeV/c (bottom plot) as function of the I_{F8L} current normalized to the magnetic rigidity.

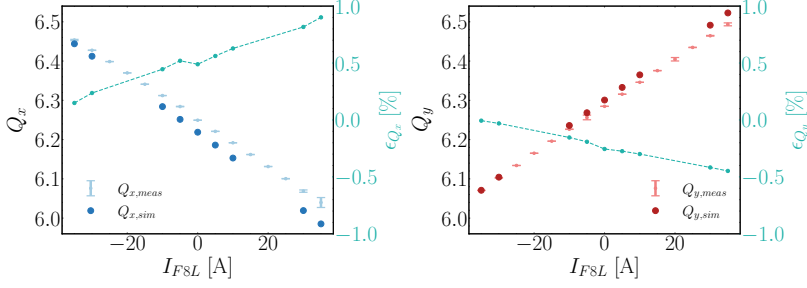
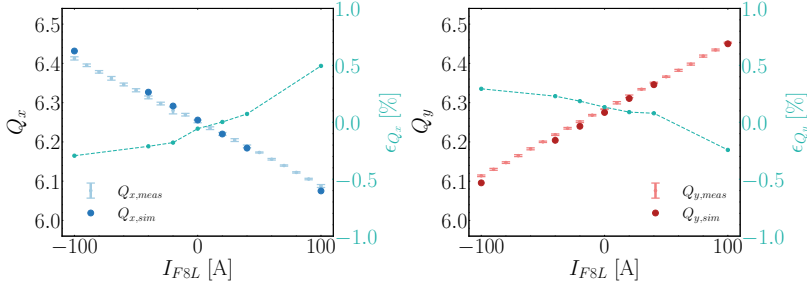
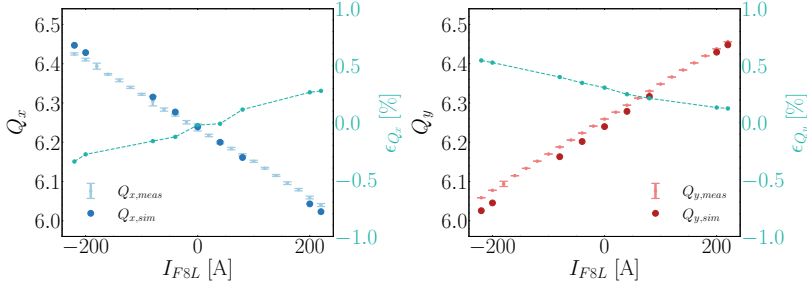
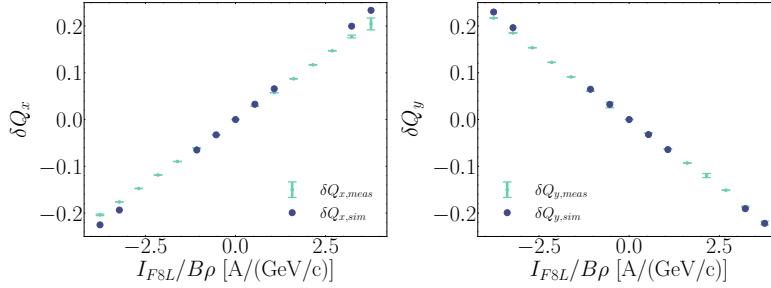
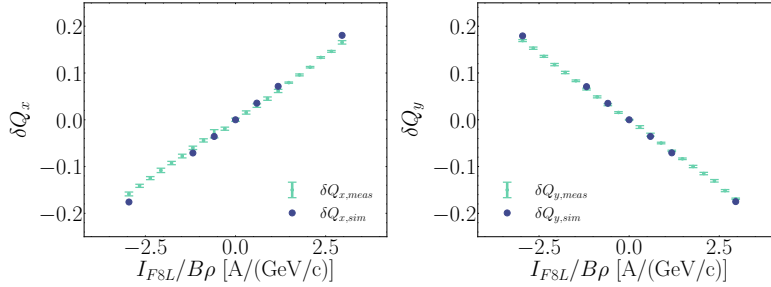
(a) Simulated and measured Q_{x-y} on the flat-cycle at 2.79 GeV/c.(b) Simulated and measured Q_{x-y} on the 10.14 GeV/c plateau.(c) Simulated and measured Q_{x-y} on the 18.00 GeV/c plateau.

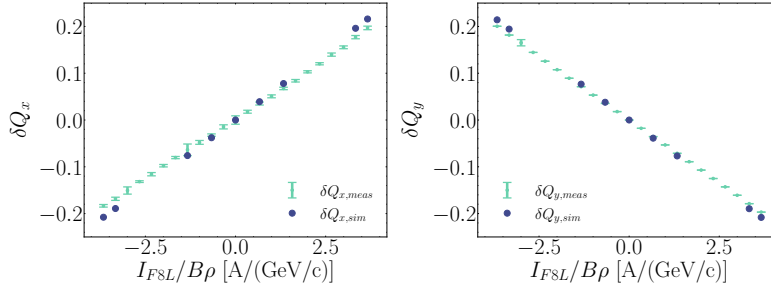
Figure 6.13. Comparison between simulated and measured tunes at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with F8L activated at different currents. Horizontal measured and simulated tunes are reported on the left in light and dark blue, respectively; on the right, measured vertical tunes are depicted in light red, simulated points in dark red. Relative error between measured and simulated points in turquoise with corresponding scale on the right of each plot.



(a) Simulated and measured δQ_{x-y} on the flat-cycle at 2.79 GeV/c.



(b) Simulated and measured δQ_{x-y} on the 10.14 GeV/c plateau.



(c) Simulated and measured δQ_{x-y} on the 18.00 GeV/c plateau.

Figure 6.14. Comparison between simulated and measured tune=shift relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with F8L activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple.

Measured data are represented in green, simulated points in purple. At 2.79 GeV/c, the tune shifts predicted by the magnetic and optics models

align well with the experimental data, except for the highest currents on the horizontal plane, where the simulated points fall outside the measurement error bars. The comparison at 10.14 GeV/c and 18.00 GeV/c shows excellent agreement on both planes. At the extremities of the I_{F8L} current range employed on each energy plateau, the models predict a larger tune increment than what is observed in the beam-based measurements. The largest simulated and measured tune increments, corresponding to the highest positive and negative I_{F8L} currents, were found to be on the order of $2 \cdot 10^{-1}$.

These analysis proves that the tune-shifts (with respect to bare-machine data) in the remanent field region (at 2.79 GeV/c) are as well modeled as at higher energy, confirming that the slight discrepancy observed in Fig. 6.13 reflected the expected remanent field contribution observed in bare-machine. Furthermore, the tune-shifts with respect to the normalized I_{F8L} current are very similar in low and high saturated regimes, both in simulation and measurements. Thus, unlike the bare-machine configuration, the tune response to F8L powering was not significantly perturbed by iron saturation, which is consistent with magnetic model expectations. This is a useful input for development of the tune control based on predictive models.

The comparison shown in Figs. 6.13 and 6.14 demonstrate that the models, incorporating the F8L circuit, accurately predict the measured tune shifts on both the horizontal and vertical planes at different beam energies. This indicates a high degree of precision in the alignment between experimental data and model predictions.

Comparison between measured and simulated chromaticity

Simulated B_3 values from the magnetic model at various I_{F8L} levels across different MU regions were integrated into the MAD-X optics model to simulate the first-order horizontal and vertical chromaticities resulting from the simultaneous powering of the main coil and the F8L circuit.

Figure 6.15 shows, on the left, the horizontal chromaticity shifts ($\delta Q'_x$) with respect to bare-machine data ($I_{F8L} = 0$), and on the right the vertical chromaticity shifts ($\delta Q'_y$) for the flat cycle at injection energy (top), the 10.14 GeV/c plateau (middle), and the 18.00 GeV/c plateau (bottom). Measured chromaticity shifts are reported in green, simulated points in

blue. The simulations confirmed the minimal sensitivity of chromaticity to I_{F8L} currents, a behavior also observed in the optics measurements. At 2.79 GeV/c and 10.14 GeV/c, the absolute predictions from the magnetic and optics models were offset by approximately one unit in both planes relative to the experimental data. However, at 18.00 GeV/c, the predicted horizontal and vertical chromaticities were within the measurement error bars. These results demonstrate the ability of the models to capture the intricate relationship between the overlapping fields generated by the main coil and the F8L circuit and their combined effect on the beam. The interplay between these fields is complex, yet the models successfully predict how this influences the chromaticity behavior across various energy levels, underscoring the robustness of the magnetic and optics simulations.

6.2.2 Validation of tune and chromaticity predictions with PFW circuit

As detailed in Section 5.6, tune and chromaticity measurements were performed at the same energy plateaus used for F8L, with uniform powering of the PFW circuits (N and W, in both half-units), including the MRP corrections. These measurements revealed tune-shifts in both planes as a function of I_{PFW} currents, along with significant variations in chromaticity across the range of I_{PFW} currents.

To replicate the experimental setup, the PFW coils were integrated into the magnetic model along with the main coil, and uniform currents were applied to all the PFW circuits. The objective was to predict the intricate effects of the PFW circuits on the simulated tunes and chromaticity, thereby validating the predictive capability of the model to support PS operation. Following, the simulated tunes and chromaticity, along with their comparison to the experimental data, are presented.

Comparison between measured and simulated tunes

Figure. 6.16 shows the comparison between measured and simulated tunes. The tune response as a function of I_{PFW} , predicted by the models, closely aligned with the experimental data across the three energy levels. The relative error remained within $\pm 0.5\%$ over the entire range of I_{PFW} currents in all cases.

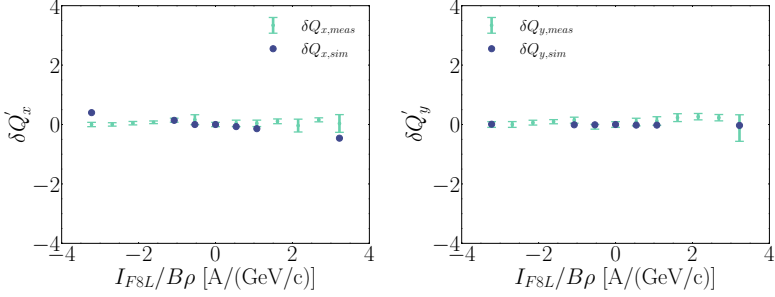
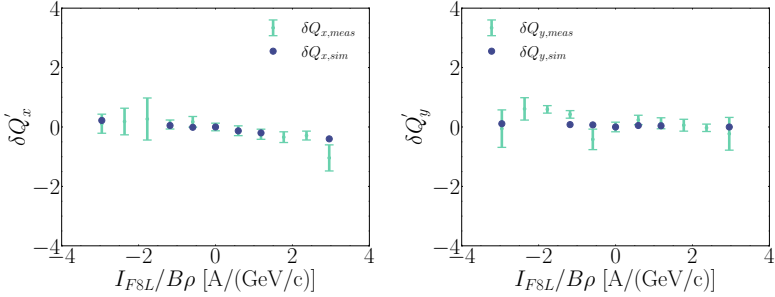
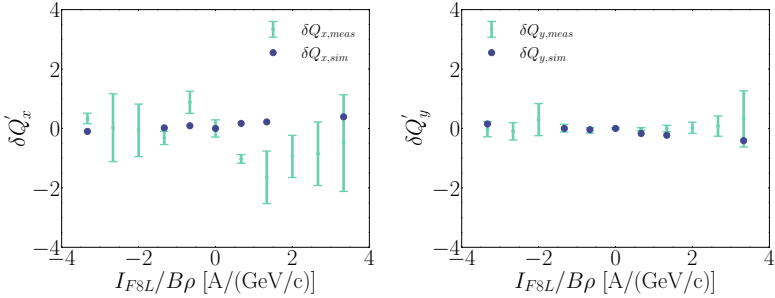
(a) Simulated and measured $\delta Q'_{x-y}$ at 2.79 GeV/c.(b) Simulated and measured $\delta Q'_{x-y}$ on the 10.14 GeV/c plateau.(c) Simulated and measured $\delta Q'_{x-y}$ on the 18.00 GeV/c plateau.

Figure 6.15. Simulated and measured chromaticity at 2.79 GeV (top), 10.14 GeV (middle) and 18.00 GeV (bottom) at different I_{F8L} currents. Horizontal measured and simulated chromaticities are reported on the left in light and dark blue, respectively; on the right, measured vertical chromaticity is depicted in light red, simulated points in dark red.

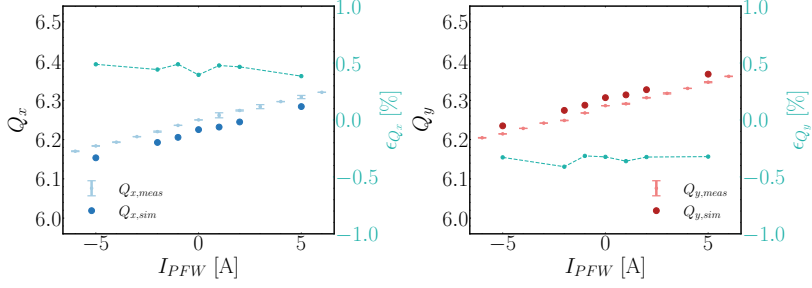
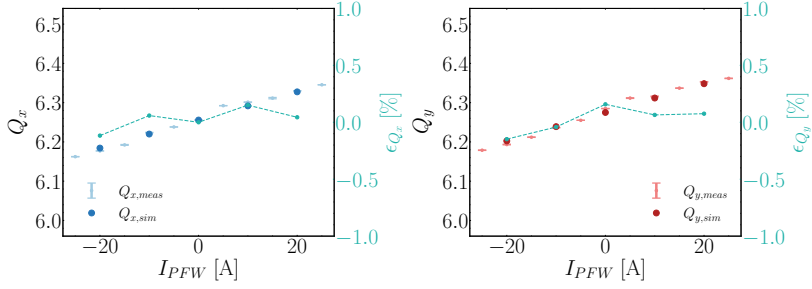
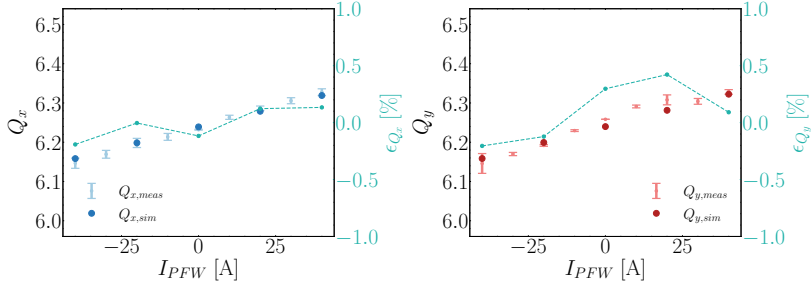
(a) Simulated and measured Q_{x-y} on the flat-cycle at 2.79 GeV/c.(b) Simulated and measured Q_{x-y} on the 10.14 GeV/c plateau.(c) Simulated and measured Q_{x-y} on the 18.00 GeV/c plateau.

Figure 6.16. Comparison between simulated and measured tunes at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with PFW activated at different currents. Horizontal measured and simulated tunes are reported on the left in light and dark blue, respectively; on the right, measured vertical tunes are depicted in light red, simulated points in dark red. Relative error between measured and simulated points in turquoise with corresponding scale on the right of each plot.

To eliminate discrepancies arising from the bare-machine configuration, the tune shift relative to the bare-machine scenario ($I_{PFW} = 0$), δQ , is presented in Fig. 6.17 as a function of I_{PFW} current, normalized to the magnetic rigidity. Across the range of I_{PFW} currents, the tune shifts predicted by the models with respect to the bare-machine were consistent with the measurements, falling within the experimental error bars. Minor discrepancies were observed only in the vertical plane at high I_{PFW} currents. These differences are likely attributable to noise in the measurement spectrum at high I_{PFW} currents or saturation effects in the magnetic model.

Comparison between measured and simulated chromaticity

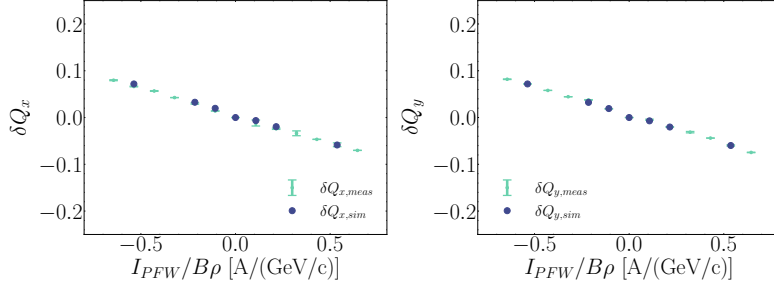
As with the tune comparison, Fig. 6.18 illustrates the chromaticity shifts ($\delta Q'$) as a function of the I_{PFW} currents normalized to the magnetic rigidity. The simulated chromaticity shifts showed excellent agreement with the experimental data, remaining within the standard deviation of the measurements. A slight discrepancy was observed at 18.00 GeV/c for high I_{PFW} currents.

6.3 Predictions from simultaneous powering of MU coils

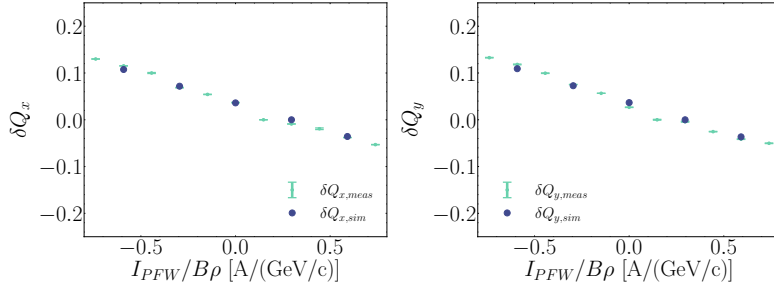
After assessing the tune and chromaticity in the bare-machine configuration and with the individual powering of the auxiliary circuits, Section 5.7 introduced beam-based measurements in a more complex scenario involving the simultaneous powering of all MU circuits. These measurements were conducted using powering settings from an LHC operational cycle on the bare-machine plateaus at 10.14 GeV/c and 18.00 GeV/c. This section aims to evaluate the models' ability to predict tunes and chromaticity in this configuration characterized by intricate interaction of multiple circuits.

Figure 6.19 presents the comparison between measured and simulated tunes (left plot) and chromaticity (right plot). Simulated data for the horizontal and vertical planes are shown in light blue and light red, respectively, while measured data are represented in dark blue and dark red.

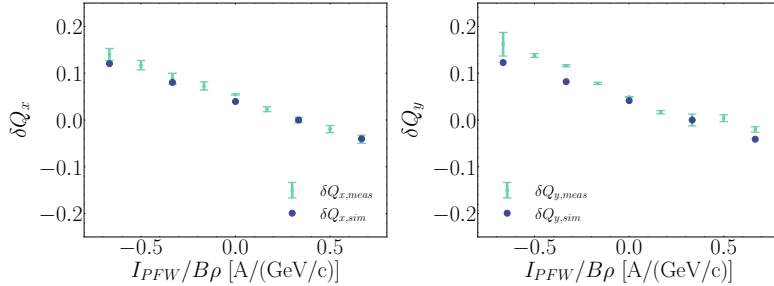
The tune variation between 10.14 GeV/c and 18.00 GeV/c exhibited a



(a) Simulated and measured δQ_{x-y} on the flat-cycle at 2.79 GeV/c.



(b) Simulated and measured δQ_{x-y} on the 10.14 GeV/c plateau.



(c) Simulated and measured δQ_{x-y} on the 18.00 GeV/c plateau.

Figure 6.17. Comparison between simulated and measured tune-shifts relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with PFW activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple.

consistent trend between the simulations and measurements. The absolute tune discrepancy was approximately $2 \cdot 10^{-2}$ on both planes at both en-

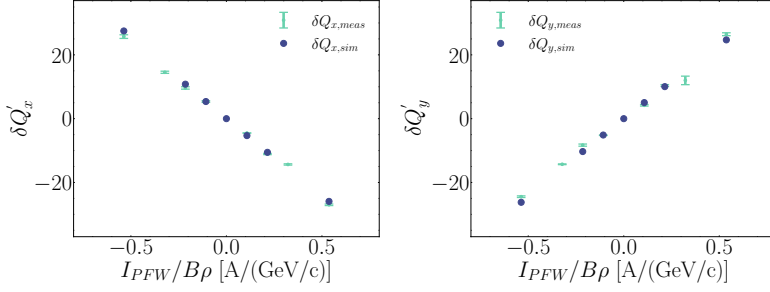
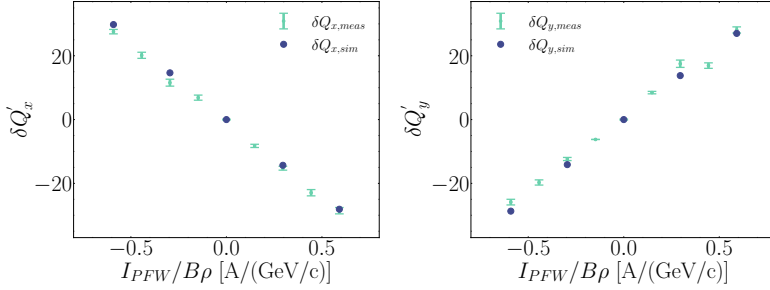
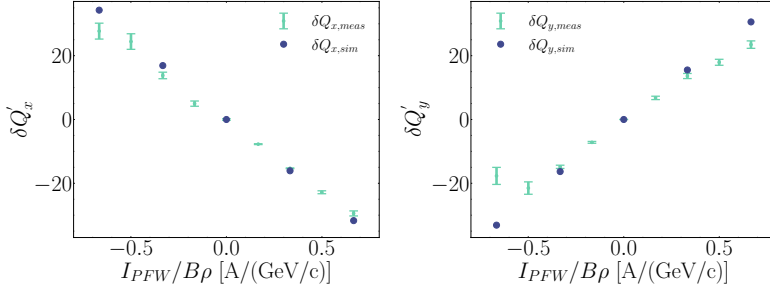
(a) Simulated and measured $\delta Q'_{x-y}$ on the flat-cycle at 2.79 GeV/c.(b) Simulated and measured $\delta Q'_{x-y}$ on the 10.14 GeV/c plateau.(c) Simulated and measured $\delta Q'_{x-y}$ on the 18.00 GeV/c plateau.

Figure 6.18. Comparison between simulated and measured chromaticity-shifts relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV/c (middle plot) and 18.00 GeV/c (bottom plot) with PFW activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple.

ergy levels, which is comparable to the typical error coming from the F8L

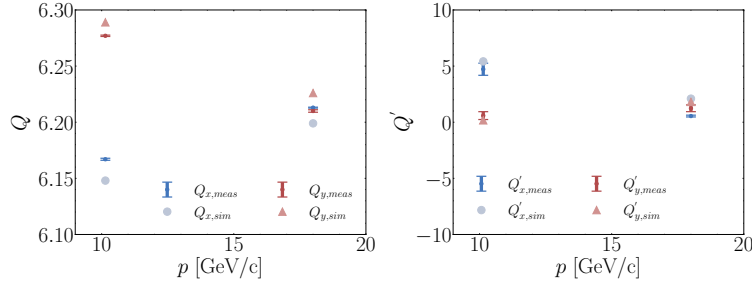


Figure 6.19. Measured and simulated tunes (left) and chromaticity (right) using the LHC cycle powering settings at 10.14 GeV/c and 18.00 GeV/c. Light blue and dark blue dots represent the simulated and measured data, respectively, for the horizontal plane, while light red and dark red correspond to the simulated and measured data for the vertical plane, respectively.

response, detailed in Section 6.2. Regarding the chromaticity comparison, the predicted values fell within the measured standard deviation. However, a minor discrepancy of approximately a factor of 3 between measured and simulated data was observed in the horizontal plane at 18.00 GeV/c. Nevertheless, the absolute difference remains approximately 1.5, which is comparable to the discrepancies observed in the benchmarking of the bare machine and with the individual F8L/PFW powering.

From this analysis, the model demonstrated its capability to accurately predict both tune and chromaticity, even in a complex operational scenario involving the simultaneous powering of multiple circuits. This achievement highlights the model's robustness and reliability, establishing it as a valuable predictive tool for supporting and optimizing PS operations.

6.4 Advanced optics studies

In the preceding sections, benchmarking of the model predictions of tune and chromaticity against beam-based measurements has been evaluated, considering both the bare machine configuration, and the response of the auxiliary F8L and PFW circuits necessary for operational control. Predicted tunes and chromaticities demonstrated excellent agreement across the different machine configurations, particularly after model based corrections for the magnetic length were incorporated in the programmed

momentum computation.

Tune and chroma represent the key parameters of interest to operation, and were also the focus of historical studies of PS modelling outlined in Chapter 3. As global observables, however, it is possible that tune and chromaticity measurements could fail to capture optics distortions which cancel globally, but still distort the optics locally around the ring. By complementing the tune and chromaticity studies with local optics measurements an even more detailed benchmarking of the model can be achieved. Results of these optics studies are presented in this section.

6.4.1 Beta-beating

Tunes are a critical parameter affecting the performance and stability of the beam within a particle accelerator. However, they represent a global property of the beam across one full revolution of the machine. A more localized metric for assessing discrepancies between beam-based measurements and simulations is the β -beating, introduced in Section 1.4.

To measure β -beating, the beams were excited with an AC-dipole kick applied by the PS transverse damper. Turn-by-turn data were acquired at the BPMs during the AC-dipole kicks, over thousands of turns. These data were post-processed to perform the necessary spectral analysis and compute key beam optics parameters, including the β function around the ring, as described in Section 1.4. Optics measurements were conducted in the bare-machine configuration on the flat-cycle at injection energy, and on the 10.14 GeV/c and 18.00 GeV/c plateaus.

Figure 6.20 presents, as an example, the measured horizontal (top) and vertical (bottom) β functions in red, acquired across the 10.14 GeV/c plateau, and averaged over approximately 20 shots of the super-cycle. An excellent reproducibility of the measurements was obtained, as evinced by the small error-bars in the plots. The same models used to evaluate the tune benchmarking, also provided simulation of the horizontal and vertical β functions. Simulated β functions are reported in blue in Fig. 6.20. A coherent pattern between simulated and measured β functions was found, with slight deviations in specific BPMs.

The principal figure-of-merit for assessing the local optics quality is the β -beating (the relative error between modeled and measured β -functions, introduced in Section 1.4). Large β -beat could point to local errors in the

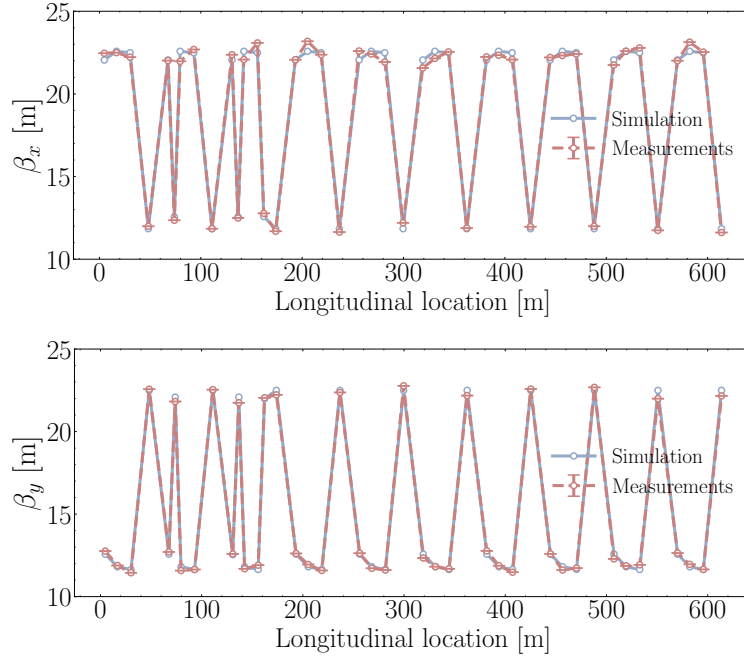


Figure 6.20. Comparison between simulated and measured β functions at 10.14 GeV in blue and red, respectively. Horizontal β functions are reported in the top plot, vertical in the bottom.

optics model. The β -beat is also directly relevant for operation, as predictions of the β functions can provide input to certain beam-measurements, for example at instrumentation such as the wire-scanners used to measure emittance. Fig. 6.21 shows the measured β -beat for the horizontal and vertical planes (top and bottom plots, respectively). The red, green, and blue curves represent the β -beating at 2.79 GeV/c, 10.14 GeV/c, and 18.00 GeV/c, respectively.

A slight increase in the peak β -beating is seen as the energy increased, most notably in the horizontal plane. In practice however the scale of the β -beat represents an excellent level of agreement between the predictions of the OPERA-MAD model and the real PS machine, the peak β -beating remaining within approximately $\pm 8\%$. For context, without dedicated beam-based corrections typical β -beat in other proton machines such as

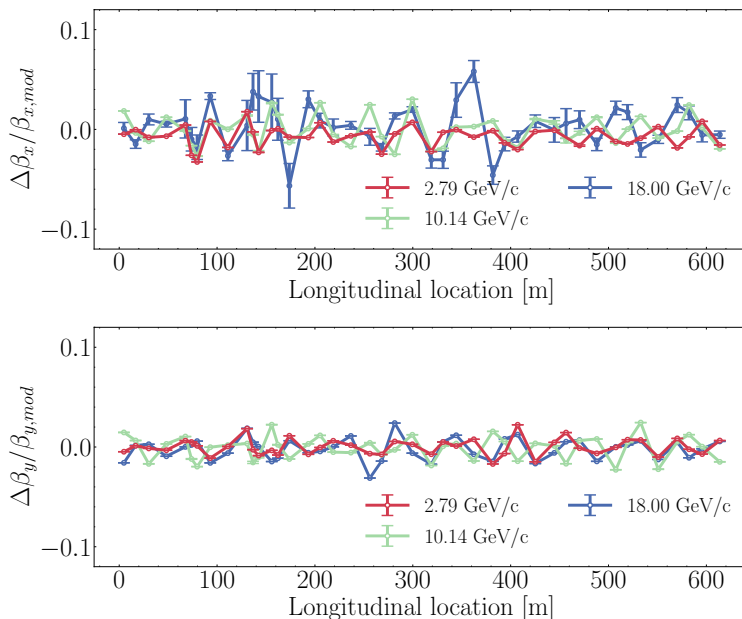


Figure 6.21. Comparison between simulated and measured tune=shift relative to the bare-machine configuration at injection energy (top plot), 10.14 GeV (middle plot) and 18.00 GeV (bottom plot) with F8L activated at different currents. Horizontal tune-shifts are reported on the left, vertical on the right. Measured data in green, simulated points in purple.

the LHC and PSB are typically around the 15 – 30% level [138–140].

The low β -beating demonstrates the robustness of the combined magnetic and optics models in accurately describing the beam optics locally around the ring. The increase in β -beating with energy is consistent with the slightly larger tune discrepancies observed at higher energies between the model predictions and the measurements, as shown in Fig. 6.10.

6.4.2 Chromatic optics-beating

Similarly to how β -beat provides a complementary local observable to studies of the tune, studies of the chromaticity can be complemented by measurements of the chromatic-optics: the shift to local optics functions seen upon introducing a momentum offset. Such measurements of the

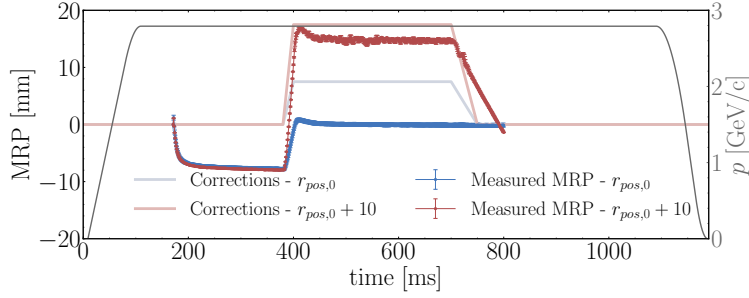


Figure 6.22. Measured MRP for study of the chromatic optics shifts.

r_{pos}	Q'_x	Q'_y
$r_{pos,0}$	-5.07 ± 0.28	-6.57 ± 0.47
$r_{pos,0} + 10$	-5.08 ± 0.38	-6.54 ± 0.32

Table 6.5. Comparison of chromaticity measurements on the bare-machine flat-cycle with 0 MRP, and with a 10mm MRP shift corresponding to $\frac{dp}{p} = 3 \times 10^{-3}$.

chromatic optics were performed on the bare-machine flat-cycle at injection energy.

An initial reference configuration was established by correcting the MRP to zero. Subsequently, the r_{pos} trim setting was deliberately shifted by 10 mm, similar to the procedure utilized for chromaticity measurements outlined in Chapter 5, introducing a relative momentum offset at the level of $\frac{dp}{p} = 3 \times 10^{-3}$. Fig. 6.22 illustrates the MRP measurements and corresponding corrections.

Chromaticity measurements were repeated for the zero-MRP and off-momentum configurations, summarized in Tab. 6.5. The first-order chromaticity showed no significant change following the MRP shift. This demonstrates that even with a significantly off-center beam there was no clear impact or feed-down from non-linearities of higher than sextupole order.

Optics measurements via AC-dipole kicks were performed in both on- and off-momentum configurations. Fig. 6.23 presents the measured BPM-to-BPM betatron phase advance for the horizontal and vertical planes,

shown on the top and bottom plots, respectively, in unit of $\text{rad}/(2\pi)$. The phase advance off-momentum with the MRP shift (green curve) aligns closely with the reference phase advance at zero MRP (blue curve) in both planes.

The very small impact of the momentum/ r_{pos} trim is consistent with the model prediction, obtained by introducing the corresponding momentum offset (dp/p_0) into the MAD-X model. The simulated BPM-by-BPM phase advance for on- and off-momentum configurations is presented in Fig. 6.24.

Subtracting the model inter-BPM phase advances (Fig. 6.24) from the measurements (Fig. 6.23) defines the ‘phase-beating’, a calibration independent measure of the optics errors. Fig. 6.25 shows the inferred phase-beat. On this scale a very slight shift to the phase-beat can be discerned when going off momentum, however both on- and off-momentum the residual phase-beat with respect to the OPERA-MAD predictions are extremely small compared to the BPM-to-BPM phase advance, indicating a good quality of the local optics predictions both on- and off-momentum.

The chromatic optics beating was further analyzed by introducing a new parameter, $\delta\phi$, the chromatic phase shift, defined as the difference in inter-BPM phase advance between cases with and without a momentum offset, in both simulations and measurements:

$$\delta\phi_{sim} = \phi_{x-y,sim}(dp/p_0) - \phi_{x-y,sim}(dp/p) \quad (6.13)$$

$$\delta\phi_{meas} = \phi_{x-y,meas}(dp/p_0) - \phi_{x-y,meas}(dp/p) \quad (6.14)$$

This chromatic phase shift is shown in Fig. 6.26. The measured chromatic phase-shift was found to be slightly larger (and with a less uniform pattern) than that expected in simulation. This could point, for example, to the existence of some small additional sextupole errors present in the machine at injection but not included in the model. In practice however the discrepancy in measured chromatic phase-shift is extremely small (two orders of magnitude below the typical inter-BPM phase advance), which reflects the good prediction of the local optics both on- and off-momentum.

It would be interesting to apply the chromatic optics approach (developed here on the flat-cycle) also at high energy, where saturation is

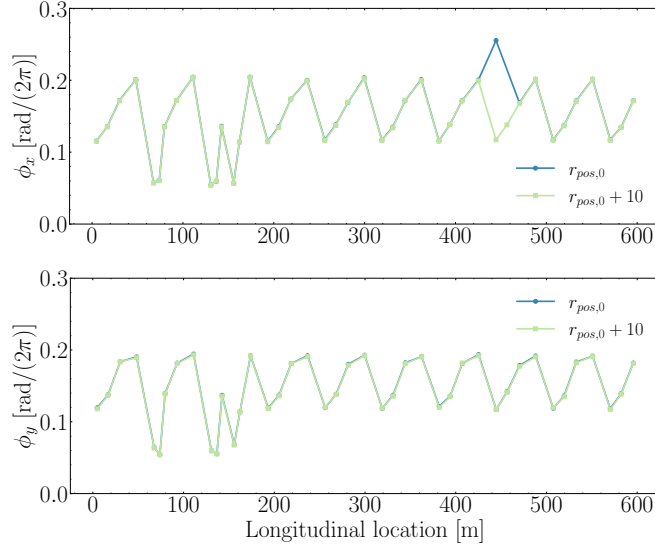


Figure 6.23. Measured BPM-to-BPM phase advance. Measurements on-momentum with $r_{pos} = r_{pos,0}$ in blue, and off-momentum ($\frac{dp}{p} = 3 \times 10^{-3}$) with MRP-shift ($r_{pos} = r_{pos,0} + 10$) in green.

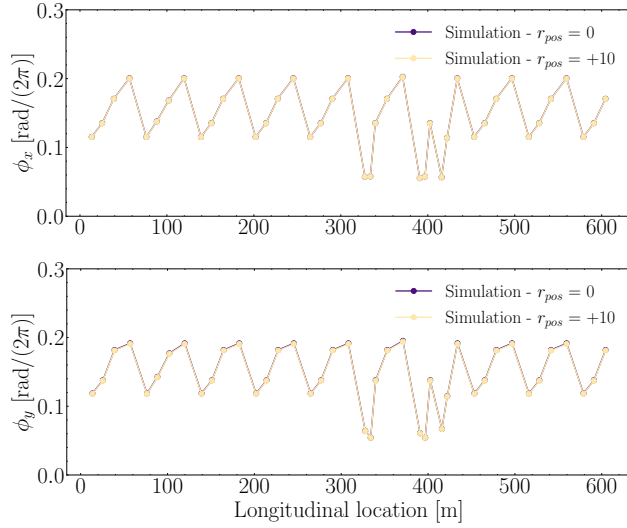


Figure 6.24. Simulated BPM-to-BPM phase advance. Data with no momentum offset in violet, data with momentum offset ($\frac{dp}{p} = 3 \times 10^{-3}$) in yellow.

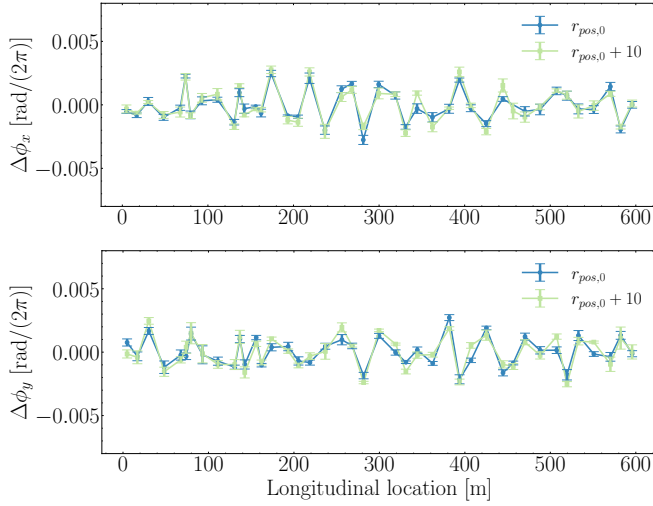


Figure 6.25. Measured BPM-by-BPM delta-phase advance with respect to the model on the horizontal (top) and vertical plane (bottom). Measurements with $r_{pos} = r_{pos,0}$ in blue, those and with MRP-shift in green.

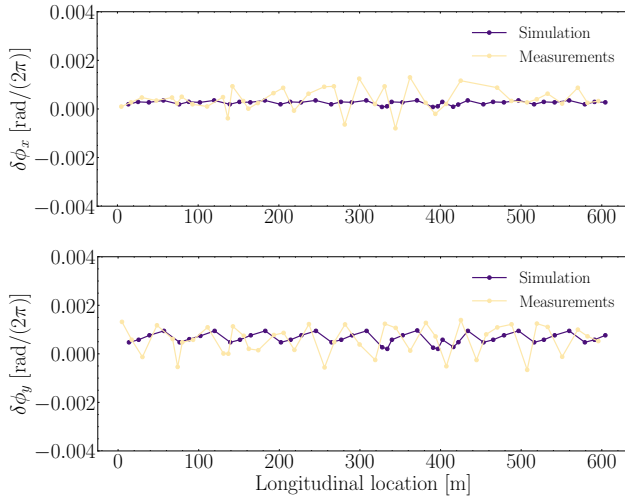


Figure 6.26. BPM-by-BPM delta simulated phase advance on the horizontal (top) and vertical plane (bottom). Reference measurements ($r_{pos} = r_{pos,0}$) and with MRP-shift ($r_{pos} = r_{pos,0} + 10$) in violet and light yellow, respectively.

expected to generate large sextupoles (as discussed earlier in the chapter). This ongoing work, however, requires further development of the bare-machine cycles to lengthen the stable plateau region on high-energy bare machine cycles (above 20 GeV/c), which is challenging due to powering limitations.

6.4.3 Optics measurements with degraded closed orbit

In the previous section the predictive power of the models with regard to local optics off-momentum with a systematic shift of the mean radial position was considered. A further concern regarding the predictive power of the model, considers the sensitivity of the optics to a degraded closed orbit. Feed-down forces depend on the beam transverse position when passing thorough magnetic elements, so a substantially degraded closed orbit could perturb the optics away from model predictions. At high-energy this is expected to be dominated by the large saturation or auxiliary circuit induced non-linearities (which as seen in previous sections were well reproduced by the model). At low-energy however any additional nonlinear errors not included in the model could influence the optics predictions. To evaluate the impact on the optics of feed-down effects, studies on the 2.79 GeV/c flat-cycle were performed while purposefully degrading the horizontal and vertical closed orbits in the machine.

Degraded vertical orbit

The vertical orbit was degraded by purposefully miss-powering one of vertical orbit correctors (normally used to correct the closed-orbit) to the maximum strength permitted by the LSA control system. By changing the sign of the corrector a large ($\approx 15\text{mm}$) vertical closed orbit shift could be induced, as seen in Fig. 6.27, illustrating the measured vertical position of the beam at the BPMs as a function of the longitudinal location corresponding to two different polarities of excitation.

Tune and chromaticity measurements were conducted to assess whether the degraded vertical closed orbit generated a measurable effect on the beam observables. Fig. 6.28 reports the measured MRP (which was unaffected by the vertical orbit corrector) on the top plot; horizontal and vertical tunes are reported in the bottom plot in turquoise and light red,

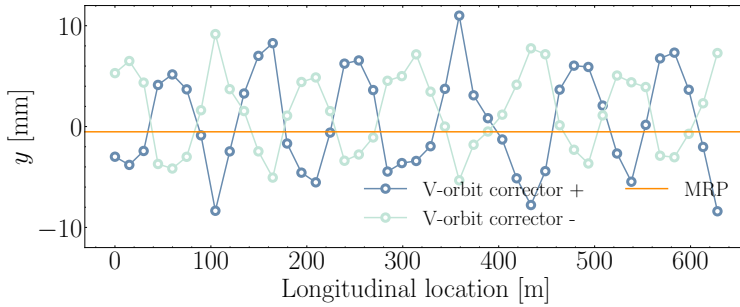


Figure 6.27. Degraded vertical orbit measured at the BPMs for positive and negative maximum powering of the PR.DVT02 vertical orbit corrector.

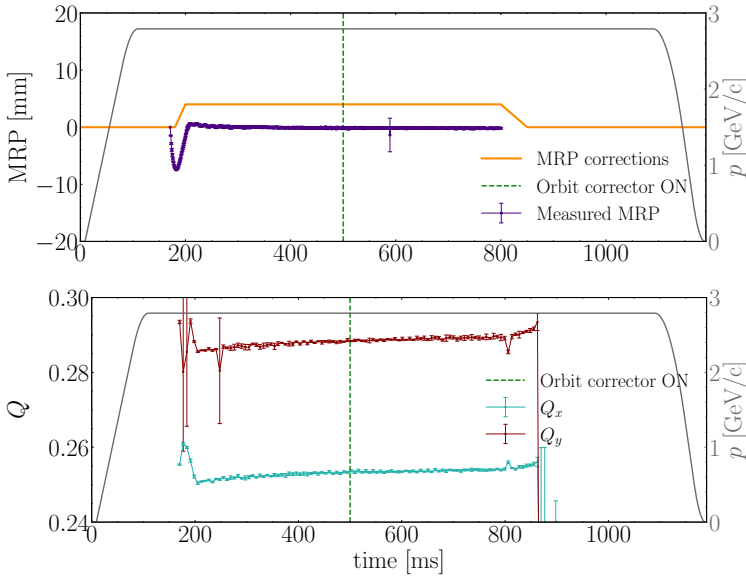


Figure 6.28. Measured tunes (bottom) during introduction of the degraded vertical closed orbit. The PR.DVT02 vertical orbit corrector is powered on to its maximum permitted strength at $t = 500$ ms, then powered to its maximum permitted negative strength at $t = 600$ ms, before being powered off at $t = 750$ ms. No effect from the vertical orbit corrector on the MRP (top) is observed.

V-orbit corrector	Q'_x	Q'_y
OFF	-5.07 ± 0.28	-6.57 ± 0.47
ON	-5.11 ± 0.12	-5.82 ± 0.72

Table 6.6. Comparison of chromaticity measurements on the bare-machine flat-cycle with and without the degraded vertical orbit.

respectively. It can be observed that even the large vertical closed-orbit shift illustrated in Fig. 6.27 did not measurably perturb the tunes. A similar effect was seen in the chromaticity measurements, reported in Tab. 6.6, showing that the chromaticity change due to the larger vertical closed orbit is within the measurements standard deviation.

The vertical closed orbit distortion considered in these measurements is at least 5 times larger than the typical residual vertical closed-orbit encountered in operation. As no significant impact on the tune and chromaticity was observed this reveals no concern regarding the predictive power of the models with respect to typical operational variations in the vertical closed-orbit at low-energy.

Degraded horizontal orbit

A degraded horizontal orbit was generated by purposefully mispowering a horizontal orbit corrector (PR.DHZOC05). In this case the strength of the orbit corrector was increased until limited by beam losses. A very significant closed-orbit shift was generated as seen in Fig. 6.29. The horizontal closed orbit, recorded at each BPM around the ring, prior to the activation of the horizontal orbit corrector (at $t = 300$ ms), is shown in the bottom plot of the same figure in blue, showing a maximum amplitude of the horizontal closed orbit confined within ± 5 mm. Upon the activation of the horizontal orbit corrector, a larger horizontal closed orbit is produced, as shown by the light green curve, with a peak horizontal orbit of ± 35 mm. The activation of the horizontal orbit corrector did not produce any significant variation in the orbit on the vertical plane or the MRP.

Figure 6.30 reports the measured horizontal and vertical tunes during introduction of the degraded closed-orbit in the top and bottom plots, respectively. The results of chromaticity measurements before and after

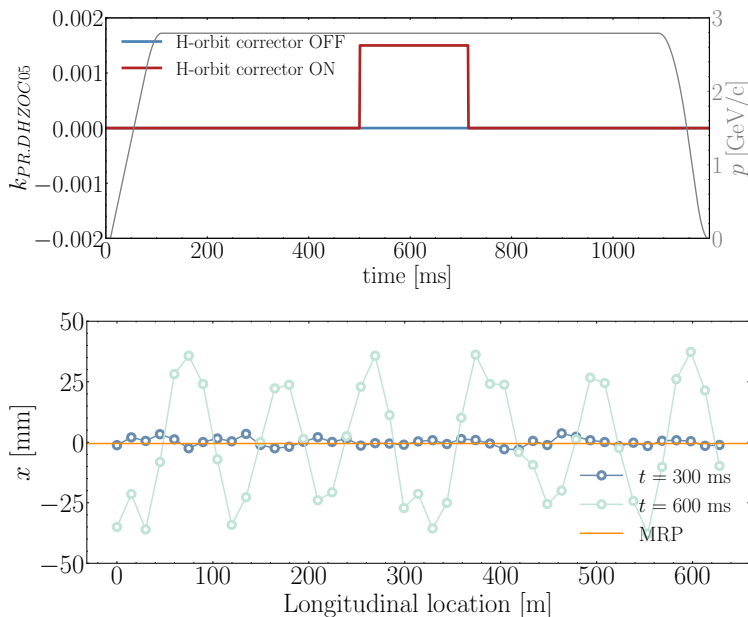


Figure 6.29. Activation of the horizontal orbit corrector $t = 500$ ms and $t = 700$ ms is shown in the top plot; the blue curve represents the amplitude used for conventional optics measurements, while the red curve corresponds to the amplitude used to create a larger closed orbit. On the bottom plot, horizontal closed orbits at $t = 300$ ms (before activation of the horizontal orbit corrector) showed in blue and at $t = 600$ ms in light green.

introduction of the degraded closed-orbit are summarized in Table 6.7.

$k_{DHzOC05}L$	Q'_x	Q'_y
0	-5.07 ± 0.28	-6.57 ± 0.47
$-1.5 \cdot 10^{-3}$	-5.59 ± 0.38	-6.50 ± 0.32

Table 6.7. Comparison of chromaticity measurements with the horizontal orbit corrector deactivated and activated.

No significant chromaticity variations were observed on the vertical plane. A slight difference was noted on the horizontal plane, but comparable to the measurement uncertainty. The horizontal tune did not show any

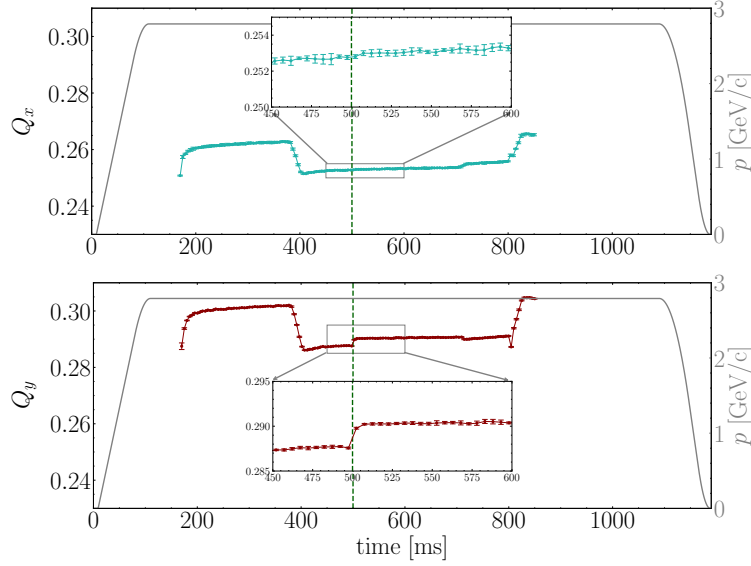


Figure 6.30. Horizontal (top) and vertical (bottom) tunes during application of the degraded horizontal orbit, at $t = 500$ ms.

appreciable shift due to the degraded horizontal closed orbit. A small shift was seen for the vertical tune, on the level of $\Delta Q \approx 2 \cdot 10^{-3}$, however this is comparable with typical tune variations which can also be generated by shot-to-shot jitter and does not represent a sizable optics shift.

Local optics measurements with AC-Dipole kicks were also performed for both configurations of the horizontal orbit corrector (off and on) to allow for a direct evaluation of the impact of feed-down effects on the local beam optics.

Figure 6.31 shows measurements of the BPM-to-BPM phase advance. Blue curves represent the phase advance in the reference configuration, while the green curves correspond to the phase advance with the amplified orbit. Fig. 6.32 illustrates the corresponding phase-beating (BPM-by-BPM phase advance deviations with respect to the model predictions) for both planes. The blue and green curves represent the reference measurements and those obtained with the degraded orbit, respectively.

Only extremely small differences in the phase-beat are observed on introduction of the degraded orbit. These shifts are very small compared

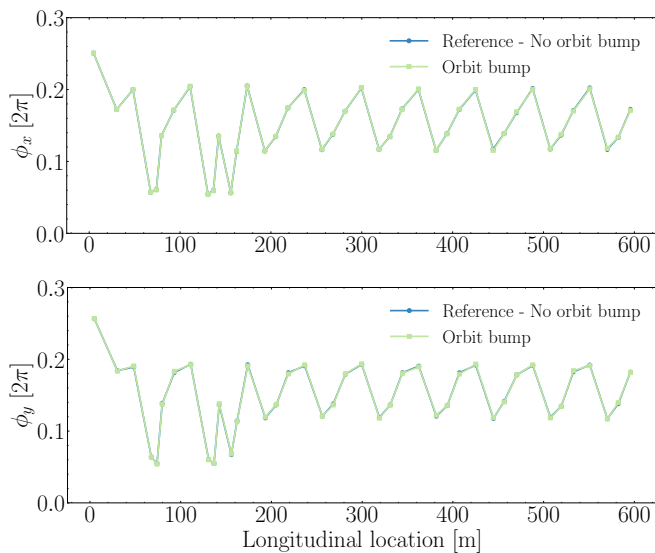


Figure 6.31. Measured BPM-to-BPM phase advance without (blue) and with (green) the degraded orbit.

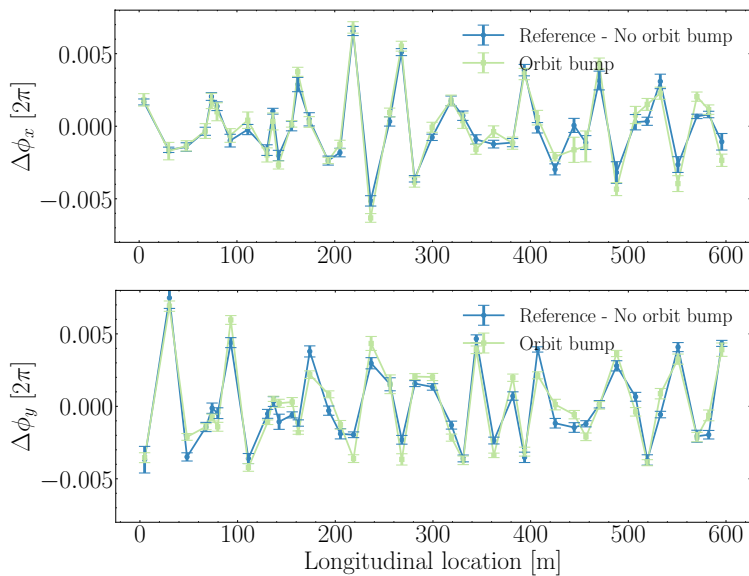


Figure 6.32. Measured phase-beating with respect to the model predictions without (blue) and with (green) the degraded orbit.

to both the BPM-to-BPM phase-advance, and the residual phase-beating at the reference orbit. The differences between the two configurations are also comparable to the measurement uncertainties at the BPMs.

No significant impact was seen on the tunes, chromaticities, and local phase-beating upon implementation of even an extremely large horizontal closed-orbit shift (approximately an order of magnitude larger than typical residual closed orbit variations in operation). This finding leads to the conclusion that the measured optics are not significantly influenced by feed-down effects due to any unknown optics errors at injection, and raises no concern regarding the predictive power of the models in response to variation in orbit at low-energy.

Conclusions

This thesis has presented the development and validation of predictive magnetic and optics models for the CERN Proton Synchrotron (PS) main magnets (Main Units or MUs). The overarching objective was to address the challenges of accurately modeling the PS-MUs to support operational decision-making and improve machine performance. Unlike traditional empirical models heavily reliant on experimental data, the new models aim to provide predictive capabilities, serving as a tool to support and inform machine operation, even under evolving operational scenarios. The methodology consisted in simulating the field map in the aperture with a 3D finite-element magnetic model of the MU. The computed harmonics served as input for beam dynamics simulation with an optics model of these magnets.

The performance of the pre-existing magnetic model of the MU was investigated. A key limitation was found in the unmatched mesh density in the pole and the rest of the iron, generating tiny-angles mesh domain and causing the a dramatic slow-down in simulation times. To meet the requirement of providing input to operational decisions in a timely manner, as well as performing a large number of simulations to predict (and benchmark) the model over multiple machine configurations and energy levels, an improved meshing structure was needed. A new finite-element magnetic model of the PS-MUs was developed, incorporating a refined meshing strategy. Contrary to the meshing structure of the pre-existing MU magnetic model, which was purely based on hexahedral mesh domains,

the new model was designed with tetrahedral domains which adapted better to the complicated MU pole geometry. This aspect, combined with the careful distribution of the mesh domain density, enabled the new magnetic model to achieve a substantially improved time-efficiency compared to the pre-existing model, with simulation times reduced by an order of magnitude, enabling faster prediction of the optics without compromising accuracy. The new magnetic model predictions were validated across a wide range of currents against B-train magnetic measurements, which are used as a reference for machine operation. The percentage error between field predictions and magnetic measurements was below 1 %, even in saturation-affected powering regimes, with the agreement improving with increasing energy.

PS optics simulations, used in operation and to perform beam-dynamics studies, were previously based simply on effective models, where strengths in the MU elements were matched to generate desired beam parameters (tune and first order chromaticity). In contrast to these pre-existing MU optics models, the new optics model takes as input the integrated harmonics from the new magnetic model. This integrated approach aimed to provide operation of the PS with predictive tools to help make decisions on the machine and support development of new tune and chromaticity control systems, without requiring repeated extensive measurement campaigns to define beam-based references or recalibrate circuit responses, which may have limited validity.

An extensive beam-based measurement campaign was conducted to benchmark the new magnetic and optics models. The bare-machine configuration was analyzed to isolate the contribution of the MU on the beam parameters, deactivating the auxiliary circuits and all the corrector magnets distributed around the ring. An open question in the PS operation was whether dynamic effects impact the beam parameters during ramps in bare-machine. To assess this, preliminary measurements of tune and chromaticity were conducted across multiple static energy plateaus, then later measurements were also conducted continuously during a ramp to a 23.11 GeV/c plateau. Initially discrepancies were seen when comparing the static measurements from the individual plateaus with the dynamic measurements acquired during the ramp (at the same energy level). After investigation, a strong sensitivity of the Mean Radial Position (MRP) to

the PS supercycle composition was identified. This was reflected in a poor reproducibility of the measurements on a day-to-day timescale. Thus, new beam-based measurements were conducted, carefully monitoring and correcting the beam MRP to constrain it within a tolerance of ± 1 mm on each energy plateau. Significant tune variations were observed upon introducing the MRP corrections at pre-defined times throughout the power cycles. After including the MRP corrections also on the ramp to 23.11 GeV/c, dynamic tune and chromaticity measurements were finally seen to align well with those taken on the static energy plateaus. This demonstrated that dynamic effects (e.g. eddy-currents) did not have a relevant effect on the measurements acquired throughout the main body of the PS ramp. This enabled the use of the new magnetic and optics MU models, which do not account for dynamic effects, also during transitory ramps (though specific periods around transition and the very end of the ramp did show significant eddy current effects, which were excluded from the analysis considered).

Reflecting operational requirements to power the auxiliary F8L and PFW circuits for tune and chromaticity control, additional measurements were conducted by individually varying the powering of the auxiliary circuits (in the case of the PFW, homogeneous currents were used for the two half-units and the N and W circuits within the same half-unit). These measurements were conducted across three different plateau: 2.79 GeV/c, where the remanent field plays a key role, 10.14 GeV/c where remanent field and iron saturation effects are negligible, and 18.00 GeV/c, where saturation effects are significant. A more complex scenario was also investigated at 10.14 GeV/c and 18.00 GeV/c. This utilized the mixed powering of the all the MU's circuits, including the F8L and PFW taken from an operational LHC cycle, to prove a typical operational test-case.

These beam-based studies served to benchmark the predictive power of the new combined magnetic and optics MU models over multiple machine configurations and energy levels. The bare-machine model predictions were investigated first. The comparison between the simulated and measured tunes showed a good agreement in both planes, with the models predicting the fast decrease of the tunes above 14.04 GeV/c. This was associated with the faster saturation of the quadrupolar component generated by the MU with respect to the dipolar component.

From the model, the vertical tune saturation demonstrated a larger dis-

crepancy with the measurements when compared with the horizontal. This discrepancy between predicted and measured vertical tune increased with energy. This was unexpected due to the similar construction of the F and D half units, and since as previously mentioned, the magnetic model predictions showed convergence with B-train measurements when approaching higher energies. Examining the magnetic model, it was seen that the dipole saturation was more rapid at the main unit extremities, leading to a reduction of magnetic length with energy. This raised the concern that such a saturation effect was not fully captured by the PS B-train system. Measurements were conducted by specialized teams at CERN to measure the transfer function of the MU with the B-train and SSW system. The SSW measurements showed a fast decrease of the transfer function at high energy (above approximately 14.04 GeV/c.), which was indeed not correctly captured by the B-train due to its location in the half-unit cores. Comparing SSW measurements to the new magnetic model this saturation of the transfer function was found to be in good agreement with the predictions.

This finding had clear implication for the optics modeling. In operation, the programmed PS beam momentum is regulated based on the B-train measurements assuming a constant magnetic length over the whole energy range, equal to the nominal magnetic length of the main units. At low energy this theoretical magnetic length was in good agreement with the magnetic model predictions, but at high energy the predicted magnetic length decreased significantly, leading to an error in the programmed beam rigidity and momentum, which in turn affects the normalization of field harmonics utilized in the optics simulation. To account for this, the programmed momentum computation of the PS was corrected by using the predicted magnetic length as a function of the main coil current from the magnetic model, instead of the theoretical magnetic length. This approach was also separately cross-checked by applying rigidity corrections to enforce a constant k_0L in the model at a 10.14 GeV/c reference value where remanent field and saturation effects were both small.

New simulations were carried out with corrected momenta used to normalize the harmonic strengths. The saturation rate was found to be comparable on the horizontal and planes, with both tunes falling now into the measurements standard deviation. These results have had a direct operational impact on the machine, as new strategy are planned to integrate the

OPERA model predictions of magnetic length saturation into the operational calculation of programmed momentum, with the aim of improving the current-to-strength calibrations globally in the PS machine.

Tune and first-order chromaticity both exhibit large saturation induced shifts with beam-energy. Ultimately however, following the benchmarking process on the PS bare-machine, the predictions of the new magnet and optics model were found to be in good agreement with the measurements on the real machine as a function of energy. The predictive power of these new models has already been put to use to support PS operation, and during 2024 the models were used to provide input to the development of new operational cycles for the PS EAST experimental area.

Building on studies of the bare-machine, the auxiliary F8L and PFW circuits were also individually included in the models to benchmark their tune and chromaticity responses. The predicted tune response at various I_{F8L} and I_{PFW} currents aligned well with the measurements, with only a small discrepancy in the expected shifts. A chromaticity shift consistent with zero observed in the F8L measurements was consistent with model predictions, while the strong chromaticity shifts observed in the measurements with varying PFW current was also precisely captured by the models. The more complex operational scenario, involving the simultaneous non-uniform powering of all circuits with LHC-like powering settings at 10.14 GeV/c and 18.00 GeV/c was also benchmarked. The chromaticity predicted by the models agreed well with the measurements at both energies. Tunes also agreed well, with a maximum discrepancy at the level of $\Delta Q = 1.5 \times 10^{-2}$, comparable with the tune response difference observed when powering individually F8L and PFW.

The models' ability to replicate the effects of auxiliary circuits on beam dynamics, capturing linear and nonlinear contributions to optics parameters, provide operation with a flexible robust tool for tune and chromaticity control, able to predict the tune and chromaticity shifts in saturated or remanent field-driven regimes.

After assessing the models' capability of predicting global beam parameters (i.e., tune and chromaticity) further analysis were conducted to analyze the optics locally in the machine. The local optics, as characterized by the β -beating at different energies in the bare-machine, was extremely small. It showed slight increases with energy up to a peak of approximately

8%, well below the typical values without optics corrections both in the LHC and other injectors.

This thesis demonstrated the feasibility of bridging magnetic and optics modeling to create predictive digital twins of accelerator magnets, providing a case study on the Proton Synchrotron, which can serve as a blueprint for similar efforts in other accelerators. The results reported in the thesis models present a shift from a traditional empirical optics models to a predictive framework, capable of anticipating machine behavior and guiding operations without extensive experimental recalibration. The predictive models developed in this work have already been useful in the PS operations to inform the establishment of new cycle settings and beam extraction setups based on model predictions, rather than iterative experimentation, and new strategies are being investigated at CERN to use the combined magnetic and optics model as input to support development of improved tune and chromaticity control systems. A similar approach to that demonstrated here for the PS, has also now been proposed to improve the modeling and support the operation of the LEIR accelerator at CERN.

Tune and chromaticity measurements in bare-machine with MRP corrections

Similarly to what is shown in Fig 5.10, Fig A.1 reports the static measurements on the 5.25 GeV/c plateau. When the ramp begins (indicated by the green dashed line), the MRP shifts from approximately 0 mm to 25 mm. This shift coincides with a significant change in the tunes. A more pronounced MRP shift occurs at the end of the ramp, where it changes from 25 mm to -25 mm, leading to an abrupt tune shift at the ramp's conclusion. On the 5.25 GeV/c plateau, the MRP stabilizes at -25 mm, resulting in relatively stable tunes. Subsequently, MRP corrections are applied, which corresponds with a decrease in the tunes of the level of $0.2 \cdot 10^{-2}$ and $0.3 \cdot 10^{-2}$ for Q_x and Q_y , respectively. These corrections are maintained over the plateau segment delimited by the gray dashed lines, keeping the MRP within the tolerance range. Over this stable portion of the plateau, the static tune measurements showed excellent stability. Chromaticities, instead, did not show a significant variation when the corrections are applied.

Figure A.2 presents the measurements taken on the 7.00 GeV/c plateau. Similar to what observed on the 5.25 GeV/c plateau, the MRP increased during the ramp from 0 mm to approximately 30 mm, leading to a significant tune shift. In addition to the initial MRP change at the start of the

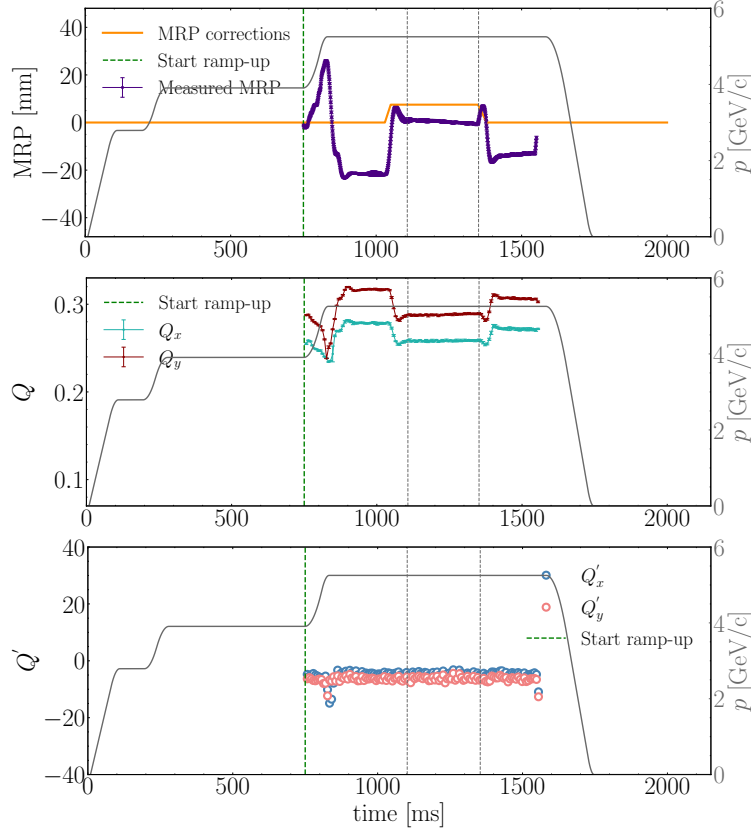


Figure A.1. Static beam-based measurements on the 5.25 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.

ramp, a pronounced variation in both the MRP and tunes is observed when crossing the transition (indicated by the blue dashed lines). At the end of the ramp, the MRP stabilizes around 35 mm, with the tunes remaining stable. As a result, corrections were applied, bringing the MRP within the tolerance range in the region marked by the gray dashed lines. Similar to the 5.25 GeV/c plateau, these MRP corrections resulted in significant shifts in both the horizontal and vertical tunes, on the order of $5 \cdot 10^{-2}$ for

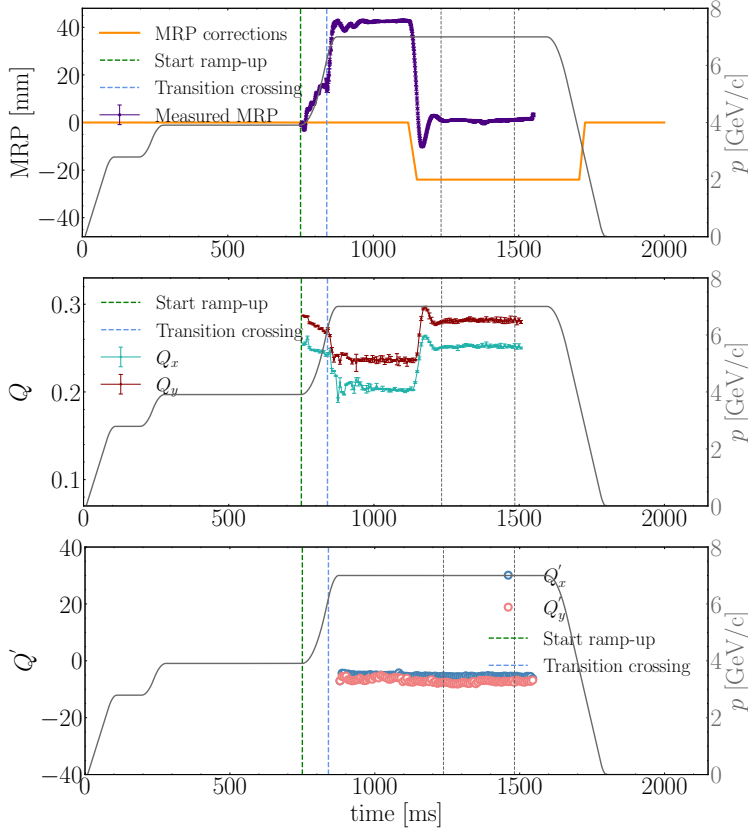


Figure A.2. Static beam-based measurements on the 7.00 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.

both Q_x and Q_y . On the contrary, the chromaticities did not exhibit any appreciable change when the corrections were applied.

Continuing the analysis of the measurements on the individual power cycles, Fig. A.3 presents the measured MRP and corrections applied, tunes and chromaticities over the 14.04 GeV/c cycle. On the ramp, a similar dynamic to that observed in previous cycles is seen, with changes in the MRP and tunes occurring when the ramp begins and when the transition is

crossed. After transition is crossed, MRP oscillates throughout the rest of the ramp. Due to the large MRP observed on the plateau (approximately, 25 mm), corrections were necessary, resulting in a tune shift of $4.4 \cdot 10^{-2}$ for Q_x and $2.8 \cdot 10^{-2}$ for Q_y . Compared to the lower energy plateaus, both the MRP and tunes exhibited shifts even after corrections were applied, and it was only possible to bring the MRP within tolerance in a small portion of the plateau delimited by the gray dashed lines. The chromaticities, however, did not show any appreciable variation following the application of MRP corrections.

More pronounced MRP oscillations were observed throughout the power cycle to the 18.00 GeV/c plateau, as illustrated in Fig. A.4 (top figure). Following significant oscillations during the ramp, the MRP reached 25 mm on the plateau. When corrections are inserted, it is kept within the accepted tolerance. However, it is interesting to observe that the MRP exhibited a considerable variation on the plateau at approximately $t = 1400$ ms, despite the application of corrections. This limited the region where a low MRP within the accepted tolerance could be maintained. Upon applying the corrections, the horizontal tune shifted significantly by $5 \cdot 10^{-2}$, while the vertical tune shift was minimal (below the 10^{-2} level). Vertical chromaticity did not exhibit any variation following MRP corrections, while horizontal chromaticity changed slightly.

A.1 Chromaticity measurements with PFW

The chromaticity measurements at different I_{PFW} currents are reported in this section. Particularly, Tab. A.1 reports the measurements on the 2.79 GeV/c plateau, Tab. A.2 refers to the measurements taken on the 10.14 GeV/c plateau, while Tab. A.3 presents those on the 18.00 GeV/c plateau. Ranging the I_{PFW} current on the different plateaus, an absolute maximum chromaticity shift of roughly 50 units was observed in both planes. This demonstrates the high impact of the PFW harmonics for the chromaticity control in the PS.

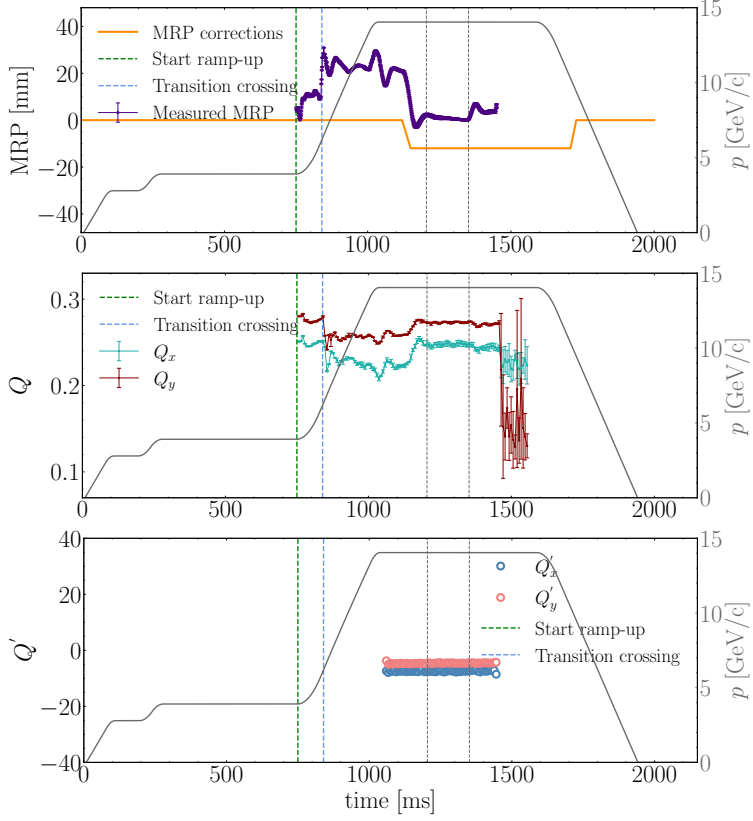


Figure A.3. Static beam-based measurements on the 14.04 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.

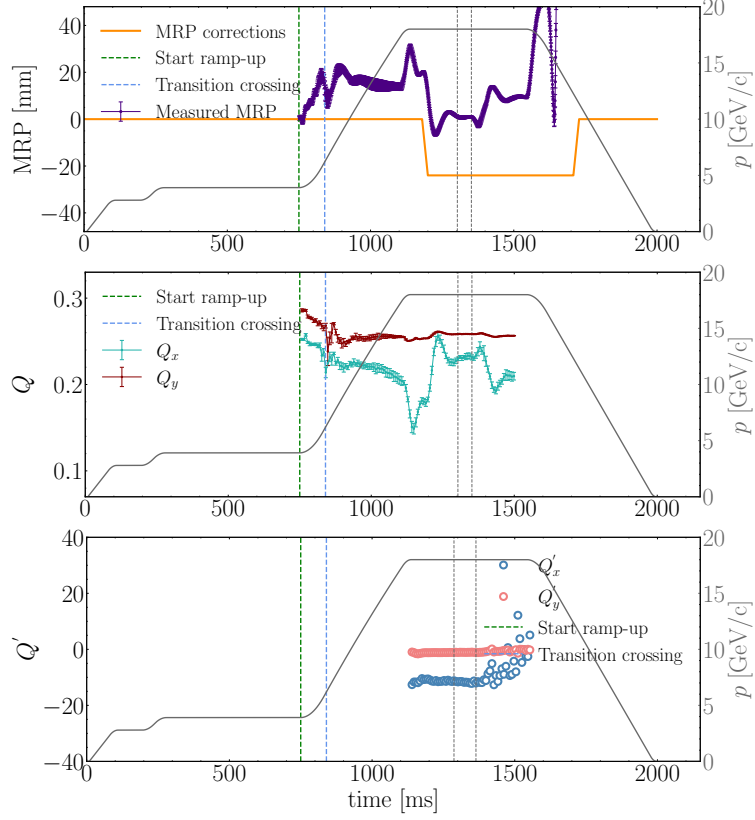


Figure A.4. Static beam-based measurements on the 18.00 GeV/c cycle with MRP corrections: MRP measurements (purple) and corrections (orange) in the top row; horizontal (turquoise) and vertical (dark red) tunes in the middle row; and horizontal (light blue) and vertical (light red) chromaticities in the bottom row.

Table A.1. Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 2.79 GeV/c flat-cycle at various I_{PFW} currents.

I_{PFW} [A]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
-5	-30.77	6.32	17.44	1.43
-3	-19.59	1.74	-7.28	1.65
-2	-14.67	2.52	1.27	26.77
-1	-10.41	0.26	-1.81	0.07
1	-0.54	5.56	-11.20	2.14
2	6.03	3.32	-17.41	1.67
3	9.30	2.15	-19.01	7.05
5	21.94	1.14	-33.49	1.34

Table A.2. Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 10.14 GeV/c plateau at various I_{PFW} currents.

I_{PFW} [A]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
-20	-33.49	2.09	19.76	4.50
-15	-27.07	3.55	13.61	5.95
-10	-17.50	6.23	6.25	8.00
-5	-12.80	6.25	0.12	25
0	-5.94	2.19	-6.12	2.61
5	2.32	21.98	-14.56	2.68
10	9.44	5.51	-20.77	4.24
15	15.00	6.4	-22.34	3.85
20	22.16	4.38	-32.74	2.60

Table A.3. Measured averaged horizontal and vertical chromaticity (Q'_x and Q'_y , respectively) with MRP corrections on the 18.00 GeV/c plateau at various I_{PFW} currents.

I_{PFW} [A]	$q'_{x,av}(p_0)$	$\sigma_{q'_{x,av}}(p_0)$ [%]	$q'_{y,av}(p_0)$	$\sigma_{q'_{y,av}}(p_0)$ [%]
-40	-39.41	1.85	16.62	2.67
-30	-36.14	6.75	20.44	9.49
-20	-25.51	4.00	13.78	3.70
-10	-16.68	4.92	6.11	4.75
0	-11.71	2.22	-1.06	2.83
10	-3.98	3.52	-7.83	6.77
20	3.59	3.34	-14.68	5.45
30	11.10	4.14	-18.99	4.95
40	17.73	4.46	-24.53	6.81

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