ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC15

ENERGY DEPENDENCE OF PS MAIN UNIT HARMONICS

V. Ferrentino*, D. G. Cotte, A. Gilardi, A. Huschauer, M. Karppinen, E. H. Maclean, T. Persson, R. Tomás Garcia, L. Von Freeden, CERN, 1211 Meyrin, Switzerland
P. Arpaia, University of Naples Federico II, Naples, Italy

Abstract

The CERN Proton Synchrotron (PS) is built with 100 C-shaped combined-function Main Units (MUs) magnets. The operation and modelling of the PS-MUs have been historically carried out with empirical beam-based studies. However, it would be interesting to understand 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 behaviour in the PS. In this paper, a comparison of tune measurements with the predicted optics is reported, showing the saturation of the quadrupolar component at high energy.

INTRODUCTION

The PS accelerates proton beams from 2 GeV up to 26 GeV kinetic energy [1]. It consists of 277 room temperature magnets, including 100 Main Unit (MU) bending dipoles [2]. The MUs are actually combined-function magnets consisting of 10 C-shaped iron blocks, 5 consecutive focusing (F), a transition area air-gap, and 5 consecutive defocusing (D), generating a quadrupolar components in the aperture [3].

Each MU is powered with 3 different coils: a main coil (MC) creating the main dipole and quadrupole fields, and two additional circuits, the Figure-of-eight loop (F8L) and the Pole Face Windings (PFW), creating extra quadrupole and higher-order field components to control tune, optics, and chromaticity. When the F8L and PFW are off, the PS operates in bare-machine configuration.

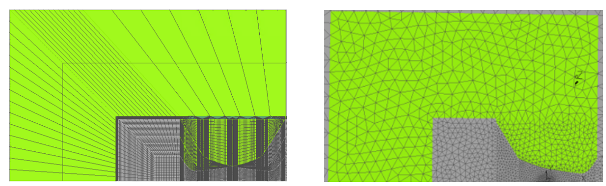
The optics and the magnetic modelling of such complicated magnets have been under investigation for decades [4–7]. The PS-MU optics model is developed with the Methodical Accelerator Design tool (MAD-X) [8,9]. Historically, it consisted of an effective model, meaning magnet strengths were chosen to match beam-based measurements. In the existing models, the magnet strengths were assumed to be constant with beam energy. However, some phenomena, such as eddy currents and iron saturation, might also cause a variation of the magnet strengths during operation.

This paper aims to assess the possibility of predicting the beam optics, merging the simulated harmonics from the PS-MU magnetic model in Opera 3D [10] into a MAD-X optics model. The predicted optics is then validated with beam-based measurements. The analysis reported in this paper refers only to the bare-machine configuration.

* Also with University of Naples Federico II, Naples, Italy; email: vittorio.ferrentino@cern.ch

MAGNETIC AND OPTICS MODELS

As a first step, the existing PS-MU magnetic model [11] was investigated. Its mesh structure, reported in Fig. 1a, consisted of a huge amount of mesh domains (6.5×10^6 elements in the volume). This caused the model to become very heavy, with simulation times on the order of days. Furthermore, the different discretization between the pole and rest of the iron block led to numerical errors. For this reason the mesh was redesigned, as reported in Fig. 1b. The new mesh presents a tetrahedral structure with 5.4×10^6 mesh elements in the model volume. The new model was significantly more manageable and time-efficient, allowing to complete a simulation in about 8 hours. It has been compared with magnetic measurements and the results were consistent [12].



(a) Old model. (b) New model.

Figure 1: PS-MU magnetic model: meshing structure of the old (left) and new (right) models.

The existing PS-MU MAD-X model, reported in Fig. 2 (top row), consisted of two sector bending magnets (SBENDs, blue), representing the two half-unit cores, and three thin MULTIPOLE lenses (red), representing the fields in the magnet fringes and the focusing-defocusing transition area air gap. The previous effective model matched measured tunes using the quadrupolar component (B_2) in the SBENDs, assuming no B_2 component at the magnet extremities or in the focusing-defocusing transition area. Higher-order harmonics (B_3 and B_4) in the fringe and transition multipoles were used to match chromaticities. The existing matched model did not attempt to predict the energy dependence of the optics assuming constant magnet strengths over the operational range of energy.

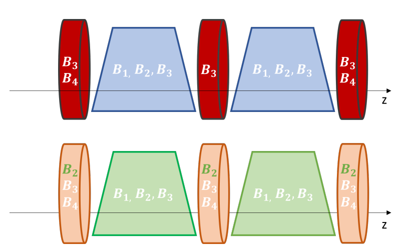


Figure 2: PS-MU optics model: old effective model (top row) and new one (bottom row).

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC15

The new PS-MU optics model, reported in Fig. 2 (bottom), is based on the predicted harmonics from the new Opera model, calculated as a function of the main coil current. Quadrupole and higher-order integrated harmonics are computed for the MU-half units, fringes, and F/D transition area and applied to the corresponding elements in the MAD-X model. This allows the contributions from the MU cores and the fringe fields on the global tunes to be separated.

Although defined with varying energy, the magnetic and optics models are static. Thus, they should be validated against measurements unaffected by dynamic effects.

OPTICS MEASUREMENTS

To benchmark the new models, bare-machine cycles with plateaus at different energies were created from 2.79 GeV to 23 GeV (the highest energy reachable in the bare-machine without losing the beam). Table 1 reports the power cycles with the measured current in the MC and the magnetic field measured with the B-train system [13].

Table 1: Measured Current and Magnetic Field on the Plateau of Each Power Cycle

Plateau energy [GeV]	I_{meas} [A]	B_{meas} [T]
2.79	531	0.13
5.25	998	0.25
7.00	1329	0.33
10.14	1925	0.48
14.04	2668	0.67
18.00	3428	0.86
23.11	4443	1.10

As an example, Fig. 3 reports in gray the bare-machine power cycle with a plateau at 10 GeV, together with the beam intensity evolution. Initially the beam was consistently lost at the end of the ramp on bare machine cycles, as shown with the purple curve. It was found that a brief excitation via a chirp pulsing or the AC dipole [14] at low energy allowed the beam to survive the ramp, as shown in Fig. 3 in orange. This was consistently observed over the whole year and for different cycles. The mechanism is not yet understood, but is perhaps related to emittance blow-up from the excitation.

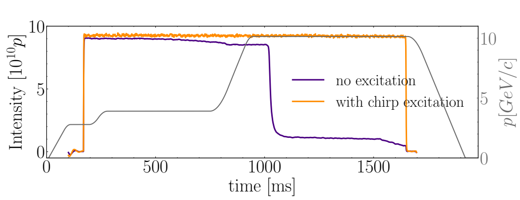


Figure 3: 10 GeV cycle and beam intensity evolution.

Tune measurements were carried out on each power cycle. Multiple shots were acquired, then averaged for each time step. As an example, in Fig. 4 the $Q_{x,y}$ tune measurements are reported over the 23 GeV cycle. It can be observed that when the ramp starts (green dashed line) and beam crosses transition (yellow dashed line), large transient dynamic effects are observed in the tunes. This also happens at the end of the ramp. This can be explained by harmonic distortion from eddy-currents (via feed-down) due to the abrupt field change resulting in high d^2B/dt^2. These transient regions are excluded from the benchmarking.

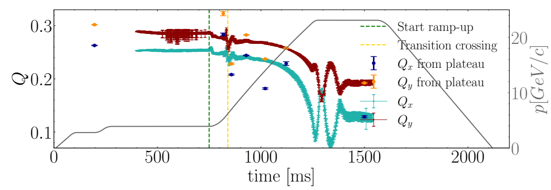


Figure 4: Q_x and Q_y measurements on the 23 GeV cycle, in turquoise and red, respectively. Q_x and Q_y measurements from individual plateaus in blue and orange, respectively.

In addition to the continuous tune measurements in Fig. 4, the measured tunes from the individual plateaus are reported (see as an example the 10 GeV in Fig. 3). A generally poor agreement was seen comparing the continuous and static measurements.

After investigation, the tune evolution showed a poor reproducibility on timescales typically longer than a day. Subsequently, it was found that there was a very strong sensitivity of the Mean Radial Position (MRP) [15, 16] of the bare machine cycles on the PS supercycle composition, which was affecting the measured tunes due to the feed-down effect.

This was mitigated by performing measurements on the various cycles on the same day, introducing a consistent pre-cycle to the supercycle prior to the bare-machine cycles under investigation, and by measuring and correcting the beam MRP. As an example, Fig. 5 reports the measured tunes (top) and MRP (bottom). It can be seen that when the MRP correction is trimmed in (ramp of the light red curve) the tunes undergo to a shift on the order of $4 \cdot 10^{-2}$. These corrections allowed a 0 MRP portion of the plateau to be created, delimited by the dashed vertical gray lines. With this

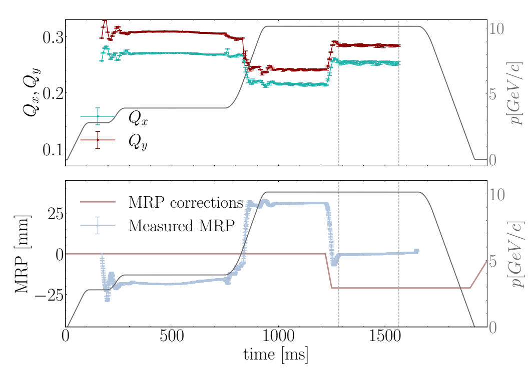


Figure 5: Q_x and Q_y measurements over the 10 GeV cycle (top), in turquoise and dark red respectively, and MRP measurements (bottom) in light blue and corrections in light red.

approach, tune measurements were repeated on each power cycle. Similarly to Figs. 4 and 6 reports tune measurements over the 23 GeV cycle but this time with MRP corrections

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC15

trimmed in throughout the cycle, and showing the static tune measurements from the individual plateaus with MRP corrections. With this strategy (dedicated pre-cycle and

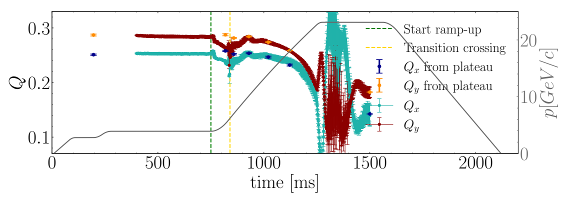


Figure 6: Continuous tune measurements over the 23 GeV cycle and static measurements with MRP corrections.

MRP corrections) the agreement between continuous and static measurements is excellent, with good long-term reproducibility. The two sets of measurements are equivalent for the benchmarking of the models. This proves that, besides from the aforementioned transient phases at the start and end of ramp and at transition, there are no relevant dynamic or eddy-current effects during the rest of the ramp. This demonstrates that the continuous measurements on the ramp can be used for benchmarking at various energies without needing to create a new bare-machine cycle each time, and that the static Opera and MAD-X models can be used to predict the tune evolution during the main body of the ramp, even though they do not include any dynamic effects.

The continuous measurements in Fig. 6 reveal a clear decrease of both tunes above 10 GeV. This can be due to the quadrupolar component of the MU saturating faster than the dipolar component. Indeed, the magnetic model predicts a more rapid saturation of the quadrupole field versus energy. This can be understood from Fig. 7, reporting the 2D field map at 10 GeV and 18 GeV where it is seen that the hyperbolic pole, which is part of an ideal quadrupole, saturates firstly in its edges. Thus, the quadrupole from the MU does not increase by the same amount as the dipole.

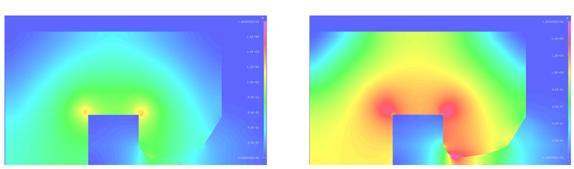


Figure 7: PS-MU magnetic model: 2D field map at 10 GeV (left) and 18 GeV (right).

MODELS' VALIDATION

To validate the optics and magnetic models, the predicted tunes were compared with the beam-based measurements. Figure 8 reports the comparison between the predicted Q_x and Q_y and the measurements, top left and top right, respectively. The horizontal gray lines represent the predicted tunes from the old PS-MU effective model. The dark blue and dark red curves represent the predicted Q_x and Q_y, respectively, from the new optics and magnetic models, while the turquoise and light red curves represent the measured Q_x and Q_y, respectively, with MRP corrections.

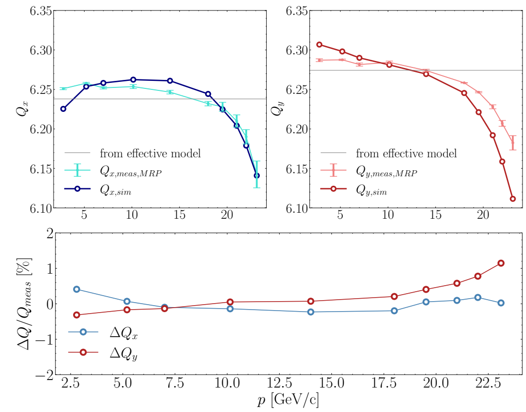


Figure 8: Comparison between predicted and measured Q_x (top left), Q_y (top right), and relative error in percentage (bottom).

This comparison shows that the combination of the magnetic and optics models can predict the tune saturation observed from the measurements and discussed in the previous Section, revealing a good agreement between the model predictions and the measurements. In the same figure, the plot on the bottom reports the relative difference in % between the measured and simulated tunes. It shows that the maximum relative errors are of 0.4% for Q_x at injection energy and 1.1% for Q_y at 23 GeV.

CONCLUSION

In this paper, the possibility of predicting the beam optics in the PS-MU in a bare-machine configuration, combining the magnetic and optics models of the PS-MU, is investigated. The existing PS-MU magnetic model was improved by redesigning its meshing structure. This allowed a reliable, manageable and time-efficient model to be created, which was validated by magnetic measurements. The MAD-X optics model was changed by inserting the simulated B_2 in the thin MULTIPOLE lenses to take into account the contribution to the global tunes from the fringe fields and the F-D transition area. To validate these static models, beam-based measurements were carried out on different bare-machine power cycles, foreseeing a plateau at a specific energy. After correcting for the influence of the supercycle composition on the mean radial position, a good, long-term reproducibility of the continuous and static measurements was obtained. The measurements showed a decrease of the tunes above 10 GeV, due to the faster saturation of the B_2 generated by the MU with respect to the dipole field. This was also predicted by the new magnetic model. The final comparison between model predictions and beam-based measurements revealed a good agreement, with a maximum error of 0.4% for Q_x and 1.1% for Q_y.

ACNKOWLEDGMENTS

The authors would like to thank the OP-PS and PSB teams for their help during the 2023 MD sessions.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUPC15

REFERENCES

[1] E. Regenstreif, "The CERN proton synchrotron", CERN, Geneva, Switzerland, Rep. CERN-1959-029, 1959. doi:10.5170/CERN-1959-029

[2] The Proton Synchrotron, https://home.cern/science/accelerators/proton-synchrotron

[3] S. Gilardoni *et al.*, "Fifty years of the CERN Proton Synchrotron: Volume 1", CERN, Geneva, Switzerland, Rep. CERN-2011-004, 2011. doi:10.5170/CERN-2011-004

[4] M. Juchno, "Magnetic Model of the CERN Proton Synchrotron", PhD thesis, EPFL, Lausanne, Switzerland, 2013. doi:10.5075/epfl-thesis-5964

[5] M. Juchno, "Electromagnetic FEM analysis of the CERN Proton Synchrotron main magnetic unit", Master thesis, Cracow University of Technology, Cracow, Poland, 2009, https://cds.cern.ch/record/1314838

[6] A. Huschauer, "Beam Dynamics Studies for High-Intensity Beams in the CERN Proton Synchrotron", PhD thesis, Technische Universität Wien, Austria, 2016, https://cds.cern.ch/record/2194332

[7] A. Huschauer, "Working point and resonance studies at the CERN Proton Synchrotron", Master thesis, Technische Universität Wien, Austria, 2012, https://cds.cern.ch/record/1501943

[8] MAD-X, https://mad.web.cern.ch/mad/

[9] H. Grote *et al.*, "Mad-X - an upgrade from mad8", in *Proc. PAC'03* Portland, OR, USA, paper FPAG014, pp. 3497–3499. doi:10.1109/PAC.2003.1289960

[10] Opera, https://www.3ds.com/products/simulia/opera

[11] "A reference magnetic model of the Proton Synchrotron main units", CERN, Geneva, Switzerland, Tech. Note 2140704, 2019.

[12] M. Pentella *et al.*, "Integral dynamic characterization of the PS main dipole unit", CERN, Geneva, Switzerland, Tech. Note 3011202, 2023.

[13] P. Arpaia *et al.*, "Real-Time Magnetic Measurement Monitoring under cRIO-LabVIEW Based Platform", in *EasyChair Preprint*, no. 1335, Jul. 2019.

[14] V. Ferrentino, "Magnetic modelling and beam-based measurements of the PS MUs", presented at Injectors Performance Panel MD days 2024, CERN, Geneva, Switzerland, unpublished.

[15] V. Chohan *et al.*, "An on-line evaluation of the relative mean radial position of the CERN PS beam using a high-precision chronometer", CERN, Geneva, Switzerland, Rep. CERN-PS-OP-NOTE-76-29, 1978.

[16] J. Belleman *et al.*, "Measurement of the mean radial position of a lead ion beam in the CERN PS", in *Proc. EPAC'96*, Sitges, Barcelona, Spain, Jun 1996, paper TUP021L, pp. 1603-1605.