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LHC OPTICS MEASUREMENT AND CORRECTION SOFTWARE PROGRESS AND PLANS

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Abstract

LHC Optics Measurements and Corrections (OMC) require efficient on-line software applications to acquire and analyze data and to compute the necessary corrections. During Run 2 various measurement and correction techniques have been merged to yield unprecedented optics quality, increasing the required number of steps to finalize the optics commissioning and the size of the software project. In turn, this calls for a higher level of automation, with possible implementation of machine learning techniques. During the Long Shutdown 2 the codes are being largely re-factored to improve performance, maintainability and extensibility. A description of the current status of the software and future plans is given.

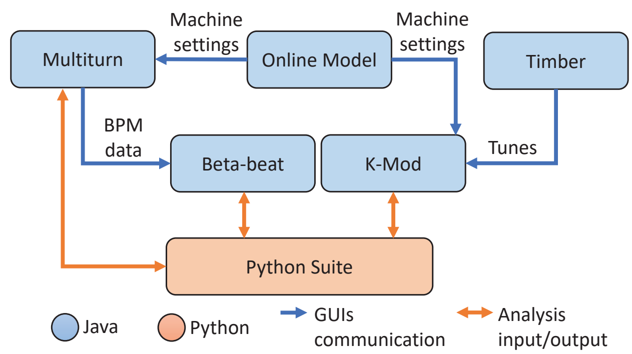

Figure 1: Flow chart of software applications involved in the optics measurement and corrections.

DESCRIPTION OF THE SOFTWARE

The OMC software aims at enabling accurate and efficient beam-based optics measurements and corrections online. LHC machine safety and performance have been the main drivers for the software development over more than a decade [1–27]. The main structural philosophy is to place the data analysis algorithms in independent Python codes that can be invoked from a command or from GUIs written in Java to be compatible with the LHC controls software, LSA [28]. This structure has allowed to easily adapt analysis codes to other accelerators [19, 29–38] and to package them using Docker software for use in other applications [39]. Profiting from the Long Shutdown 2 (LS2) between end of 2018 and end of 2020, a thorough review, extension, and consolidation of software is taking place. Python software is being migrated to Python 3.6 as Python 2 development will stop by the end of 2019 and, more importantly, the Python 2 backwards compatibility is already abandoned for new features in scientific packages such as numpy, scipy, pandas and matplotlib.

Figure 1 shows a schematic view of the ensemble of the OMC applications used in the control room. Multiturn is a Java GUI that controls the transverse beam exciters (AC dipoles, tune kickers or aperture kickers) and acquires the turn-by-turn (TbT) Beam Position Monitor (BPM) data. It automatically executes the Python codes for the first analysis of TbT data, especially to allow for fast coupling correction [40]. Online Model is a set of Java libraries to extract information on the machine settings [13]. TIMBER is the software developed by the CERN Beams Department Controls group to log and access time-series data [41]. Beta-beat and K-mod represent the two core applications to measure and correct optics from TbT data and from quadrupole strength modulations. The Beta-beat GUI written in Java executes appropriate Python codes for analysis and provides interactive view of the results. Optionally, it performs additional data cleaning and submits corrections to the hardware. The K-mod GUI [25], written in Java, modulates quadrupole strengths and records tune data, which are later automatically analysed by Python suite. The Beta-beat GUI imports results from the k-modulation analysis to be included in the optics corrections calculations.

The flow chart within the Python 3 suite corresponding to data analysis and optics calculations is shown in Fig. 2. The TbT data in binary SDDS format [42] is first cleaned. This

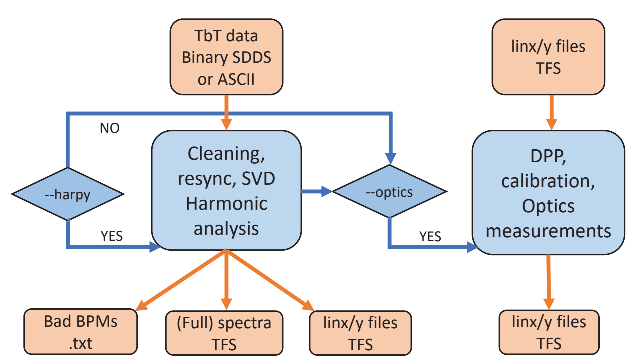

Figure 2: Flow chart of the Python 3 suite for harmonic analysis of TbT data and calculation of the optical parameters.

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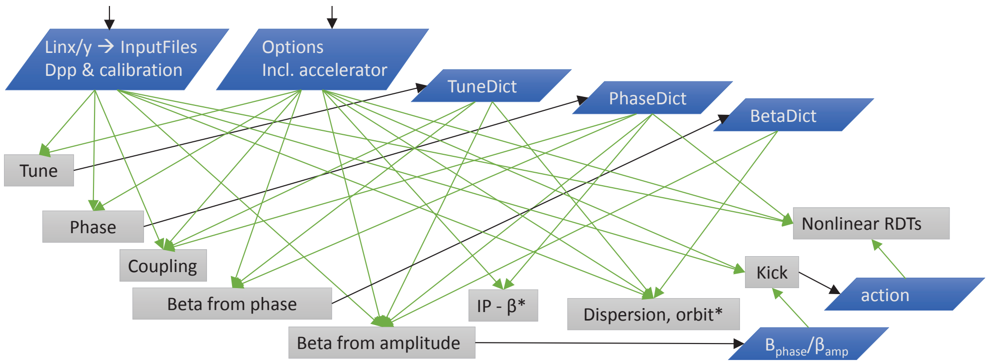

Figure 3: Sketch of optics measurements modules in Python 3 taking as input harmonic analysis results in linx/y files together with the module inputs (green arrows) and outputs (black arrows).

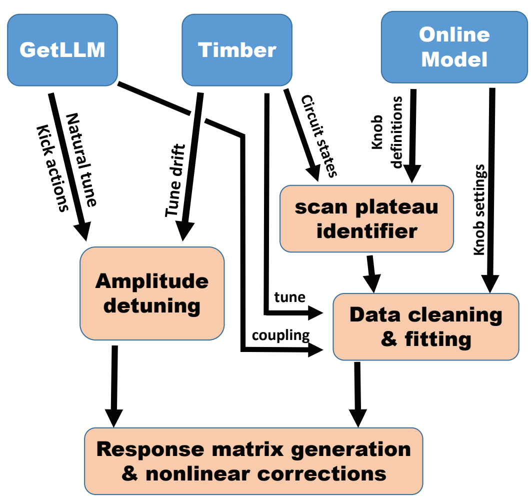

Figure 4: Sketch of the workflow of the software for non-linear measurements. GetLLM is Python 2 equivalent to optics measurement modules from Fig. 3.

is achieved by removing malfunctioning BPMs and applying noise reduction to the data via singular value decomposition [43]. Harmonic analysis is performed either with the Python code harpy [20] or with the Fortran code Sussix [44]. The harmonic analysis results are output into files with suffixes "linx" and "liny" for horizontal and vertical planes, respectively. Further BPM cleaning can be applied at this stage based only on tune values or on a collection of features applying Isolation Forest [21–24].

The cleaned linx/y files are passed to the Python suite for optics calculations, which is called GetLLM in the Python 2 suite. A sketch of the different modules in the Python 3 suite to compute optics parameters and their dependencies is shown in Fig. 3. Measured optics parameters are displayed in grey boxes including tunes, phase advances, coupling [8], β functions (from phase and from amplitude) [10, 17] at BPMs and at Interaction Points (IPs) [9, 12, 15], dispersion [27], amplitude of the excitation (kick) and resonance driving terms (RDTs) [45–47].

Non-linear measurements and corrections, in particular amplitude detuning and crossing angle scans, require a large human effort. Amplitude detuning is measured by acquiring many AC dipole excitations with increasing strength in the horizontal and vertical planes. The natural tunes represent a small signal in the spectra of the driven TbT data. It is fundamental to use noise-cleaning techniques to uncover the natural tunes. Often, human intervention is required to avoid confusing the natural tunes with spectral lines arising from the non-linear motion. Crossing angle scans are performed to sample the non-linear components of the triplet by measuring their feed-down to tune and linear coupling. The bump non-closure when changing the crossing angle is corrected to avoid contributions from other non-linear components in the machine. AC dipole excitations are also applied at every step of the scan. A variety of extra codes are used for these measurements, which are not fully incorporated into the above main environment. Figure 4 shows the work flow corresponding to these non-linear measurements and corrections with the connections to modules already described.

Table 1 shows the lines of code, the commits in 2018, and the static issues of the different software packages. The incomplete Python 3 suite, currently being migrated from Python 2, is included in the table. A sizable improvement is observed in the static analysis issues.

DEVELOPMENT PLANS

A new frequency analysis framework has been developed [48] within the Python 3 showing superior performance with respect to the current software.

During Run 2, optics measurements based on 3D beam excitation were experimentally demonstrated [49, 50]. In the LHC, such measurements are an order of magnitude faster compared to standard methods. Dedicated analyses are being implemented in the Python 3 suite.

The measurement of second order dispersion is currently being tested with experimental data from Run 2 [27] and should become fully operational on-line for 2021.

The possibility of improving the linear optics corrections by using machine learning techniques is currently under

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Table 1: Lines of code, commits, and static code analysis issues in 2018. Corresponding data during 2017 for a fraction of these codes can be found in [16]. In Python 3 repository, the git squash command is used. Therefore, the actual number of commits would be considerably higher.

Language	Lines of Code	Commits	Issues
Python 2	48007	1214	16051
Python 3	4196	31	69
Java (GUIs)			
β-beat	32139	108	82
Multiturn	20425	20	788
K-mod	16272	32	43

investigation [51]. First promising results suggest first applications in Run 3. Strength limitations in the quadrupolar circuits might appear when operating at 7 TeV, requiring new algorithms for the calculation of corrections. True local observables of linear imperfections are being developed in [52] in view of the 2021 commissioning.

During Run 2 various limitations in the current algorithms for the measurement of IP optics parameters were observed and new techniques were successfully tested [53]. One improvement consists in using the existing high-resolution DOROS BPMs [54] in the IRs to measure the minimum β function near the IP via phase advance. Currently, these BPMs are not included in the regular acquisition requiring new developments. Luminosity scans will be fundamental for accurate measurement of the betatron waist displacement from the IP [53] and for verifying the linear coupling correction at the IP. Studies are on-going to explore how these tasks could benefit from existing operational software for luminosity optimization and scanning.

An experimental demonstration of RDT correction was accomplished in [45–47]. The actual software to perform this correction on-line needs to be developed for 2021.

Automation of crossing angle scans and amplitude detuning is being investigated. This includes monitoring and correcting tune and orbit jitters of the machine [55, 56]. A challenging target for Run 3 is to fully validate IR dodecapolar corrections as a first step towards the even more complex HL-LHC non-linear commissioning in Run 4 [56].

With the increasing use of Python in LSA, it should be possible to establish new communications between the Python suite and the machine, that is currently done in the Java GUIs. More efficient solutions for data management concerning input data and output results should be explored to allow staged analyses and easy access to stored measurements.

REFERENCES

[1] R. Tomás *et al.*, "Procedures and Accuracy Estimates for Beta-beat Correction in the LHC", in *Proc. EPAC'06*, Edinburgh, UK, Jun. 2006, paper WEPCH047, pp. 2023–2025.

[2] R. Calaga, R. Tomas, and F. Zimmermann, "BPM Calibration Independent LHC Optics Correction", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper THPAS091, pp. 3693–3695.

[3] M. Aiba *et al.*, "First β-beating measurement and optics analysis for the CERN Large Hadron Collider", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 081002 (2009).

[4] R. Tomás *et al.*, "CERN Large Hadron Collider optics model, measurements, and corrections", *Phys. Rev. ST Accel. Beams* vol. 13, p. 121004 (2010).

[5] R. Tomás *et al.*, "Record low beta beating in the LHC", *Phys. Rev. ST Accel. Beams* vol. 15, p. 091001 (2012).

[6] T. Bach *et al.*, "Improvements for Optics Measurement and Corrections software", CERN-ACC-NOTE-2013-0010.

[7] T. Persson *et al.*, "Chromatic coupling correction in the Large Hadron Collider", *Phys. Rev. ST Accel. Beams* vol. 16, p. 081003 (2013).

[8] T. Persson and R. Tomás, "Improved control of the betatron coupling in the Large Hadron Collider", *Phys. Rev. ST Accel. Beams* vol. 17, p. 051004 (2014).

[9] J.M. Coello de Portugal *et al.*, "OMC Software Improvements in 2014", in *Proc. 6th Int. Particle IPAC'15*, Richmond, VA, USA, May 2015, pp. 426–429. doi:10.18429/JACoW-IPAC2015-MOPJE056

[10] A. Langner and R. Tomás, "Optics measurement algorithms and error analysis for the proton energy frontier", *Phys. Rev. ST Accel. Beams* vol. 18, p. 031002 (2015).

[11] E.H. Maclean *et al.*, "First measurement and correction of nonlinear errors in the experimental insertions of the CERN Large Hadron Collider", *Phys. Rev. ST Accel. Beams* vol. 18, p. 121002 (2015).

[12] M. Kuhn, V. Kain, A. Langner, and R. Tomas, "First K-Modulation Measurements in the LHC During Run 2", in *Proc. IBIC'15*, Melbourne, Australia, Sep. 2015, pp. 152–155. doi:10.18429/JACoW-IBIC2015-MOPB046

[13] T. Persson *et al.*, "Review of LHC On-line Model Implementation and of its Applications", in *Proc. IPAC'16*, Busan, Korea, May 2016, pp. 1505–1508. doi:10.18429/JACoW-IPAC2016-TUPMW030

[14] T. Persson *et al.*, "LHC optics commissioning: A journey towards 1% optics control", *Phys. Rev. Accel. Beams* vol. 20, p. 061002 (2017).

[15] L. van Riesen-Haupt, A. Seryi, J. M. Coello de Portugal, E. Fol, and R. Tomas, "K-Modulation Developments via Simultaneous Beam Based Alignment in the LHC", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2159–2162. doi:10.18429/JACoW-IPAC2017-TUPVA042

[16] E.H. Maclean *et al.*, "New LHC optics correction approaches in 2017", LHC Evian workshop 2017. https://indico.cern.ch/event/663598/contributions/2781846/

[17] A. Wegscheider *et al.*, "Analytical N beam position monitor method", *Phys. Rev. Accel. Beams* vol. 20, p. 111002 (2017).

[18] R. Tomás *et al.*, "Review of linear optics measurement and correction for charged particle accelerators", *Phys. Rev. Accel. Beams* vol. 20, p. 054801 (2017).

[19] L. Malina *et al.*, "Improving the precision of linear optics measurements based on turn-by-turn beam position monitor data after a pulsed excitation in lepton storage rings", *Phys. Rev. Accel. Beams* vol. 20, p. 082802 (2017).

[20] L. Malina *et al.*, "Performance Optimisation of Turn-by-Turn Beam Position Monitor Data Harmonic Analysis", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 3064–3067. doi:10.18429/JACoW-IPAC2018-THPAF045

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW116

[21] E. Fol, "Evaluation of Machine Learning Methods for LHC Optics Measurements and Corrections Software", Master thesis, CERN-THESIS-2017-336.

[22] E. Fol, F. S. Carlier, J. M. Coello de Portugal, A. Garcia-Tabares, and R. Tomas, "Machine Learning Methods for Optics Measurements and Corrections at LHC", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 1967–1970. doi:10.18429/JACoW-IPAC2018-WEPAF062

[23] E. Fol, J. M. Coello de Portugal, and R. Tomas, "Application of Machine Learning to Beam Diagnostics", presented at IBIC'18, Shanghai, China, Sep. 2018, paper TUOA02.

[24] E. Fol *et al.*, "Unsupervised Machine Learning for Detection of Faulty BPMs", presented at IPAC'19, Melbourne, Australia, May 2019, paper WEPGW081, this conference.

[25] M.L. Spitznagel, "K-modulation software development and automation", project thesis, CERN-THESIS-2019-013.

[26] F.S. Carlier *et al.*, "First experimental demonstration of forced dynamic aperture measurements with LHC ac dipoles", *Phys. Rev. Accel. Beams* vol. 22, p. 031002 (2019).

[27] J. Keintzel *et al.*, "Second Order Dispersion Measurement in LHC", presented at IPAC'19, Melbourne, Australia, May 2019, paper MOPMP027, this conference.

[28] G. Kruk *et al.*, "LHC Software Architecture (LSA) – Evolution towards LHC beam commissioning", in *Proc.* ICALEPCS'07, Knoxville, Tennessee, USA, pp. 307-309.

[29] R. Tomás *et al.*, '"Measurement of Resonance Driving Terms in the ATF Damping Ring", in *Proc. EPAC'08*, Genoa, Italy, Jun. 2008, paper THPC073, pp. 3155–3157.

[30] Y. Renier *et al.*, "Turn-by-turn Measurements in the KEK-ATF", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper TUPME045, pp. 1664–1666.

[31] R. Tomás *et al.*, "Linear and Non-Linear Optics Measurements at SOLEIL", in *Proc. PAC'09*, Vancouver, Canada, May 2009, paper TH6PFP075, pp. 3877–3879.

[32] R. Calaga, M. Aiba, R. Tomás, and G. Vanbavinckhove, "Linear and Chromatic Optics Measurements at RHIC", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper THPE053, pp. 4638–4640.

[33] C. Hernalsteens *et al.*, "CERN PS Optical Properties Measured with Turn-by-turn Orbit Data", in *Proc. IPAC'13*, Shanghai, China, May 2013, paper WEPEA054, pp. 2627–2629.

[34] P. Skowronski *et al.*, "Linear and non-linear optics measurements in the CERN PS using turn-by-turn BPM data", presented at IPAC'19, Melbourne, Australia, May 2019, paper MOPTS102, this conference.

[35] A. Garcia-Tabares *et al.* , "Optics measurements in the CERN PS Booster using turn-by-turn BPM data", presented at IPAC'19, Melbourne, Australia, May 2019, paper MOPGW080, this conference.

[36] A. Langner *et al.*, "Utilizing the N beam position monitor method for turn-by-turn optics measurements", *Phys. Rev. Accel. Beams* vol. 19, p. 092803 (2016).

[37] I. Agapov *et al.*, "Linear and Nonlinear Optics Measurements With Multiturn Data at PETRA III", in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 170–173. doi:10.18429/JACoW-IPAC2017-MOPAB040

[38] P. Conrad, "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300.

[39] G.H. Hemelsoet *et al.*, "Online Coupling Measurement and Correction Throughout the LHC Cycle", in *Proc. ICALEPCS'17*, Barcelona, Spain, Oct. 2017, pp. 686–691. doi:10.18429/JACoW-ICALEPCS2017-TUPHA119

[40] E. Fol, *et al.*, "LHC MD 1988: Automatic coupling correction test", CERN-ACC-NOTE-2017-0010.

[41] R. Billen, C. Roderick, "The LHC Logging Service Capturing, storing and using time-series data for the world's largest scientific instrument", AB-Note-2006-046 (CO).

[42] M. Borland, L. Emery, H. Shang, and R. Soliday, "User's Guide for SDDS Toolkit Version 3.5.1", https://ops.aps.anl.gov/manuals/SDDStoolkit/SDDStoolkit.html

[43] R. Calaga and R. Tomás, "Statistical analysis of RHIC beam position monitors performance", *Phys. Rev. ST Accel. Beams* vol. 7, p. 042801 (2004).

[44] R. Bartolini and F. Schmidt, "SUSSIX : A Computer Code for Frequency Analysis of Non–Linear Betatron Motion", CERN SL/Note 98-017 (AP).

[45] F. S. Carlier, J. M. Coello de Portugal, E. H. Maclean, T. Persson, and R. Tomás, "Observations of Resonance Driving Terms in the LHC during Runs I and II", in *.Proc. IPAC'16*, Busan, Korea, May 2016, pp. 3468-3471.

[46] F. S. Carlier, E. H. Maclean, T. Persson, and R. Tomás, "Nonlinear Correction Strategies for the LHC Using Resonance Driving Terms", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 161-164.

[47] F. Carlier *et al.*, "Correction of skew octupoles with Resonance Driving Terms", LMC 30 May 2018, https://indico.cern.ch/event/733065/.

[48] L. Malina, "Harpy: A fast, simple and accurate harmonic analysis with error propagation", to be published.

[49] L. Malina and J.M. Coello de Portugal, "Optics Measurements in Storage Rings Based on Simultaneous 3-Dimensional Beam Excitation", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 3068–3071. doi:10.18429/JACoW-IPAC2018-THPAF046

[50] L. Malina *et al.*, "LHC MD 4505", to be published.

[51] E. Fol *et al.*, "Optics corrections using Machine Learning in the LHC", presented at IPAC'19, Melbourne, Australia, May 2019, paper THPRB077, this conference.

[52] A. Wegscheider *et al.*, "Local linear observable", to be published.

[53] J. Coello *et al.*, "New local optics measurements and correction techniques for the LHC and its luminosity upgrade", to be published.

[54] M. Gasior *et al.*, "A High-resolution Diode-Based Orbit Measurement System - Prototype Results from the LHC", CERN-BE-2011-024.

[55] D.W. Wolf, "Analysis of tune modulations in the LHC", Bachelor thesis, CERN-THESIS-2018-251.

[56] F. Carlier *et al.*, "LHC Run 2 Optics Commissioning Experience in View of HL-LHC", presented at IPAC'19, Melbourne, Australia, May 2019, paper MOPMP033, this conference.