OMC IMPROVEMENTS AND PROSPECTS FOR 2015

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Abstract

LHC 2015 operation requires more precise and more efficient optics measurements and corrections. Improvements in these directions are presented including a potential coupling feedback based on DOROS. Furthermore β-beating estimates for 2015 are given and the optics commissioning is described for the non-linear circuits MCO, MCD, MCS and MSS.

IMPROVED OPTICS MEASUREMENT RESOLUTION

A large effort has been put over the past decade in achieving the high precision optics needed for the safe and efficient operation of the LHC [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. A new phase will start in 2015 where the higher energy and the new modes of operation will further challenge the LHC optics measurements tools and algorithms. Soon after the start of the LHC first Long Shutdown (LS1) a review was organized [11] to identify the required improvements in the LHC Optics Measurement and Correction (OMC) techniques to guarantee a high optics quality at 6.5 TeV in 2015. This review is the second of its kind [12]. A summary of the 2013 review [13] collected the highlights and the actions to face the challenges of operating LHC at its highest energy.

Improvements in the β function measurements

The optics resolution in 2012 was insufficient to understand beam size measurements [14] and determine β^* from beam position monitor (BPM) turn-by-turn measurements. Recent improvements to the measurement of β functions follow: (i) a new algorithm, the 7-BPM method, takes more BPM combinations into account and selects the ones which are best suited for the measurement, (ii) the cleaning of measurement data using a singular value decomposition (SVD) technique, (iii) improvements of the optics model including the use of the dipole quadrupole errors and a new more accurate calibration of MQY magnets. The resulting improvements on the β-function uncertainties are shown in Fig. 1.

Measurements from the 2012 run have been re-analyzed [15, 16] with a significant higher accuracy, which allowed the calculation of β values and demonstrated to be critical in the understanding of emittance evolution.

Improvements in the error bar

When deriving the β-function, two phase advances between BPMs are used ($\phi_{i,j}$, $\phi_{i,k}$) in which the BPM at s_i appears twice. This introduces a correlation which must

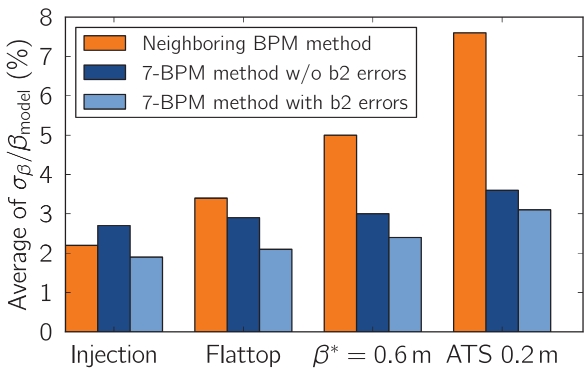

Figure 1: Improvements in the measured β-function uncertainties thanks to the 7-BPM algorithm and the model improvement with the dipole quadrupolar components (b_2).

be regarded in the error propagation. Furthermore the β-function at one position is calculated by combining three β-functions that are obtained from using different BPM combinations, which increases the contribution of correlations, because the same BPMs might be used more often. The error of the measured phase advance can be derived from the standard deviation

$$\sigma_{\phi_{i,j}} = t(n)\sqrt{\frac{1}{n-1}\sum_{k=1}^{n}\left(\overline{\phi_{i,j}} - \phi_{i,j,(k)}\right)^2} \qquad (1)$$

where $t(n)$ is the t value correction from the Student's t distribution, which compensates the underestimation of the uncertainty for a small sample size. During the LHC Run I the error was calculated from a normal standard deviation without the t correction and by dividing the sum by n instead of (n-1). This has been changed since the mean value of the phase advance is also obtained from the measurements, and there are only (n-1) degrees of freedom left for the calculation of the standard deviation. Table 1 shows $t(n)$ for different number of measurements, which shows that this correction is needed since due to limits in the beam time, the amount of measurements is always limited. The correlation between two phase advances which have one BPM in common, $\phi_{i,j}$ and $\phi_{i,k}$, depends on the uncertainty of the single phase ϕ_i at the common BPM. The error of the single phase ϕ_i is not known, because it cannot be compared among the measurement files since its value is arbitrary and may vary. However simulations show that the uncertainty of the phase measurement depends on the β-function at this position, $\sigma_\phi \sim \beta^{-\frac{1}{2}}$ cf. Fig. 2. Therefore

Table 1: Values for the t correction for a confidence interval of 68.3%.

Number of measurements	$t(n)$
2	1.84
3	1.32
4	1.20
5	1.15
10	1.06

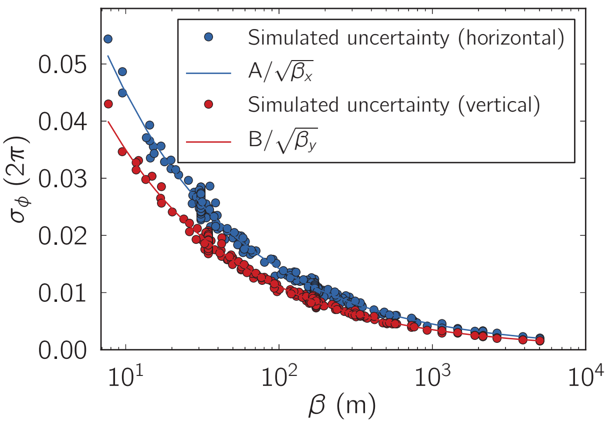

Figure 2: Simulated single phase uncertainties depending on the β-function. The error has been derived from the variation of the phase when a Gaussian noise of 300μm was added to the BPM turn-by-turn data which was obtained from tracking with MAD-X [17].

the error of the single phase can be approximated by

$$\sigma_{\phi_i} = \sigma_{\phi_{i,j}} \left(1 + \frac{\beta_i}{\beta_j}\right)^{-\frac{1}{2}}. \tag{2}$$

The correlation between two phase advances is then

$$\rho(\phi_{i,j}, \phi_{i,k}) = \frac{\sigma^2_{\phi_i}}{\sigma^2_{\phi_{i,j}} \sigma^2_{\phi_{i,k}}}. \tag{3}$$

Let the phase at the probed BPM be ϕ_1, all other phase advances can be calculated with respect to this BPM. The elements of the correlation matrix for the different phase advances $\phi_{1,2}$ to $\phi_{1,n}$ are defined by

$$C_{i-1,j-1} = \frac{\partial \phi_{1,i}}{\partial \phi_1} \frac{\partial \phi_{1,j}}{\partial \phi_1} \rho(\phi_{1,i}, \phi_{1,j}) \sigma^2_{\phi_{1,i}} \sigma^2_{\phi_{1,j}}, \tag{4}$$

which is $\sigma^2_{\phi_{1,i}}$ on the diagonal axis and $\sigma^2_{\phi_1}$ elsewhere. Using the transformation matrix

$$T = \begin{pmatrix} \frac{\partial \beta_1}{\partial \phi_{1,2}} & \cdots & \frac{\partial \beta_3}{\partial \phi_{1,2}} \\ \vdots & \ddots & \vdots \\ \frac{\partial \beta_1}{\partial \phi_{1,n}} & \cdots & \frac{\partial \beta_3}{\partial \phi_{1,n}} \end{pmatrix}, \tag{5}$$

the correlation matrix for the phases can be transformed to a correlation matrix for the three β-functions which are calculated from using different BPM combinations,

$$V = T^T C T. \tag{6}$$

The final β-function is then a weighted average of the three β_i

$$\beta = \sum_{i=1}^{3} w_i \beta_i \tag{7}$$

where the weights can be calculated from the inverse correlation matrix

$$w_i = \frac{\sum_{k=1}^{3} V_{ik}^{-1}}{\sum_{k=1}^{3} \sum_{j=1}^{3} V_{jk}^{-1}} \tag{8}$$

This equation replaces the simple average introduced in [4]. The uncertainty for this measurement is

$$\sigma_\beta^2 = \sum_{k=1}^{3} \sum_{j=1}^{3} w_j w_k V_{jk} \tag{9}$$

Simulation of the uncertainties

In order to determine the requirements on the number of measurements for a reasonable error bar, simulations of the optics measurement have been performed. These simulations are furthermore a test of the correct implementation of the equations in the optics analysis code. Particles were tracked for 2000 turns using MAD-X, while at the beginning a kick with an amplitude of 1 mm was applied to the particle. The oscillations of the orbit at the BPM positions were recorded and afterwards a Gaussian noise of 300 μm was added. This has been done to create 500 sets of BPM turn-by-turn data, which correspond to 500 measurements.

Since in contrast to a real measurement, in this simulation the phase at each BPM is comparable, it is possible to derive the uncertainty of the phase for each BPM position from its variation. As the uncertainties of the single phases and also of the phase advances are known, they were used directly in Eq. (3) to create the correlation matrix. The afore described error propagation was applied and the β-function derived according to Eq. (7), with its uncertainty according to Eq. (9).

The distribution of the β-function in these 500 data sets has been fitted to a Gaussian for each BPM. The value of the σ from the fit was then compared to calculated uncertainties of the β-function, cf. Fig. 3. The calculated values of the uncertainty fit well to the expected value from the variations of the β-function, which is not the case for the old equations for the error calculation. In this plot one can furthermore see that most of the points are located at two levels. This is due to the fact that the BPMs in the arcs, which are most of the BPMs, are alternating between two β values, and the larger β-function can be measured with a higher relative precision.

Hardware improvements

The accuracy of the phase measurements can be increased by recording the turn-by-turn data for more turns.

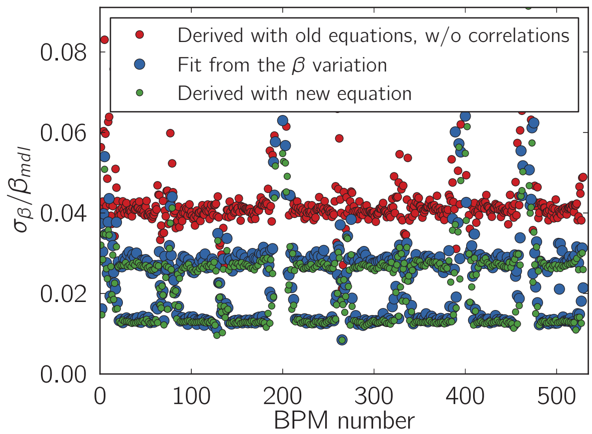

Figure 3: Relative uncertainty of the β-function derived in the error propagation compared to a fit of the variation of calculated β-functions.

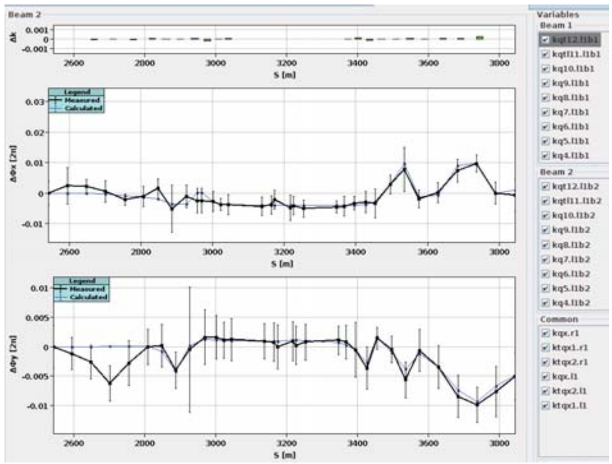

Figure 4: Screenshot of the implementation of the automatic local correction tool in the GUI.

This is limited by the AC dipole excitation time and the BPM acquisition software. It is foreseen to increase the maximum number of measured turns by a factor of three. This will allow for a more precise phase measurement and a better time efficiency during the measurements. Furthermore improved non-linear calibrations for BPMs are expected [18].

β-beat estimates for 2015 at $\beta^* = 40\,cm$

Simulations show that the β-beating due to the dipole b_2 errors for injection optics at 6.5 TeV is around 5% and may reach up to 7% for squeezed optics at $\beta^* = 0.4\,$m. Due to a broken MQT magnet, four MQT magnets of the same circuit will be switched off in order to minimize the β-beat and dispersion-beat and they will be compensated by increasing the strength of other MQT magnets in the same arc. For a tune shift of 0.08 this will lead to a peak β-beat in arc81 of around 2% for injection optics or 4% for ATS $\beta^* = 0.2\,$m optics at 7 TeV. The β-beat due to this is negligible in the other arcs.

In 2012 the local corrections for $\beta^* = 0.6\,$m accounted for a β-beat of 80% for Beam 1 and 100% for Beam 2. Extrapolating this to a $\beta^* = 0.4\,$m this number increases to 100% for Beam 1 and 130% for Beam 2.

Another source for β-beating is the uncertainty of the saturation component of quadrupole magnets [19]. The impact of this uncertainty is studied by creating 60 different lattices where the saturation component is changed by a Gaussian distributed random value within its uncertainty. The resulting β-beat shows a peak β-beat of around 1% in the worst case.

The distribution of the resulting β-beat if the b_2 errors, hysteresis error, saturation uncertainty and the extrapolation from local corrections in 2012 are regarded together has a maximum for a peak β-beat of 100% for Beam 1 and 140% for Beam 2. It should be noted that this estimate is for the $\beta^* = 0.4\,$m optics and it is not clear if this optics will be used in 2015. This simulation covers the worse cases, since optics with a larger β^* will have a smaller β-beating.

TOWARDS A COUPLING FEEDBACK

The control of the betatron coupling is fundamental for the safe operation of the tune feedback. Recent advancements in methods and algorithms for the coupling measurement and correction follow [20]: (i) a more precise formula relating the Resonance Driving Term (RDT) f_{1001} to the ΔQ_{min}, (ii) the quality of the coupling measurements is increased, with about a factor 3, by selecting BPM pairs with phase advances close to $\pi/2$ and through data cleaning using Singular Value Decomposition (SVD) with an optimal number of singular values. These improvements are beneficial for the implemented automatic coupling correction, which is based on injection oscillations. Furthermore, a coupling feedback for the LHC is under development. The system will rely on a new BPM electronics system, Diode ORbit and OScillation (DOROS) [21], which will be operational when LHC restarts in 2015. The feedback will combine the coupling measurements from the available DOROS BPMs in order to calculate the best correction.

AUTOMATIC LOCAL CORRECTIONS

During Run I all local corrections have been computed manually by optics experts usually off-line. During LS1 automatic routines for the computation of corrections have been developed using the MADX matching module [22]. These routines are being incorporated to the OMC Graphical User Interface (GUI) for a flexible selection of correcting quadrupoles and constraints from measurements. Figure 4 shows the implementation in the GUI.

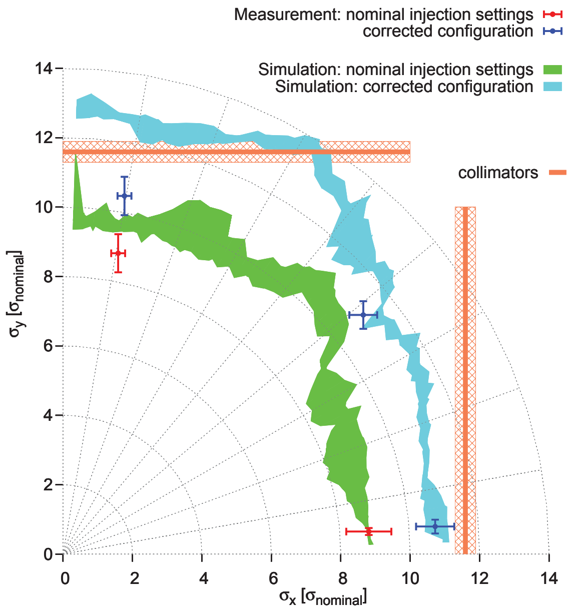

Figure 5: Measured and modeled dynamic aperture before and after correction at injection for Beam 2.

SETTING OF MSS, MCS, MCO AND MCD

MCS correctors are used for the compensation of b_3 errors in arc dipoles, but no beam based checks have been performed so far. The π orbit bump method introduced in [23] can be used to assess the correction quality, and its implementation is recommended for the commissioning of Run II.

Dynamic aperture and amplitude detuning

In [24] it was demonstrated that non-linear chromaticity, amplitude detuning and dynamic aperture could be corrected simultaneously at injection, see Fig. 5. It is desired that such corrections are implemented during the commissioning at low intensity to provide an obstacle free playground for finding optimum settings of Landau octupoles with higher intensities.

In 2012 amplitude detuning was measured for the first time via forced adiabatic betatron oscillations using AC dipoles [8]. This functionality has been added to the OMC GUI to allow fast measurements and corrections during commissioning. Corrections are proposed especially for injection, using the MCO correctors. At flattop the measured amplitude detuning in 2012 with depowered landau octupoles was negligible.

Chromatic coupling

Beam-based techniques were applied for the first time in 2012 to correct chromatic coupling [9] in the LHC. The resulting corrections turned out as efficient as previously computed corrections based on magnetic measurements but requiring significantly weaker correctors. However these corrections were not used in nominal operation. The OMC GUI has been equipped with the required algorithms to allow for the chromatic coupling corrections to be set during commissioning. These corrections using the MSS magnets should be implemented in Run II.

Inner triplet high order corrections

Higher order triplet errors were studied via their feed-down to both tune and linear coupling. These measurements were compared with model predictions incorporating magnetic measurements of the non-linear errors in the IR magnets. Where observation and simulation agree, or deviations are well understood, the model may be used to calculate corrections for the non-linear errors. This is the case for IR2 and certain multipoles in IR1, however discrepancies were particularly notable in IR5. Further studies in Run II are needed to allow identification of the sources, their incorporation into the model, and eventual correction.

Table 2: Results of cleaning and improving OMC software (C/Fortran, Python and Java (GUI)).

	2013-01	2014-02
Lines of code	331,312	141,195
Static analysis issues	479,680	165,531
GUI Critical bugs	7	0
GUI Time startup to corrections	25 min	2 min
GUI Memory usage per shot	100 MB	12 MB
GUI Units test coverage	0	43%

SOFTWARE IMPROVEMENTS

Since 2012 computer scientists are cleaning, refactoring, optimizing and parallelizing the OMC software [10, 25]. The refactoring of the main programs (Python/C/FORTRAN/Java) and removing of obsolete source code led to a clean software base and a robust execution. The removal reduced lines of code and static analysis issues significantly. Cleaner code facilitates further changes and corrections to the algorithms. Moreover professional software development techniques, like using static analysis tools, version control software, an integrated development environment, a bug tracker and automated tests, were applied to improve software quality. Table 2 shows a comparison of metrics between the old and the current software base.

Software development is one of the fundamental pillars for improved optics measurements and corrections in the LHC. In 2015, the implementation of new techniques and further optimizations will be faster and safer than ever.

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REFERENCES

[1] M. Benedikt, A. Faus-Golfe, F. Schmidt, R. Tomás, P. Urschütz, "Driving Term Experiments at CERN' ', Phys. Rev. ST Accel. Beams **10**, 034002 (2007).

[2] R. Calaga, R. Tomás, F. Zimmermann, "BPM calibration independent LHC optics correction", PAC 2007 .

[3] R. Tomás, Y. Papaphilippou, S.D. Fartoukh, F. Zimmermann, R. Calaga, A. Franchi, M. Giovannozzi, O .S. Brüning, S. Peggs, "Procedures and accuracy estimates for beta-beat correction in the LHC", LHC-PROJECT-Repor t-941 (2006).

[4] M. Aiba, S. Fartoukh, A. Franchi, M. Giovannozzi, V. Kain, M. Lamont, R. Tomás, G. Vanbavinckhove, J. Wenninger, F. Zimmermann, R. Calaga, and A. Morita, "First beta-beating measurement and optics analysis for the CER N Large Had ron Collider", Phys. Rev. ST Accel. Beams **12**, 081002 (2009).

[5] R. Tomás et al, "LHC optics model, measurements and corrections", Phys. Rev. ST Accel. Beams **13**, 121004 (2010).

[6] R. Miyamoto, R. Calaga, M. Aiba, R. Tomás and G. Vanbavinckhove, "Measurement of coupling resonance driving terms in the lhc with ac dipole", IPAC 2011.

[7] R. Tomás, T. Bach, R. Calaga, A. Langner, Y. I. Levinsen, E. H. Maclean, T. H. B. Persson, P. K. Skowronski, M. Strzelczyk, G. Vanbavinckhove, and R. Miyamoto "Record low beta beating in the LHC", Phys. Rev. ST Accel. Beams **15**, 091001, (2012).

[8] S. White, E. Maclean, R. Tomás, "Direct amplitude detuning measurement with AC dipole", Phys. Rev. ST Accel. Beams **16**, 071002, (2013).

[9] T. Persson, Y. Levinsen, R. Tomás, E. Maclean, "Chromatic coupling correction in the Large Hadron Collider", Phys. Rev. ST Accel. Beams **16**, 081003, (2013).

[10] T. Bach and R. Tomás, "Improvements for Optics Measurement and Corrections software", CERN-ACC-NOTE-2013-0010.

[11] LHC Optics Measurement and Correction Review, June 2013: http://indico.cern.ch/event/OMC-review

[12] "Optics Measurements, Corrections and Modeling for High-Performance Storage Rings": http://indico.cern.ch/conferenceDisplay.py?confId=132526

[13] O. Brüning, M. Giovannozzi, V. Kain, M. Lamont, Y. Levinsen, S. Redaelli, P. Skowronski, R. Steinhagen, R. Tomás, F. Zimmermann, "Summary of the 2013 LHC Optics Measurement and Correction review", CERN-ACC-2013-0130.

[14] M. Kuhn, G. Arduini, P. Baudrenghien, J. Emery, A. Guerrero, W. Hofle, V. Kain, M. Lamont, T. Mastoridis, F. Roncarolo, M. Sapinski, M. Schaumann, R. Steinhagen, G. Trad, and D. Valuch, "Investigations of the LHC Emittance Blow-Up During the 2012 Proton Run", IPAC 2013

[15] A. Langner et al, "Improvement of the LHC optics measurement methods" to be submitted to PRSTAB..

[16] A. Langner and R. Tomás, "Improvements in the Optics Measurement Resolution for the LHC", IPAC 2014

[17] MAD-X, `http://cern.ch/mad`

[18] A. Nosych, "Geometrical non-linearity correction procedure of LHC beam position monitors", CERN EDMS Id: 1342295

[19] N. Aquilina et al, "LHC magnets towards 7 TeV operation", to be published

[20] T. Persson, R. Tomás, "Improved Control of the Betatron Coupling in the Large Hadron Collider", Phys. Rev. ST Accel. Beams, 17, 051004 2014.

[21] J. Olexa, O. Ondracek, Z. Brezovic, and M. Gasior, "Prototype system for phase advance measurements of LHC small beam oscillations", Tech. Rep. CERN-ATS-2013-038 http://cds.cern.ch/record/1546401/

[22] P. Skowronski, "Measurements at β^{*}=0.4 m and automatic local corrections", in [11].

[23] M. Hayes, "Tolerances of the spool piece correction system for the LHC", LHC Project Report 590

[24] E.H. Maclean, R. Tomás, F. Schmidt and T.H.B. Persson, "Measurement of LHC non-linear observables using kicked beams", accepted for Phys. Rev. ST-AB.

[25] V. Maier, "Software Quality Improvement of the OMC Team", University of Applied Sciences Kaiserslautern, Bachelor's thesis CERN-THESIS-2014-028.