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PROSPECTS FOR THE LHC OPTICS MEASUREMENTS AND CORRECTIONS AT HIGHER ENERGY

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Abstract

LHC will resume operation in 2015 at 6.5 TeV. The higher energy allows for smaller IP beta functions, further enhancing the optics errors in the triplet quadrupoles. Moreover the uncertainty in the calibration of some quadrupoles will slightly increase due to saturation effects. The complete magnetic cycle of the LHC will take longer due to the higher energy and extended squeeze sequence. All these issues require more precise and more efficient optics measurements and corrections to guarantee the same optics quality level as in 2012 when a 7% peak beta-beating was achieved. This paper summarizes the on-going efforts for achieving faster and more accurate optics measurements and corrections.

OPTICS AND SOFTWARE DEVELOPMENTS

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 [1–10]. 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 [12] 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 [13]. A summary of the 2013 review [14] 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 [15] and determine β^*. Recent improvements to the measurement of β functions follow: (i) a new algorithm, the 7-BPM method, takes more beam position monitor (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 reanalyzed [16, 17] with a significant higher accuracy, which allowed the calculation of β values and demonstrated to be critical in the understanding of emittance evolution.

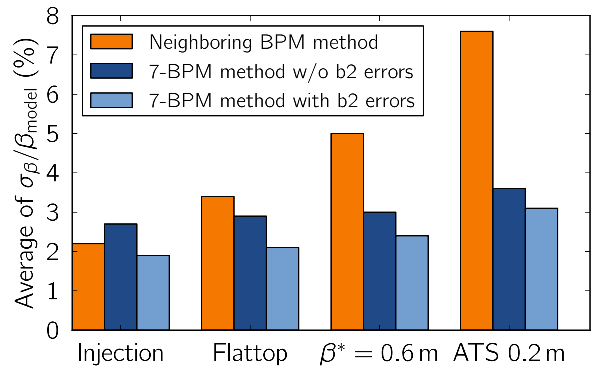

Figure 1: Improvements in the measured β-function uncertainties thanks to the 7-BPM algorithm and the model improvement with the dipole quadrupolar components (b_2).

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 [18]: (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) [19], which will be operational when LHC restarts in 2015. The feedback will combine the coupling measurements from the available BPMs in order to calculate the best correction.

K-Modulation

At locations with individually powered quadrupoles it is possible to measure the beta functions with k-modulation. This method is essential for locations with a non-optimum phase advance between BPMs. A new automatic and online k-modulation tool is under development [20]. It will also offer sinusoidal modulation of the quadrupole currents to shorten the measurement time and improve accuracy.

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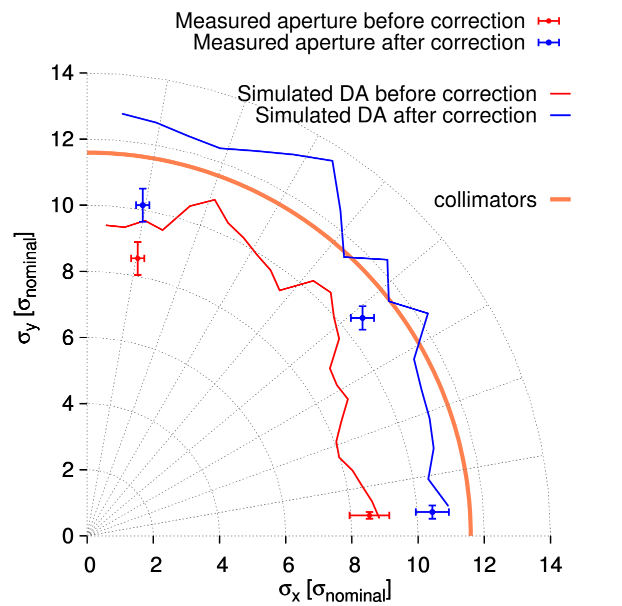

Figure 2: Measured and modeled dynamic aperture before and after correction at injection for Beam 2.

Automatic 2-beam 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 [21]. These routines are being incorporated to the OMC Graphical User Interface (GUI) for a flexible selection of correcting quadrupoles and constraints from measurements.

Dynamic Aperture and Amplitude Detuning

In [22] it was demonstrated that non-linear chromaticity, amplitude detuning and dynamic aperture could be corrected simultaneously at injection, see Fig. 2. It is desired that these 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.

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.

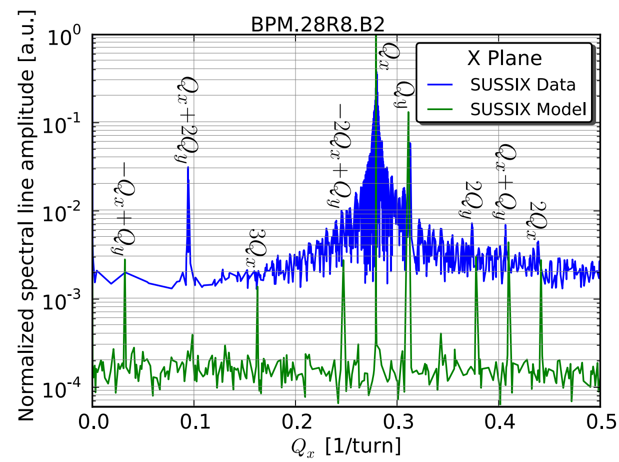

Figure 3: Measured and modeled spectrum for a large horizontal kick in Beam 2. The unexpectedly large line $Q_x + 2Q_y$ has already been identified as BPM non-linearity to be corrected in 2015.

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 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.

Resonance Driving Terms

For the first time in LHC a collection of spectral lines related to high order resonances could be observed in the large kick data from 2012, see Fig. 3. The software is being extended to analyze more resonances exploring also possible improvements in resolution. Unit tests for these extensions have been written, which rely on tailored BPM data for a complete verification of the algorithms. In addition alternative and more efficient analysis tools are under development.

2^{nd} Order Dispersion

Algorithms are under development in order to probe the LHC 2^{nd} order dispersion for the first time in 2015. This is expected to improve the linear dispersion measurements in some locations where the 2^{nd} order dispersion dominates.

Software

Since 2012 computer scientists are cleaning, refactoring, optimizing and parallelizing the OMC soft-

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Table 1: 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%

ware [10, 11]. 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 1 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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