FIRST BETA-BEATING MEASUREMENT IN THE LHC

R. Tomás, M. Aiba, S. Fartoukh, A. Franchi, M. Giovannozzi, V. Kain, M. Lamont,
G. Vanbavinckhove, J. Wenninger and F. Zimmermann, CERN; R. Calaga, BNL; A. Morita, KEK

Abstract

In 2008 beam successfully circulated in the LHC. Thanks to an excellent functioning of the beam position monitor (BPM) system and the related software, injection oscillations were recorded for the first 90 turns at all BPMs. The analysis of these data gives the unique opportunity of evaluating the periodic optics and inferring possible error sources.

INTRODUCTION

The LHC has a beta-beating tolerance lower than any other previous hadron collider. This requires the use of the most precise numerical algorithms, as well as a highly-performing BPM system. After dedicated studies over several years, the procedures to measure and correct the LHC optics have been established via numerical simulations and measurements in existing accelerators [1, 2, 3, 4].

After the successful LHC injection tests [5] the counter-clockwise Beam 2 was circulated in the LHC with an excellent lifetime. The turn-by-turn beam positions of the first 90 turns at about 500 double plane BPMs were acquired using the YASP [6] software.

This paper compares the different techniques used to measure the machine optics. New optics error reconstruction algorithms have been developed and applied to this exceptional situation with largely constrained data plus the current unavailability of the LHC to iterate corrections and measurements. The coupling measurement from the secondary spectral lines of BPM data is presented in the last section.

THE BETA-BEATING MEASUREMENT

The LHC Beam 2 optics measurement was severely constrained due to the availability of only one turn-by-turn BPM data set, acquired right at injection and containing only 90 turns. In addition the transverse coupling was uncorrected and the chromaticity was estimated to be 30 units [7]. Despite these set backs, reliable optics measurements were accomplished and described in [8].

The optics is probed through the phase advance between BPMs as it provides a robust and calibration independent observable. The beta functions are extracted from the phase advances between 3 BPMs as it was done in LEP [9]. No statistical error can be assigned to the measurement due to the existence of only a single data acquisition. However by using multiple combinations of 3 BPMs, several beta functions measurements can be obtained for the same BPM location. The average and rms of these measurements yield the beta function and its error bar, respectively.

Three different algorithms are used to measure the phase advance between BPMs, namely SVD [10], SUSSIX [11]
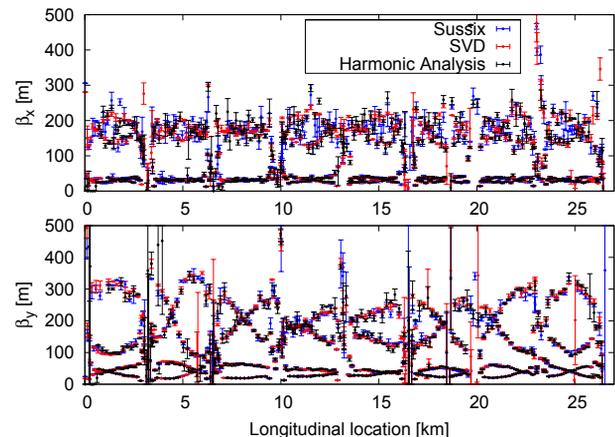

Figure 1: The measurement of the horizontal (top) and vertical (bottom) β functions around the LHC Beam 2.

and harmonic analysis (or DTFT). The three algorithms yield consistent beta function values as shown in Fig. 1. However the SVD approach features a more accurate measurement as displayed in the histograms of the beta functions relative error, Fig. 2. The vertical beta function is measured with an rms error of about 2%, corresponding to a phase error of 0.8 degrees [2] in the arcs. This is smaller than the 1 degree resolution required to correct the LHC optics as presented in [3]. The better performance of the SVD algorithm can be attributed to the fact that it takes advantage of the correlation between a large set of BPMs as in the case of the LHC. The SVD technique is used as the reference in the rest of the paper.

Figures 3 and 4 compare the LHC Beam 2 observed beta-beating to the tolerances as presented in Ref. [12] and to simulations with realistic errors. The horizontal beta-beating is within expected values for a first measurement and not far from tolerances. However the large vertical beta-beating suggests that a few large quadrupolar errors might exist at defocusing locatiions. New algorithms have been developed in order to identify possible gradient errors in this regime outside the linear reconstruction approach.

OPTICS ERRORS RECONSTRUCTION

A typical approach for optics correction in accelerators uses the inverse model response matrix of some observables such as phase advances, beta functions or dispersion on gradient strengths, see e.g. [2, 14, 15].

However, this approach is not suitable for this exceptional situation where the size of the errors exceeds the linear regime and there was no possibility to iterate corrections on the machine.
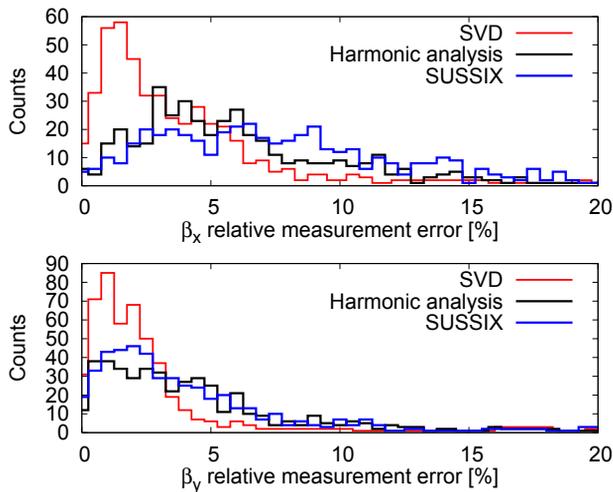
Figure 2: Measurement error comparison of the three different algorithms used to measure the β functions. Histograms of the horizontal and vertical beta function relative measurement errors are shown on the top and bottom plots, respectively.
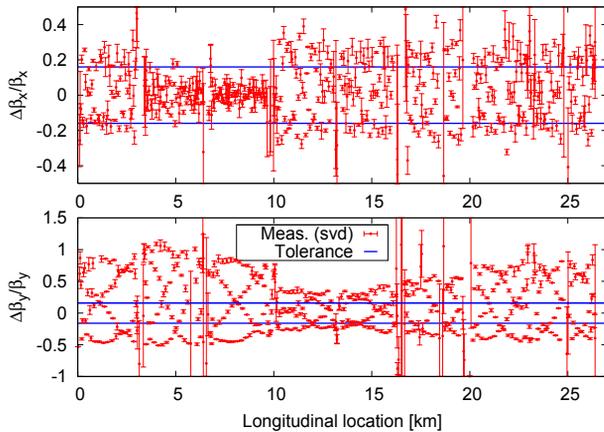

Figure 3: Measured horizontal (top) and vertical (bottom) beta-beating versus longitudinal location together with tolerances.
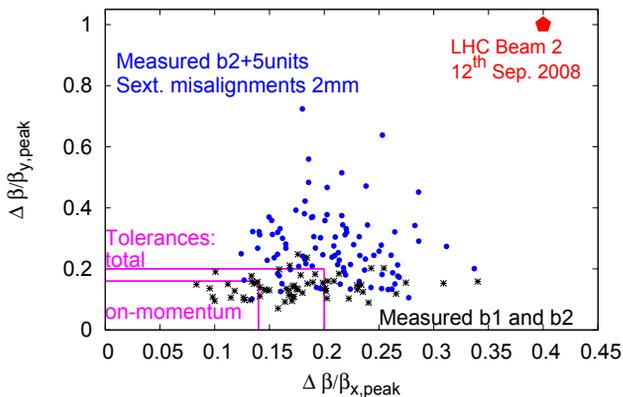

Figure 4: Simulations (black and blue), observation (red) and tolerances (magenta) of the peak beta-beating in the LHC, showing an unexpectedly large measured beta-beating in Beam 2.
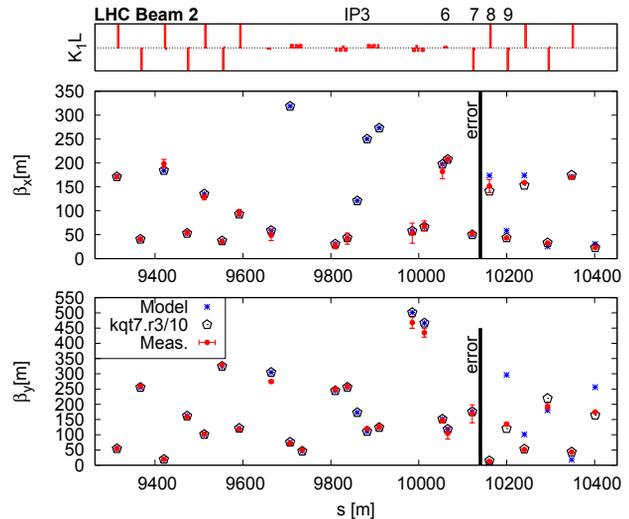

Figure 5: Segment-by-segment approach in IR3. The top plot shows the gradient distribution versus longitudinal location. The two bottom plots show the horizontal and vertical beta functions from measurement and for ideal and corrected models.

A more local approach aiming at identifying errors has been developed. The entire machine is split into several segments (IRs and arcs) and each of these segments is treated as an independent transfer line. The measured periodic alpha and beta functions at the entrance of the segment are used as initial conditions for the optics of the respective segment.

This method proved most useful for the momentum collimation insertion IR3. This segment consists of 17 independent quadrupoles as shown on the top plot of Fig. 5. The two bottom plots show the horizontal and vertical beta functions from measurement and for the ideal and the reconstructed models (propagated by taking the initial α and β as measured). The ideal model is represented by the blue stars which shows an excellent agreement with the measurement until the location 10200 m, where the vertical beta functions largely differ. This suggests that a gradient error exists between the 6th and the 9th quadrupoles (as indexed on the top plot). To restore the good agreement between model and measurement the quadrupole mqtli7r3b2 had to be switched off or reduced by a factor of ten (black pentagons on the figure), clearly suggesting some hardware problem with this quadrupole. This same feature was also observed from dispersion measurements in Ref. [16]. The most likely hypothesis to explain this observation was a cable swap between the magnets of the two beams, namely mqtli7r3.b2 and mqtli7r3.b1. This hypothesis was confirmed from previous hardware tests [17].

In spite of this success, the segement-by-segment approach cannot identify the small distributed errors all around the machine. Yet a new method has been implemented to achieve the best possible optics error reconstruction. This method is based in the already mentioned inverse model response matrix. The key feature is to al-
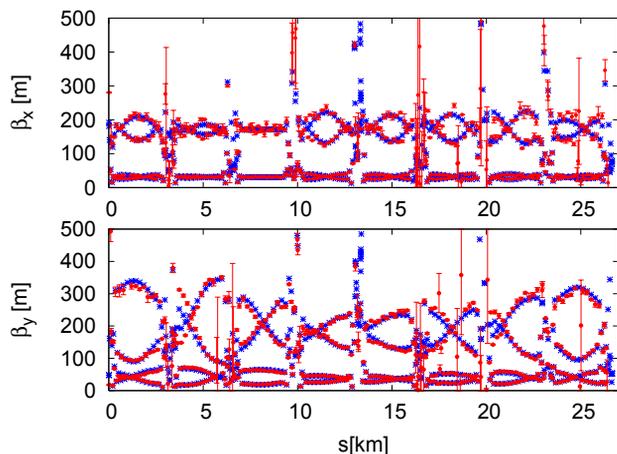
Circular Colliders

Figure 6: Comparison of model and measured beta functions after five iterations of the model iterative correction (having started from the segment-by-segment results).
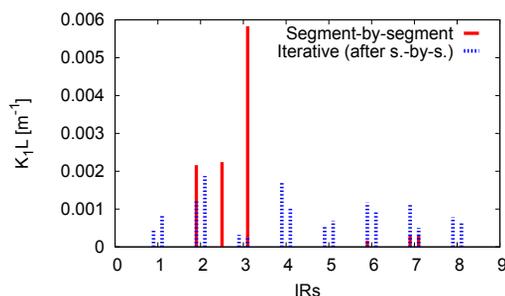

Figure 7: Integrated error distribution as obtained by the segment-by-segment and the iterative approaches.

low for iterations: After each step the change in the model phase advance (obtained by introducing the corrections in the ideal model) is subtracted to the measured phase advances as a means to simulate an iterative correction in the real machine. To obtain the best possible results we have applied this new model iterative correction starting from a model already including the optical errors from the segment-by-segment approach. After five iterations a very satisfactory agreement is found between model and measurement, Fig. 6. The qualitative summary of the integrated strengths used in the correction is shown in Fig. 7.

COUPLING MEASUREMENT

The linear coupling parameters are inferred from the secondary spectral lines [18], i.e. the vertical tune in the horizontal signal and vice-versa. Figure 8 compares the real part of the difference coupling resonance driving term f_{1001} with a fitted model. The five periods observed in the oscillations of the real part of f_{1001} correspond to the integer tune split between the horizontal and vertical tunes, thus experimentally confirming that the machine had the same integer tune split as the model.

SUMMARY

In the constrained circumstances with only 90 turns BPM data, uncorrected coupling and large chromaticity, the SVD measurement technique proved to be the most accurate. The measured vertical beta-beating is found to be
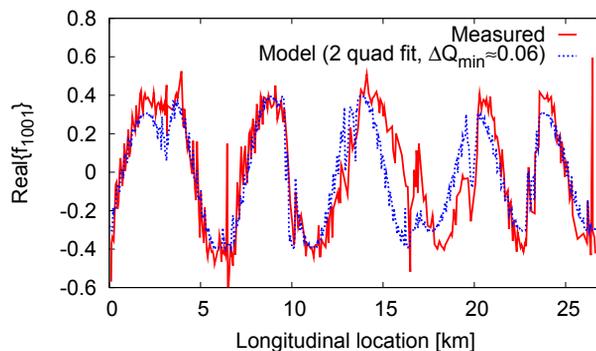

Figure 8: Real part of the coupling resonance driving term f_{1001} compared with a model prediction that is obtained by exciting two skew quadrupoles to approximately reproduce the measurement.

unexpectedly large. Two new optics correction methods were developed, namely segment-by-segment and model iterative correction. The application of the segment-by-segment approach to IR3 led to the identification of a dominant quadrupole error in the LHC Beam 2 ring. Evidence from previous hardware tests supported the hypothesis that this error was caused by a cable swapping between the Beam 2 and Beam 1 magnets mqtli7r3.b2 and mqtli7r3.b1. Using the model iterative correction the optics has been very well reconstructed by using distributed sources all around the ring.

ACKNOWLEDGMENTS

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