First beta-beating measurement in the LHC

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Summary

This note reports on the first LHC beta-beating and coupling measurements. Thanks to an excellent functioning of the BPM system and the related software, injection oscillations were recorded for the first 90 turns at all BPMs of Beam 2. Three different algorithms are used to measure the optics parameters from the BPM data. All algorithms show consistent measurements but feature different accuracy. The Singular Value Decomposition (SVD) approach shows a high resolution despite the limited number of turns.

The vertical beta-beating is observed to be about a factor of two larger than in the horizontal plane. This asymmetry is partly due to sextupoles misalignments but also suggests the possible existence of focusing errors at defocussing locations. Rather large coupling is observed since no skew quadrupole was excited at the time of the data acquisition.

We also report a list of suspected malfunctioning BPMs identified through various analyses.

1 Introduction

During many years the procedures to measure and correct the optics of the LHC have been studied via numerical simulations and measurements in existing accelerators [1] [2] [3] [4]. 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.

During September the 12th of 2008, Beam 2 was circulating in the LHC with an excellent lifetime of a couple of hours. The turn-by-turn beam position of first 90 turns at about 500 double plane BPMs were acquired using the YASP [5] software. These injection oscillations give the unique opportunity to probe the status of LHC optics and test the existing algorithms.
Figure 1: Illustrative beam position data at two BPMs (in a focusing and defocusing location, respectively) from the data file InjTurns_LHCRING_12-09-08_12-38-16_F831.data.zip

Figure 2: Closed orbit from the data file InjTurns_LHCRING_12-09-08_12-38-16_F831.data.zip
2 The BPM data

As an illustration of the quality of the BPM data, Fig. 1 shows the beam positions at two BPMs on the right side of IR1, having large horizontal and vertical beta functions, respectively. The betatron oscillations are clearly seen, showing the right oscillation amplitude ratio with respect to the beta functions. Also a typical beating pattern due to coupling between the horizontal and vertical oscillations is observed. The existence of coupling was expected since no skew quadrupole corrector was powered.

The closed orbit is extracted from the BPM data and shown in Fig. 2. Closed orbit correction of Beam 2 was underway while the data was obtained. The peak of orbit distortion is about 8 mm in both planes, and an average shift of about -1.5 mm in horizontal plane is observed implying the mismatch between dipole field and beam momentum. In the next sections the tunes, the beta functions and the coupling are measured from all the BPM data using various algorithms.

3 The Tunes

We have used three different algorithms to compute the tunes and the phase advance between BPMs, namely:

- Harmonic analysis: Also named DTFT (Discrete-Time Fourier Transform), is a special form of a Fourier transform, where a discrete input function is transformed into a continuous frequency spectrum giving more precise measurements of the betatronic phase and amplitude.

- SUSSIX [6]: This algorithm identifies the dominant frequency by an interpolation in the frequency domain, removes this dominant oscillation in the time domain and iterates this procedure.

- SVD: Singular Value Decomposition of the BPM data where the cosine-like and sine-like parts of the betatron oscillations appear as two singular modes.

The betatron tunes are computed using the Harmonic Analysis and SUSSIX algorithms. Tune statistics cannot be extracted from the SVD analysis since only two singular modes feature the same tune. Figure 3 shows a histogram of the tunes for all the BPMs. The consistency of the tune measurement among the BPMs is remarkable, achieving a precision below the $10^{-3}$ level with only 90 turns. The Harmonic Analysis seems to perform slightly better for the horizontal signal while performance on the vertical plane is very similar. These histograms also serve to reveal suspicious BPMs. There are few horizontal BPMs giving a tune far from the rest of the BPMs. The names of these BPMs have been displayed on the plot. Section 6 reports on the observed malfunctioning or suspicious BPMs.

4 Measurement of lattice parameters

The phase of the spectral tune line is used to compute the phase advance between BPMs. Beta functions are inferred from the phase advances between 3 consecutive BPMs as done in LEP [7]. This is a model-dependent measurement and from previous simulations [4] we expect a systematic error between 5% and 10% for these particular beam conditions. The beta and alpha are computed three times at the same location using three different sets of consecutive BPMs. The measurement
Figure 3: Histograms of the horizontal (left) and vertical (right) tunes as measured from all BPMs using SUSSIX and Harmonic Analysis algorithms.

errors are defined from the discrepancy among these three values. Coupling does not introduce extra errors in the measurement but it does change the beta functions. Therefore we measure the coupled beta-functions as defined in [8].

The resulting betas obtained from the three analysis algorithms described in section 3 are plotted in Fig. 4. All three measurements give consistent results taking into account the error bars, however the SVD results in smaller error and a smoother beating pattern. A performance comparison between the different analysis algorithms is shown in Fig. 5. The better performance of the SVD algorithm is probably due to the fact that it takes advantage of the correlation between all the BPMs. The SVD measurement is used as the reference in the rest of the paper. We expect that for BPM data with larger number of turns the differences in the performances is less pronounced.

Figure 6 compares the betas from the SVD measurement to the design model, directly in the top two plots and displaying the beta-beating ($\Delta\beta/\beta$) in the two bottom plots. The design model is used as reference to properly compare to the specified tolerances [9]. The vertical beta-beating is about a factor of 2 larger than in the horizontal plane. This asymmetry is expected from the quadrupolar errors generated by feed-down from sextupoles [2]. However the beta-beating is too large to be explained only by orbit and sextupoles misalignments, therefore it is suspected that other beta-beating sources exist at defocussing locations. For instance, the abrupt jump in the amplitude of the horizontal beta-beating oscillations at IR3 (10 km) clearly reveals a location with relatively large quadrupolar error. Other smaller errors are also visible in other IRs.

Alpha functions computed in the same way as beta functions are obtained from the phase advance of 3 BPMs. The measured alpha functions are plotted in Fig. 7 together with the ideal model. Same qualitative conclusions as above are inferred from this measurement.

5 Coupling measurement

The linear coupling parameters are inferred from the secondary spectral lines, i.e. the vertical tune in the horizontal signal and vice-versa, see, e.g., Ref. [10]. Figure 8 shows the real and the
Figure 4: Horizontal (top) and vertical (bottom) beta functions obtained from the phase advances given by the SUSSIX, SVD and Harmonic Analysis algorithms.

Figure 5: Performance comparison between the different analysis algorithms, horizontal (top) and vertical (bottom). The SVD technique shows more measurements at the lowest error on the beta function.
Figure 6: Direct comparison between measured and model betas in the top two plots and beta-beating in the two bottom plots.
imaginary parts 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 exactly 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.

The coupling is excited by the rotation of quadrupole magnets, the vertical closed orbit at the sextupoles and the $a_2$ magnetic errors in the superconducting dipoles. There were no skew quadrupole correctors excited during the measurement. This type of analysis with better quality data should give an insight into the sources of coupling as theory [10] and simulations [2] show.

6 Malfunctioning BPMs

The direct inspection of data, the Fourier Transform and the SVD serve to identify malfunctioning or suspicious BPMs. All BPMs found to be suspicious using these methods are listed in Table 1 together with a remark explaining the origin of the suspicion.

First, just by direct inspection of the data some BPMs outputting zeros or obviously wrong data are identified. The BPMs for the TOTEM experiment and for the interlock system are treated in a special way but other monitors giving zeros or wrong data will be checked.

With the Fourier Transform, there are five horizontal BPMs giving a horizontal betatron tune different than the rest as shown in Fig. 3.

Finally, SVD is a powerful tool for finding bad BPMs and assigning uncorrelated noise to every BPM. Figure 4 shows the histogram of uncorrelated BPM rms noise computed from SVD analysis. The BPMs giving larger rms error (those populating the tails) are candidates for being malfunctioning. It is worth mentioning that several BPMs with plates rotated by 45 degrees (type: BPMS) populate the tails.
Figure 8: Coupling measurement. Real and imaginary parts of the difference coupling resonance driving term $f_{1001}$ together with a fitted model.
<table>
<thead>
<tr>
<th>BPM name</th>
<th>Remark</th>
</tr>
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<tbody>
<tr>
<td>BPMWT.B6L5.B2</td>
<td>For TOTEM, data not recorded</td>
</tr>
<tr>
<td>BPMWT.A6L5.B2</td>
<td>For TOTEM, data not recorded</td>
</tr>
<tr>
<td>BPMWT.B4L5.B2</td>
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<tr>
<td>BPMSB.B4L6.B2</td>
<td>For interlock, data not recorded</td>
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<tr>
<td>BPMSA.A4R6.B2</td>
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<tr>
<td>BPMSA.B4R6.B2</td>
<td>For interlock, data not recorded</td>
</tr>
<tr>
<td>BPM.8L5.B2</td>
<td>Zeros in H</td>
</tr>
<tr>
<td>BPM.33L8.B2</td>
<td>Zeros in H and V</td>
</tr>
<tr>
<td>BPM.16L2.B2</td>
<td>Wrong data in V</td>
</tr>
<tr>
<td>BPM.21R5.B2</td>
<td>Wrong data in V</td>
</tr>
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<td>BPMSW.1L2.B2</td>
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</tr>
<tr>
<td>BPM.11R2.B2</td>
<td>Zero in H (turn 77)</td>
</tr>
<tr>
<td>BPM.26R3.B2</td>
<td>Large negative data in H (turn 40)</td>
</tr>
<tr>
<td>BPM.27L6.B2</td>
<td>Wrong H tune</td>
</tr>
<tr>
<td>BPMSY.4R1.B2</td>
<td>Wrong H tune</td>
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<td>BPMS.2R2.B2</td>
<td>Wrong H tune</td>
</tr>
<tr>
<td>BPMS.2R8.B2</td>
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<tr>
<td>BPMS.2L1.B2</td>
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<tr>
<td>BPMS.2R1.B2</td>
<td>Relatively large noise (SVD analysis)</td>
</tr>
<tr>
<td>BPMS.2L2.B2</td>
<td>Relatively large noise (SVD analysis)</td>
</tr>
<tr>
<td>BPMS.2L5.B2</td>
<td>Relatively large noise (SVD analysis)</td>
</tr>
<tr>
<td>BPMS.2R5.B2</td>
<td>Relatively large noise (SVD analysis)</td>
</tr>
<tr>
<td>BPMS.2L8.B2</td>
<td>Relatively large noise (SVD analysis)</td>
</tr>
<tr>
<td>(BPMSE.4R6.B2)</td>
<td>Large offset in H, the monitor covering the dumped beam orbit</td>
</tr>
<tr>
<td>(BPMYB.5R8.B2)</td>
<td>Large negative data in V for the injection beam orbit (turn 1)</td>
</tr>
</tbody>
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Table 1: List of suspicious malfunctioning BPMs.
Figure 9: BPM rms noise computed from SVD analysis

Two BPMs, BPMSE.4R6.B2 and BPMYB.5R8.B2, work correctly but are mentioned here due to their peculiar location. The horizontal beam position at BPMSE.4R6.B2 has large offset because the center of the BPM is set between the design orbit and the dumped beam orbit. The vertical beam position at BPMYB.5R8.B2 at the first turn is far from the closed orbit (about -10 mm) because the BPM is situated between the injection septum and kicker.

For several monitors listed here, the problem is already understood and will be fixed during the shutdown, for example, BPM.27L6.B2 and BPMSY.4R1.B2 have the H-V fibers switched [11].

7 Outlook

The first beta-beating and coupling measurements were successfully performed. To understand the discrepancies between model and measurement a series of aspects should be considered in the future:

- Build the most realistic machine model from the settings used during the data acquisition.
- Introduce the available magnetic imperfections as measured.
- Model the magnetic uncertainties at very low excitation currents.
- Identify possible locations with gradient errors if discrepancies remain.

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