COUPLING AND VERTICAL DISPERSION CORRECTION STUDIES FOR THE LHC USING SKEW QUADRUPOLES AND VERTICAL ORBIT BUMPS

G. Vanbavinckhove, CERN, Geneva, Switzerland and NIKHEF, Amsterdam, Netherlands
M. Aiba, Paul Scherrer Institut, Villigen, Switzerland
R. Calaga, Brookhaven National Laboratory, Upton, NY, USA
R. Tomás, CERN, Geneva, Switzerland

Abstract

After the incident in the LHC in 2008, few skew quadrupoles were damaged and subsequently removed from the tunnel. This could limit the correction of local coupling in the LHC. In order to increase the flexibility in the coupling correction it has been proposed to use of vertical orbit bumps at the sextupoles is studied. Moreover a simultaneous coupling and vertical dispersion can be implemented. Various studies are presented addressing the optimal approach for the correction of the vertical dispersion and the sum and difference coupling resonances.

INTRODUCTION

In Ref [1] it was shown that the difference resonance coupling term and the vertical dispersion could be corrected using vertical orbit bumps at the sextupoles. The correction scheme using vertical orbit bumps is studied for the LHC. Main motivation is the accident in 2008 were two families of skew quads were damaged. It was expected that the skew quads would not be sufficient to correct the coupling. As the LHC is running on injection tunes of $(59.28, 61.31)$ and collisions tunes of $(59.31, 61.32)$ difference resonance $(Q_x - Q_y = N)$ will be the main contributor. The effect of the sum resonance $(Q_x + Q_y = N)$ will be rather small. A first coupling correction was done during the LHC commissioning in 2010 using the arc skew quadrupole families. The first results will be presented and discussed in this paper.

LHC LAYOUT

In both of the rings, each sector of the machine is equipped with two pairs of skew quadrupole magnets at Q23 and Q27 (left and right) which are just trim quadrupole type magnets tilted by 45 degrees. The two pairs are either powered in series, in sectors 1-2, 3-4, 5-6, 7-8 for Ring 1 and in sectors 2-3, 4-5, 6-7, 8-1 for Ring 2, or split into two independent families in the other sectors. This layout allows compensation of the coupling coefficient due to the systematic a_2 errors of the main dipoles for each sector but implies that only four corrector circuits are available for correction of the random coupling errors. Furthermore, the betatron phase advances between the skew quadrupoles of a same family ensures that the coupling compensation can be made without generating large vertical dispersion and with a minimum excitation of the sum coupling resonance. In every interaction region there are two (left and right of the interaction point) skew quadrupoles located between Q3 and Q4. They are individually powered. As the correctors are located in the region where the two beams share the same beam pipe the skew quadrupole are common correctors for both beams. For this reason the correctors will be mainly used to correct coupling sources comming from the triplets. Horizontal and vertical orbit corrector magnets are installed at each focusing and defocusing quadrupole, that is a total of 23 or 24 orbit correctors per ring, per arc and per transverse plane. Together with the orbit correctors, sextupoles are installed at the same location. This means that a priori it is possible to correct the coupling and vertical dispersion simultaneously in this scheme, as there are as many individual correctors as sextupoles. The LHC is equipped with 538 dual plane BPMs per beam, i.e both planes can be measured at one single BPM. After the incident in the LHC in 2008 two families of skew quads were damaged and removed. For beam 1 the skew quad left from IP4 and for beam 2 the skew quad in arc 3-4, the arc between IP3 and IP4 was removed. This reduced the available arc families in beam 2 by 25 %.

THEORY

The vertical turb-by-turn motion in the presence of strong betatron coupling is written as:

$$h_{y,-}(s,N) = \cosh(2P)\zeta_y^- \\ -2i\sinh(2P)\left[\frac{f_{1001}}{P}\zeta_x^+ + \frac{f_{1010}}{P}\zeta_x^-\right] \quad (1)$$

A similar expression can be written for the horizontal plane. The derivation of equation 1 can found in Ref [2]. With $P = \frac{1}{2}\sqrt{-|2f_{1001}|^2 + |2f_{1010}|^2}$ and $\zeta_x^-, \zeta_y^-, \zeta_y^+$ being the eigenvectors,$\zeta_z^\pm = \sqrt{2I_z}e^{\mp i\psi}$. With $\psi_z = i(2\pi Q_z N + \psi_{s,z,0})$ and z being either the horizontal plane, x or the vertical plane, y. Q_z is the betatron tune and $\psi_{s,z,0}$ is the initial phase. The resonance driving terms can also be written in terms of amplitudes and phases $f_{jklm} = |f_{jklm}|e^{iq_{jklm}}$. The amplitude and phase of the secondary line is written as $B_{jklm}e^{i\phi_{jklm}}$. For the sum and difference resonance the amplitudes and phase in the verti-

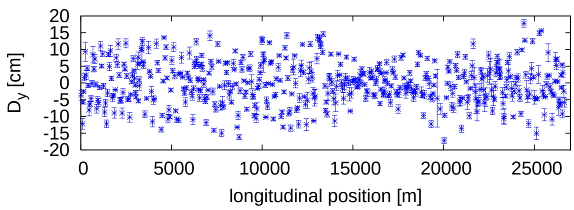

Figure 1: Vertical dispersion measured in the beginning of the run in 2010. The measured values is within tolerance.

cal plane can then be written as:

$$B_{1001} = \frac{2sinh(2P)}{P} f_{1001} \sqrt{2I_x} \tag{2}$$

$$\phi_{1001} = \psi_x - q_{1001} - \frac{\pi}{2} \tag{3}$$

$$B_{1010} = \frac{2sinh(2P)}{P} f_{1010} \sqrt{2I_x} \tag{4}$$

$$\phi_{1010} = -\psi_x + q_{1010} - \frac{\pi}{2} \tag{5}$$

The amplitudes and phases of the resonance driving terms can then be calculated as, the full derivation can be found in Ref [3]:

$$|f_{1001}| = \frac{1}{2}\sqrt{\frac{B_{1001}A_{1001}}{B_{1000}A_{1000}}} \tag{6}$$

$$q_{1001} = -\phi_{1001} + \psi_x - \frac{\pi}{2} \tag{7}$$

$$|f_{1010}| = \frac{1}{2}\sqrt{\frac{B_{1010}A_{1010}}{B_{1000}A_{1000}}} \tag{8}$$

$$q_{1010} = \phi_{1010} + \psi_x + \frac{\pi}{2} \tag{9}$$

A_{jklm} is the amplitude of the secondary line in the horizontal plane. B_{1000} and A_{1000} are respectively the main betatron tune line of the vertical and horizontal plane.

SIMULATIONS

For the studies it is assumed that the difference coupling resonance is the main contributor and for coupling and vertical dispersion is within tolerances. Meaning that the sum coupling resonance and vertical dispersion is neglected. For LHC tunes the difference resonance ($Q_x - Q_y = N$) will be the main contributor and the sum resonance ($Q_x + Q_y = N$) neglectable. The vertical dispersion is assumed to be small, and this is confirmed during the first measurements of 2010 at injection, see Figure 1.

The Simulations were done for several cases, were random skew errors were placed in the quadrupoles. As vertical orbit bumps are used to correct, the maximum vertical orbit excursion should not exceed ~ 5 mm.

Figure 2 and Figure 3 show the outcome histograms of the montecarlo simulations. In Figure 2 the coupling difference resonance (f_{1001}) is shown in the top plot and in the plot below the sum coupling resonance (f_{1010}) is shown before and after corrections. The weight was placed only on the difference coupling term. It is obvious to see

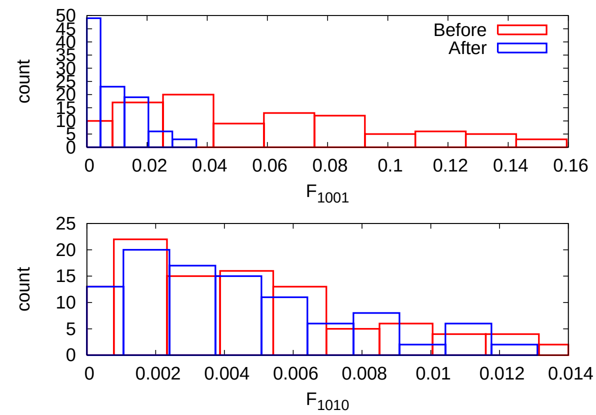

Figure 2: Figure showing difference resonance (above) and sum resonance (below) for the simulated cases. The coupling is reduced, where the sum was not altered

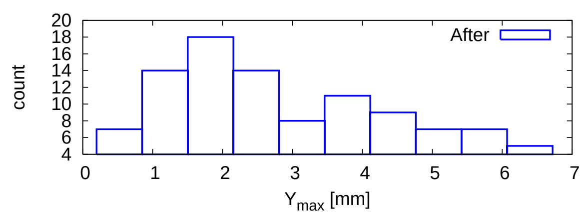

Figure 3: Figure showing the maximum vertical orbit excursion for the simulated cases. 88% of the simulated cases the beam excursion does not exceed the ~ 5mm.

from the figure that the coupling is reduced, where the sum resonance was not or slightly changed. Figure 3 shows a histogram of the maximum orbit reached for the cases. 88% is below 5 mm. The simulations show that the difference resonance can be corrected without having too large vertical orbit excursion.

MEASUREMENTS AND CORRECTIONS

During the first months of 2010 a dedicated coupling measurement was conducted. Main motivation was that the global coupling knob was pushing the skew correctors to their maximum strength. The correction using the global couping know is based on the compensation of a local measurement, i.e assuming that the coupling is constant troughout the ring, ignoring local sources.

Measurements are done by acquiring ~ 2000 turns and analyzing the turn-by-turn data using an interpolated FT (SUSSIX), Ref [4]. SUSSIX returns the main betatron tune line and the coupled tune line for both horizontal and vertical plane. The resonance driving terms are calculated using equations (6) to (9).

For this measurements the global coupling corrections was removed, such that the natural coupling, i.e coupling comming from errors in the magnets, could be measured. Fig. 4 (blue) shows the measured difference resonance coupling term and Fig. 5 (blue) shows the measured sum resonance coupling term before correction

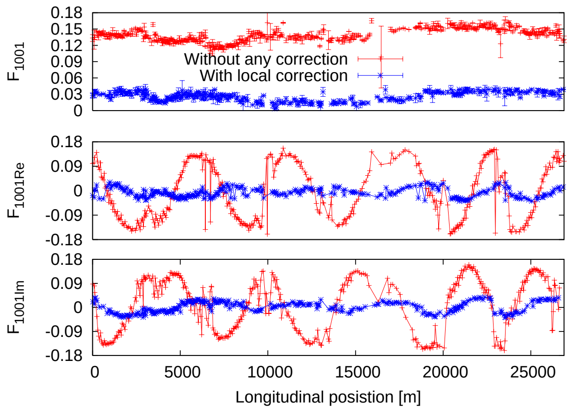

Figure 4: Plot showing the result of the dedicated measurement for correcting the difference resonance f_{1001} for beam 2. Blue lines is after and red line before corrections. From top to bottom the amplitude, real and imaginary part are shown. From here its clear to see that the difference resonance is reduced by a factor 5.

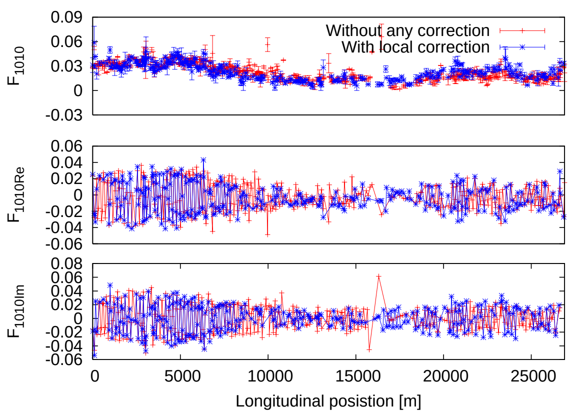

Figure 5: Plot showing the result of the dedicated measurement for correcting sum resonance f_{1010} for beam 2. Blue lines is after and red line before corrections. From top to bottom the amplitude, real and imaginary part are shown. As the weight of the correction was only placed on the difference resonance, the sum resonance was not affected.

A local coupling correction was calculated using the response matrix of the arc skew quads and f_{1001}. The calculated corrector strengths are shown in Fig. 6. This plot shows the calculated strengths from the local and global coupling knob. The strengths from SVD are factor 4 lower, which leaves more spaces for future corrections using skew quad correctors.

The correctors used for beam 2 were only the skew quad correctors in the arcs. The skew quads in the IP were not yet included.

Fig. 4 shows the results of measurement before and after corrections. Blue line shows before corrections and red line is after corrections. The difference resonance has been corrected by a factor of 5. Fig. 5 shows that the sum resonance is not affected by the correction, as the weight was only on the difference resonance.

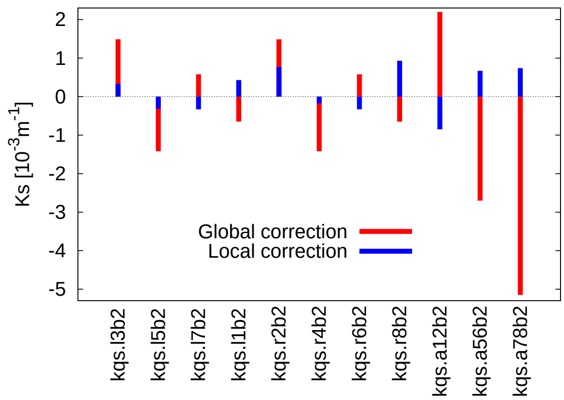

Figure 6: Corrector strengths for global correction (red) and local correction (blue). The strengths for the local correction is a factor ~ 4 lower. This shows the necessity of implementing a local correction before doing a global correction.

SUMMARY AND OUTLOOK

Simulations show that with the new corrector scheme, vertical orbit bumps, coupling can be corrected. Several coupling measurements were conducted during the first months of operations in 2010. A more local arc-by-arc correction, to avoid the use of global knobs, was computed for beam 2. The first correction for beam 2 was successfully implemented and showed the importance of localizing and correcting as local as possible before applying a global correction. Coupling could be corrected further by iterating.When the difference resonance is corrected to the same level as the sum resonance, corrections should be done for both resonance. From the measurements it follows that even with the missing skew quad families correcting the coupling in the LHC is still possible and vertical orbit bumps are not needed.

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