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ORBIT CORRECTION IN THE CERN PS BOOSTER*

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Abstract

Prior to the Long Shutdown of 2013-2014 (LS1), control of the closed orbit in the four rings of the CERN PS Booster (PSB) was achieved by adjusting the alignment of several focusing quadrupoles. After a set of orbit corrector dipoles was installed, a major realignment campaign was undertaken to remove these intentional quadrupole offsets and any other magnet misalignments. This paper summarizes the effects of the magnet realignment on the closed orbit in the PSB and the results of closed orbit correction with corrector dipoles.

INTRODUCTION

The PSB is the first synchrotron in the LHC injector chain, accelerating proton beams from 50 MeV to 1.4 GeV in about 500 milliseconds. It is composed of four vertically stacked rings and accelerates four beams simultaneously, which are recombined before being transferred to the Proton Synchrotron. The lattice has a 16-fold periodic structure with two bending magnets and an F-D-F focusing triplet in each period. The four rings share the same bending and focusing magnets, which each have four gaps through which the four beam pipes pass. Each period also contains a multipole corrector magnet stack with an integrated beam position monitor (BPM), and a horizontal and a vertical orbit corrector dipole, but hardware limitations allow for only four orbit correctors per plane per ring to be used at any given time.

These orbit corrector dipoles were not available in the PSB until 2012, and they were not used operationally until after LS1. Prior to this, closed orbit distortion was minimized by introducing horizontal, vertical, and tilt alignment offsets to certain quadrupole magnets [1]. During LS1 an alignment survey was made and a major realignment campaign was undertaken in order to correct both random magnet alignment errors and the intentional quadrupole offsets previously used for orbit correction. In total, about ninety horizontal, vertical, or tilt magnet adjustments were made.

After the shutdown, some final magnet alignment adjustments were made in order to reduce the closed orbit distortion, and then the orbit was further corrected using corrector dipoles and the console application YASP (Yet Another Steering Program) [2].

MAGNET REALIGNMENT

At the beginning of LS1, a tunnel survey was completed to determine the alignment of the main bending magnets, the triplet quadrupoles, and elements containing both beam position monitors and multipole corrector magnets. Figure 1

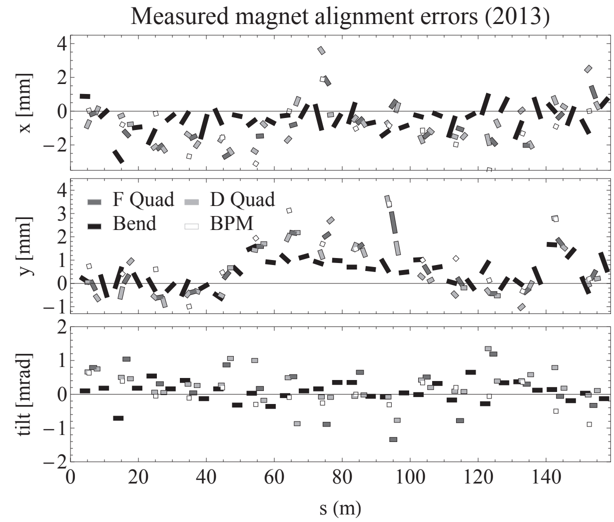

Figure 1: Initial measured alignment of bending magnets, quadrupoles, and BPM stacks, showing the transverse displacement of the ends of each element and the rotation around the longitudinal axis.

shows the measured horizontal and vertical positions of each magnet and its tilt around the longitudinal axis. To reduce aperture restrictions, a realignment strategy was formulated to minimize transverse magnet offsets and jumps between adjacent magnets, while keeping the number of hours of work in the tunnel reasonably low for radiation safety reasons.

All quadrupoles and BPMs with a radial displacement of more than 1 mm from the reference position or from the adjacent quadrupole were realigned to zero. The bending magnets have a large horizontal aperture, so they were not realigned radially. However, the bending magnets have a small vertical aperture which creates one of the main aperture restrictions in the vertical plane. Moving these magnets carries a risk of damaging them, so instead of aligning the bends and quads to the vertical reference position, the quadrupoles were aligned to a smooth curve fit to the vertical position of the bends. Quadrupole magnets and BPMs whose vertical position was more than 1 mm from this curve were moved to lie on the curve. The vertical position of bending magnets was adjusted only in a few cases where there was a jump of more than 1 mm between the position of adjacent bends.

All quadrupoles and BPMs with a tilt of more than 0.3 mrad, and all bending magnets with a tilt of more than 0.5 mrad, were corrected to zero. Note that the radial position measurements refer to the position of the magnet at beam level on Ring 3, which is the third ring up from the ground. When the magnet tilt is adjusted, the physical pivot point is at ground level. Therefore, in order to keep the ra-

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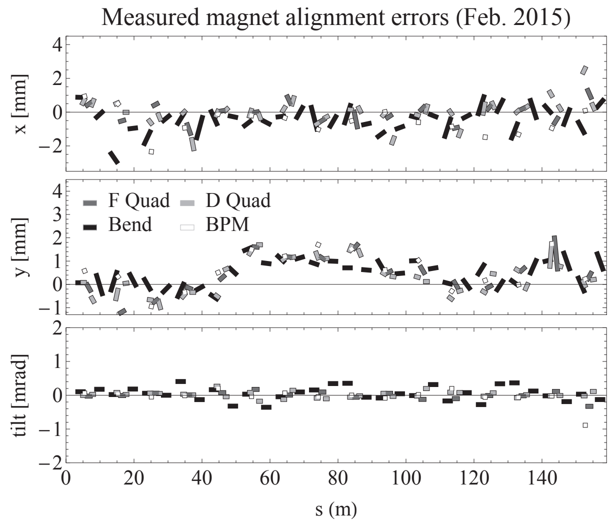

Figure 2: Final measured alignment of bending magnets, quadrupoles, and BPM stacks, showing the transverse displacement of the ends of each element and the rotation around the longitudinal axis.

dial position at Ring 3 beam level unchanged, every magnet whose tilt is adjusted must also be adjusted radially.

The magnet positions can be measured with a precision of about 0.1 mm, but the adjustments can only be made with an estimated precision of about 0.3 mm in the horizontal plane and 0.2 mm in the vertical plane [1]. About ninety magnets were moved in the first iteration of alignments during the shutdown, and the uncertainty in position adjustment propagates to an uncertainty in orbit change of several millimeters, so no attempts were made to ensure that this first iteration of magnet moves would produce the desired closed orbit. After the major realignments of LS1, the new closed orbit was measured and a small number of magnet moves was calculated to reduce the closed orbit distortion. This fine-tuning of the alignment is described in a later section.

Figure 2 shows the final magnet positions after all alignment iterations. In all, a total of 39 radial moves, 18 vertical moves, and 32 tilt adjustments were made in several iterations between the beginning of LS1 and February of 2015.

ALIGNMENT MODEL

In order to improve the accuracy of the lattice model, the transverse, longitudinal, and angular alignment errors of the main bending magnets, focusing quads, and BPMs were added to the PSB's MADX [3] file. The magnet entry positions DX and DY and transverse angles DTHETA and DPHI were calculated from the transverse position measured at the upstream and downstream ends of each magnet. Note that the vertical angle DPHI is actually defined in MADX using a left-handed convention, while the angles DTHETA and DPSI use a right-handed convention. The sign convention used in the metrology database is the same as that used by MADX for DX, DY, and DS, but the sign of the tilt in the database has the opposite sign of the MADX angle DPSI.

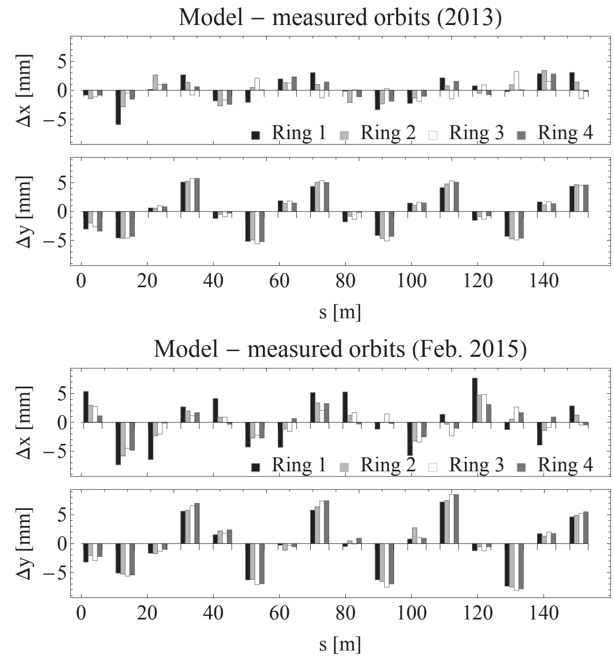

Figure 3: Difference between MADX prediction and measured orbits before (top) and after (bottom) realignment.

Comparisons of the measured orbit with the MADX model prediction both before and after the realignment are shown in Figure 3. The expected rms orbit distortion caused by a set of N steering errors is

$$\langle x^2\rangle^{1/2} \approx \frac{\sqrt{\beta_0\bar{\beta}}}{2\sqrt{2}|\sin(\pi Q)|}\sqrt{N}\theta_{rms} \tag{1}$$

where Q is the betatron tune, β_0 is the beta function at the observation point, $\bar{\beta}$ is the average beta function at the location of the errors, θ_{rms} is the rms size of the steering errors [4]. Assuming the measurement precision for each magnet position is 0.1 mm for transverse alignment, 0.3 mrad for quadrupole tilts, and 0.5 mrad for bending magnet tilts, this translates to an rms orbit uncertainty, depending on the working point, of about $x \approx 1.2$ mm for inner rings and $x \approx 2.9$ mm for outer rings (since quadrupole tilt creates a larger radial steering error for the outer rings), and $y \approx 2.8$ mm. The difference between the horizontal measured and model orbit is consistent with this estimate before realignment but not after realignment, suggesting that the uncertainty of the magnet position measurements may be larger than the estimated 0.1 mm. The difference between the vertical measured and model orbit is larger than this estimate, indicating either that the magnet position measurement uncertainty is larger than 0.1 mm or that additional, unknown vertical steering errors are present.

Certain magnets in sections 15 and 16 were unable to be aligned to the desired positions because elements in the adjacent injection and extraction lines made it impossible to access the bolts holding the magnets in place.

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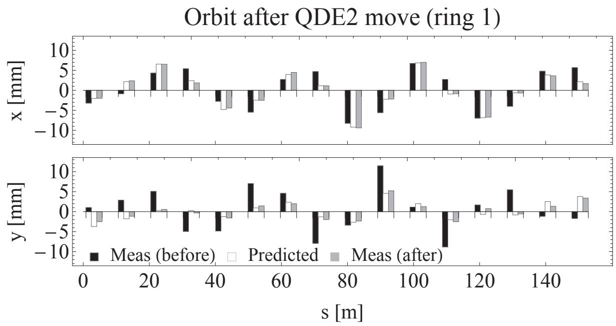

Figure 4: Measured orbit, predicted new orbit after displacement of one quadrupole magnet, and measured new orbit after displacement of the defocusing quadrupole QDE2.

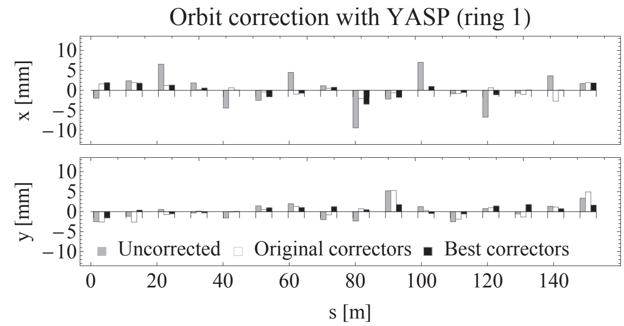

Figure 5: Measured orbits with no correction, with correction using original set of corrector dipoles, and with correction using optimal set of dipole correctors.

ORBIT AFTER FIRST REALIGNMENT

Because so many magnets were moved, the expected new orbit was not taken into account when planning the proposal for the major realignment campaign during LS1. The transverse positions can be adjusted with a precision of only around 0.3 mm, so with about 90 magnets moved, accurately predicting the resulting change to the closed orbit is not possible. Instead, the closed orbit was fine-tuned by adjusting the alignment of a few magnets based on the measured orbit after the major realignments were completed.

After the shutdown the closed orbit was found to have a very large deviation, with excursions of almost ±15 mm in the vertical plane which caused localized beam losses that quickly resulted in significant activation issues in certain parts of the tunnel. As an immediate solution, which required minimal intervention in the activated parts of the tunnel, a single quadrupole magnet displacement was calculated which would reduce the vertical orbit distortion by about half. Figure 4 shows the measured orbit immediately after LS1, the predicted orbit with the quadrupole QDE2 moved by 1.2 mm, and the measured orbit after QDE2 was moved. The observed orbit change showed good agreement with the model predictions, and later radiation surveys showed that the tunnel activation had been reduced.

A few more magnet moves were calculated to further reduce the closed orbit distortion, and these final moves were made during scheduled technical stops at the end of 2014. After all iterations of alignment, the closed orbit distortion ended up being of comparable magnitude to what it was in operation before LS1.

ORBIT CORRECTION WITH YASP

Further optimization of the closed orbit is achieved by powering the corrector dipoles with the console application YASP, which uses the MADX model with alignment errors to calculate the corrector kicks that will minimize the measured closed orbit distortion. Each ring contains thirteen corrector dipoles in each plane which may be used for orbit correction, but because a limited number of power supplies are available, only 32 correctors can be operated at any time. The set of four best correctors for each ring is chosen based primarily on minimizing the model predictions for rms residual orbit distortion, while also considering keeping the orbit excursion small in areas of the machine with higher activation levels.

Each time the alignment of the quadrupoles was adjusted, the choice of which four orbit correctors to use had to be reevaluated for the new closed orbit. Figure 5 shows the measured closed orbit after the realignment of the QDE2 quadrupole discussed in the previous section. The black bars show the closed orbit with no correction, and the light gray show the best correction obtained with the set of four correctors that had been used before the realignment. With the new closed orbit this set of correctors was no longer effective in the vertical plane, so a new set of four correctors was chosen. The dark gray bars show the corrected orbit with the new set of orbit correctors. The rms orbit deviation is reduced to about 1.5 mm in x and 1 mm in y.

CONCLUSIONS

A major realignment of magnets in the PSB was successfully completed during and just after LS1, correcting random alignment errors and removing quadrupole offsets that had been previously used for orbit correction. The closed orbit distortion after realigning about ninety magnets was initially large, with vertical excursions of nearly ±15 mm. This closed orbit distortion was reduced by making final adjustments to the positions of a few quadrupoles, and further control of the orbit is provided by corrector dipoles. Alignment errors were added to the MADX model, which now accurately predicts the effects of quadrupole offsets on the closed orbit.

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