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INFLUENCE OF THE ALIGNMENT OF THE MAIN MAGNETS ON RESONANCES IN THE CERN PROTON SYNCHROTRON

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Abstract

During the Long Shutdown 1 seven out of the one hundred combined function main magnets were removed from the tunnel to conduct maintenance. After reinstallation, the entirety of the main magnets was aligned to the reference positions and within the first week of operation of the accelerator, a beam-based alignment campaign was performed to reduce the excursions of the closed orbit. In order to further investigate and understand the source of betatronic resonances, which, already in 2011, were found to be excited by the bare machine, tune diagram measurements before and after this beam-based magnet alignment were conducted. In both cases the same resonances were found to be present; however, after the alignment, an overall increase of their strengths was observed. In this paper we present the corresponding measurement results and discuss the direct impact on the daily operation of the accelerator.

INTRODUCTION

The CERN Proton Synchrotron (PS) plays a crucial role among the accelerators in the injector chain of the Large Hadron Collider (LHC) and will provide beam to the LHC at least until 2035. Therefore, reliable performance of the accelerator components is required and extensive maintenance measures are being undertaken accordingly. This especially concerns the refurbishment of the combined-function main magnets, which are continuously subject to ionizing radiation and pulsed magnetic forces leading to degradation of these elements. In the framework of the PS main magnet consolidation program, 51 out of 100 main units (MUs) underwent maintenance between 2005 and 2009 [1] and, more recently, seven MUs were refurbished during the Long Shutdown 1 (LS1), which took place from 2013 to 2014. Before the restart of the accelerator complex after the LS1, all MUs were aligned to their reference positions. Subsequently, a beam-based realignment campaign was conducted to reduce the excursion of the closed orbit, and the effect on the betatronic resonances, which are supposedly excited by magnetic errors in the main magnets, was investigated.

The applied measurement technique, which was first proposed in [2], is based on measuring beam loss while keeping the tune constant in one plane and changing it dynamically in the other. These measurements lead to a graphical representation of the tune diagram and the underlying procedure is described in detail in [3].

In order to control the working point, two independent systems are available in the PS: the Low Energy Quadrupoles (LEQ), and the Pole Face Windings (PFW) in combination with the Figure of Eight Loop (F8L) [3, 4]. For the measurements presented in this paper, the PFW and the F8L were used, as these circuits provide larger flexibility compared to the LEQ. A single bunch with large transverse emittance and small direct space charge tune spread was required to increase the sensitivity of the measurement technique by filling the aperture at maximum. The beam parameters, which are summarized in Table 1, show that the maximum tune spreads (computed using the Laslett formula considering the variation of the optical machine parameters [5]) were basically kept constant for both cases. This is important, as it allows direct comparison of the tune scans before and after the realignment.

Furthermore, it was important to perform all measurements at injection kinetic energy of 1.4 GeV to reduce the radiological impact of the losses, as several people were required to access the machine to realign the main magnets.

MEASUREMENT RESULTS

In Fig. 1 the tune diagrams resulting from the measurements before and after the realignment are shown. In total four plots are depicted, corresponding to scans where either the horizontal or the vertical tune was kept constant.

Even though the MUs were aligned to their reference positions during the LS1, the measurements before the realignment revealed the same excited resonances as previous scans (see [3]), such as the lines $3q_y = 1$ and $2q_x + q_y = 1$. The measurements after the realignment, shown in Figs. 1c and 1d, confirm this observation, but the strengths of the various resonances appear to have increased.

Comparison of the Figs. 1a and 1c further reveals that, before the realignment, the vertical tune could be set closer to the integer resonance. In fact, the first measured line

Table 1: Comparison between Beam Parameters before and after the Realignment. The measurements were taken at extraction energy in the PS Booster.

Parameter	before	after
Intensity [10^{10} p]	120	130
Bunch length (4σ) [ns]	166	168
Relative momentum error (1σ) [10^{-3}]	0.85	0.97
Horizontal normalized emittance (1σ) [π mm mrad]	9.6	9.4
Vertical normalized emittance (1σ) [π mm mrad]	5.0	5.2
Horizontal tune spread	0.065	0.069
Vertical tune spread	0.093	0.10

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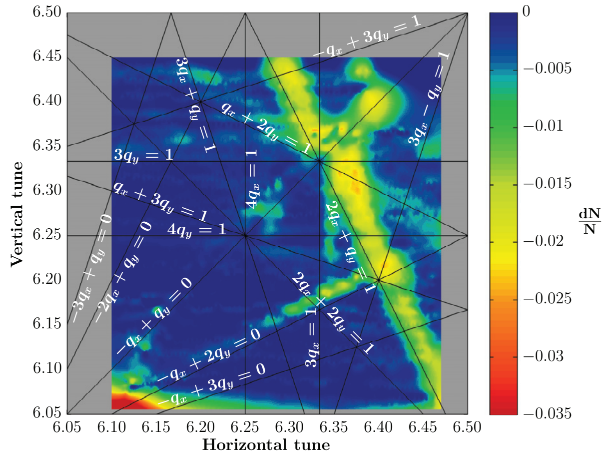
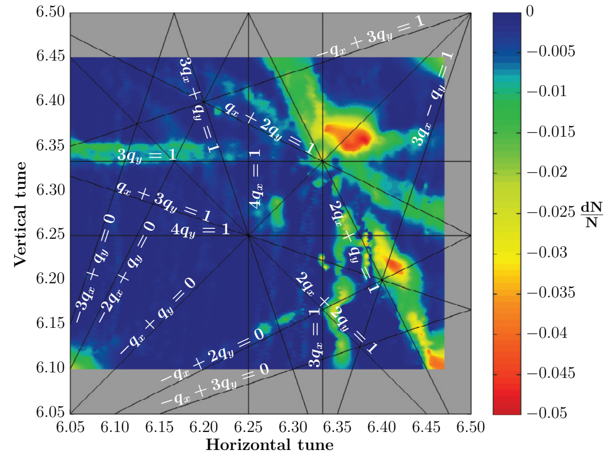
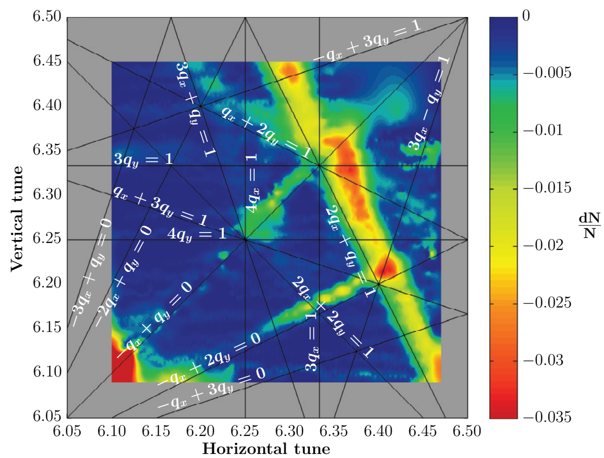


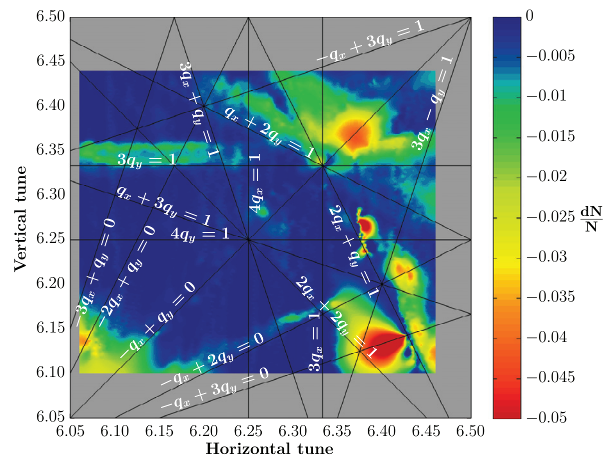
(a) Horizontal scan from left to right conducted before the realignment.



(b) Vertical scan from top to bottom conducted before the realignment. Beam loss along the vertical line $Q_x = 6.35$ corresponds to an interpolation artifact.



(c) Horizontal scan from left to right conducted after the realignment.



(d) Vertical scan from top to bottom conducted after the realignment. Beam loss along the resonance $-q_x + 3q_y = 0$ in the bottom right corner corresponds to an interpolation artifact.

Figure 1: Comparison of different tune diagrams measured before and after the realignment. The color scale is proportional to beam loss and grey areas indicate the absence of measurement data.

corresponds to a programmed vertical tune of 6.07, while after the realignment it was no longer possible to go below 6.10, which indicates an increased width of the resonance $q_y = 0$. This fact becomes especially apparent by looking at Fig. 2 where drastic beam loss is shown once the tunes are set close to the integer resonance.

The realignment of the main magnets also significantly influenced the mechanical aperture restrictions along the ring. A dedicated system of beam loss monitors (BLMs), which are installed on top of each main magnet of the PS [6], is used to localize the losses occurring during operation. In Fig. 3 the accumulated losses at the end of the measurement cycle are shown. Before the realignment beam loss was basically concentrated around MU20, while afterwards the usual restriction around the injection region, which is located between MU41 and MU42, was recovered. Additionally, losses appeared around MU18 and MU60, which renders it difficult to conclude whether the increased strength of the resonances is actually due to an increase of the respective driving terms or due to the different situation in terms of aperture restriction.

Moreover, it was investigated whether beam loss due to the integer resonance can be significantly mitigated by globally minimizing the RMS excursion of the beam by means of an orbit correction. At low energy, fifty horizontal and twenty vertical correctors are available and the effect of the correction is depicted in Fig. 4. Without correction, rapid beam loss is observed once the tunes approach the integer resonances. Active correctors immediately lead to an improvement of the situation, and the vertical tune can even

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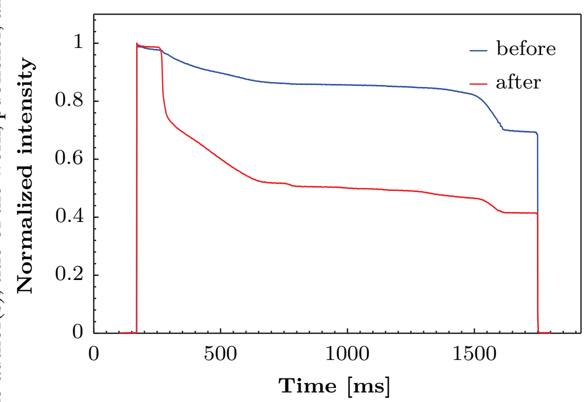

Figure 2: Comparison between intensity profiles before and after the realignment for programmed vertical tunes of 6.10. The horizontal tune is dynamically changed from 260 ms onwards, which corresponds to the drastic drop of the intensity.

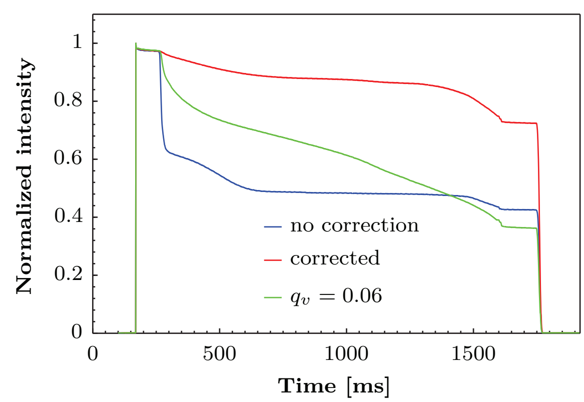

Figure 4: Influence of orbit correction on beam loss. For the blue and red curves the vertical tune was programmed to 6.10. With an active correction the vertical tune could be programmed closer to the integer resonance (green curve), which was impossible without correction.

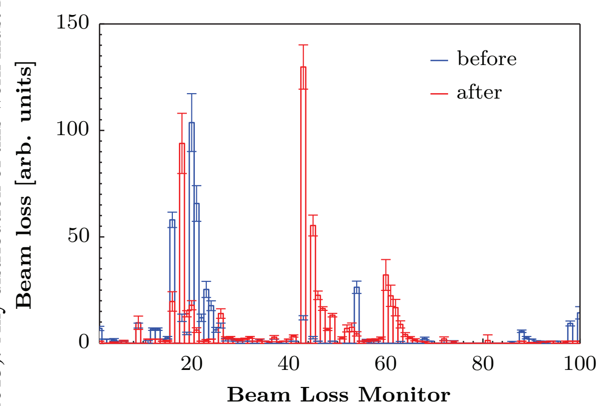

Figure 3: Comparison of loss patterns before and after the realignment measured with the BLMs. The same machine settings as in Fig. 2 were applied, and the accumulated losses at the end of the measurement cycle are depicted. The error bars represent the standard deviation calculated using three recorded data sets.

be lowered without losing the beam completely. This observation is especially important for beams prepared for the LHC, as their programmed working point is approximately ($Q_x = 6.23$, $Q_y = 6.24$) and the estimated vertical tune spread $\Delta Q_y \approx 0.3$ causes low tunes for a large fraction of particles.

SUMMARY AND CONCLUSIONS

During the LS1 several main magnets of the PS were removed from the tunnel for maintenance purpose, which required a beam-based realignment of the magnets after the restart of the accelerator complex. It was decided to investigate the effect of this procedure on the excited betatronic resonances.

Therefore, tune diagram measurements before and after the realignment were conducted, which indicate increased strengths of the resonances after moving the main magnets. This is in line with our current understanding of the machine, as the magnetic errors within the main magnets are expected to be the major source of those resonances. However, no excitation of additional resonances could be observed, and losses occurred at different locations along the ring. The increased strengths of the resonances could either be caused by the difference in mechanical acceptance or by a change of the dynamical aperture.

Especially for tunes set close to the integer resonances, beam loss was found to be drastically increased after the realignment. It was shown that an orbit correction at low energy significantly improves the situation and allows the tunes to be set to lower values. In order to improve the performance of the PS, it is therefore inevitable to minimize orbit excursions during daily operation.

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