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HIGH INTENSITY STUDIES IN THE CERN PROTON SYNCHROTRON BOOSTER

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Abstract

After the successful implementation of the LHC Injectors Upgrade (LIU) project, studies were conducted in the CERN Proton Synchrotron Booster (PSB) in order to assess the intensity reach with the increased beam brightness. The studies focused on the high intensity beams delivered to the PSB users, both at 1.4 and 2 GeV. In addition, possible intensity limitations in view of the Physics Beyond Colliders (PBC) Study were investigated. To this end, various machine configurations were tested including different resonance compensation schemes and chromaticity settings in correlation with the longitudinal parameters. This paper summarizes the results obtained since the machine recommissioning.

INTRODUCTION

During the beam commissioning period following the successful upgrades in the frame of the LIU project [1], the CERN PSB had to demonstrate an improved brightness for the LHC type beams [2], provide beam to high intensity users like ISOLDE [3] and n-TOF [4] and start exploring its intensity reach in the scope of the Physics Beyond Colliders (PBC) study [5, 6]. Limitations towards achieving the high intensities requested by the PSB users are imposed by the betatronic resonances and their interplay with the very strong space charge effects. To this end, extended resonance identification and compensation studies were conducted both before and after the implementation of the LIU project [7–9]. New resonance compensation schemes were developed that allowed reducing losses, however, remaining machine imperfections are still a cause of concern for intensities higher than 800×10^{10} protons per ring (ppr). Extended studies were conducted for ISOLDE trying to correlate losses to beam parameters such as the working point evolution and various mitigation measures were proposed and applied. A new instability was observed for the high intensity users accelerated up to the new extraction energy of 2 GeV, such as TOF. Initial studies revealed the intrabunch motion for this instability and techniques for curing it were applied, allowing normal operations.

RESONANCE COMPENSATION

Resonances up to 4^{th} order have been identified in the CERN PSB through loss map studies during the first year of operation following the completion of the LIU upgrades.

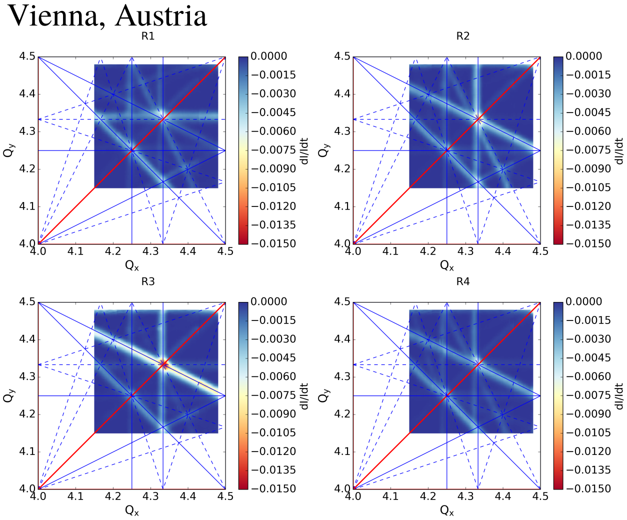

Figure 1: Loss maps resulting from dynamic tune scans in all four rings of the PSB. The tune space is color coded indicating the loss rate, calculated with a sample spacing of 1 ms. Resonance up to 4^{th} order are plotted, normal in solid lines and skew in dashed. Non-systematic resonance lines are plotted in blue and the systematic in red.

The measurements are conducted using a flat cycle at injection energy, i.e. 160 MeV, in which the beam is stored for an extended period from 275 ms to 700 ms. The loss maps are produced using the dynamic tune scan technique, in which one of the tunes is kept constant throughout the cycle while the other one is varied. The procedure is repeated for all possible configurations, i.e. at first Q_x is kept constant while Q_y initially varies from max to min and then from min to max, and similarly for constant Q_y. The intensity is recorded during the tune change and resonances are revealed through induced losses. A beam with a small space charge tune shift of $\Delta Q_{x,y} = -0.035$ was used to increase the sensitivity of the measurements to machine driven resonances [10]. Figure 1 summarizes the results. All 3^{rd} order (both normal and skew) and all 4^{th} order (normal) resonances are excited in all rings. In ring 1 the 3^{rd} order skew resonances appear stronger while in rings 2, 3 and 4 the normal components are dominant. It should be noted that it was the first time that such a behaviour was observed and the first time that any 4^{th} order resonances were seen in loss maps in the PSB.

The resonances identified in Fig. 1 were individually compensated using the appropriate corrector magnets. The initial compensation values have been obtained by combining experimental and analytical techniques as discussed in [9]. However, the octupole correctors used for the compensation

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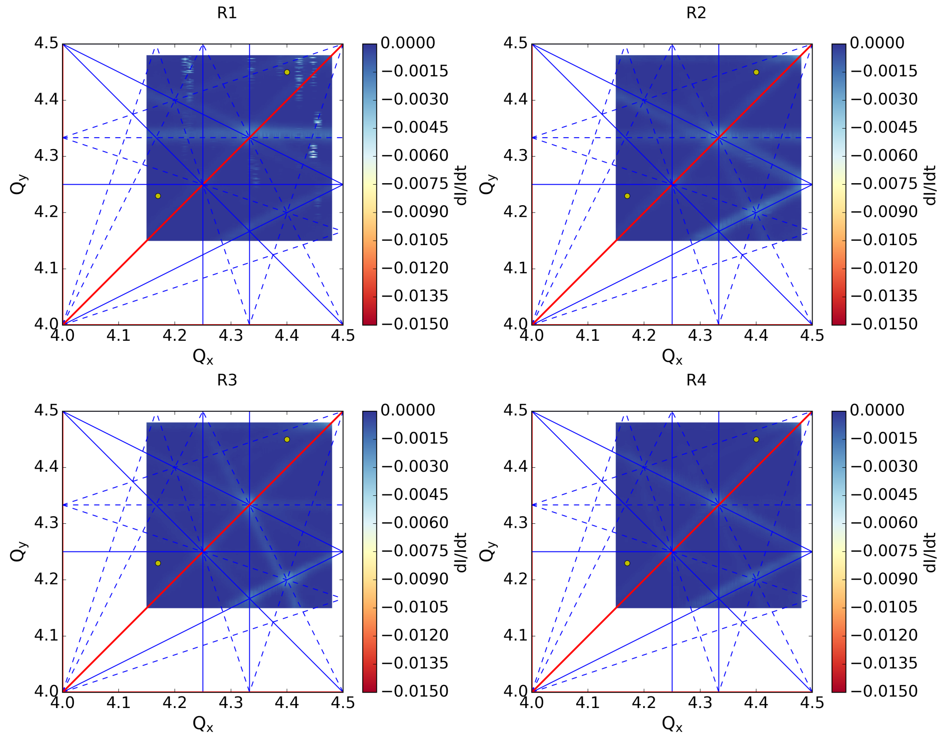

Figure 2: Loss maps resulting from dynamic tune scans in all four rings of the PSB with octupoles and sextupoles for the simultaneous correction of the 3rd and 4th order resonances. The color coding and the resonance lines are as in Fig. 1. The yellow points correspond to the tune ramp used in the optimization framework.

of the 4th order resonances affected the excitation of the 3rd order resonances. In addition, the compensation of the 4th order resonances was only partial due to current limitations in the power converters of the corrector magnets. To this end, the Generic Optimisation Frontend and Framework (GeOFF) [11–14] was used to refine the compensation scheme including extra corrector magnets and crossing multiple resonances at once as the tunes are programmed to change from $Q_x = 4.4$ to $Q_x = 4.17$ and $Q_y = 4.45$ to $Q_y = 4.23$ in the operational cycles. The refined resonance settings to globally compensate the resonances were applied and the loss map studies were repeated as shown in Fig. 2.

The global resonance compensation settings acquired with the optimization framework largely suppress all resonances as demonstrated in Figs. 1 and 2. The remaining resonance excitation is different per ring. In particular, 3rd order skew resonances are still observed in rings 1, 2 and 3. The $3Q_y = 13$ is still excited in rings 1 and 2 and the $2Qx + Qy = 13$ in ring 3. This was an expected behaviour as only three skew sextupole correctors were available for the instantaneous correction of the 3rd order skew components, while four to six correctors were available for the 3rd and 4th order resonances depending on the ring. Nevertheless, the 3rd order normal resonance $Q_x + 2Q_y = 13$ is still observed in rings 2 and 4. It should be noted that the resonance $Q_x - 2Q_y = -4$ is excited in all rings in the loss maps of Fig. 2 inducing even more losses than before the global compensation. However, this resonance is out of the regime of interest for operation and is thus not a concern. The improved resonance compensation settings were put into operation and were essential for the increased performance of the LHC beams.

HIGH INTENSITY BEAMS

The high intensity beams are particularly sensitive to losses due to their large emittances. Many parameters have to be adjusted to ensure a good transmission such as the working point evolution, the resonance compensation settings and the painting at injection [15]. In addition, known instabilities [16] have to be cured using the new transverse feedback system [17].

ISOLDE

ISOLDE is one of the PSB users that requires very high intensity. For normal operations 800×10^{10} ppr at 1.4 GeV are extracted. The working point at injection for this user is set at $Q_x, Q_y = (4.22, 4.45)$ to avoid blow-up at the integer resonances, as the space charge induced incoherent tune shift approaches $\Delta Q_x, \Delta Q_y \approx (0.3, 0.43)$. A tune change from 450 ms to 500 ms brings the tunes to the extraction values of $Q_x, Q_y = (4.17, 4.23)$ at a resonance-free transverse tune space. Similarly, the energy spread at injection is $\Delta E = 440$ keV to minimize the longitudinal line density and hence the space charge induced incoherent tune shift [18]. Measurements of the losses along the cycle were conducted for this configuration as shown in Fig. 3 (top). All results shown in this section are measurements of ring 4 (the situation is similar in all rings).

The losses increase for higher intensities reaching values > 14%. The compensation of the resonances improves the

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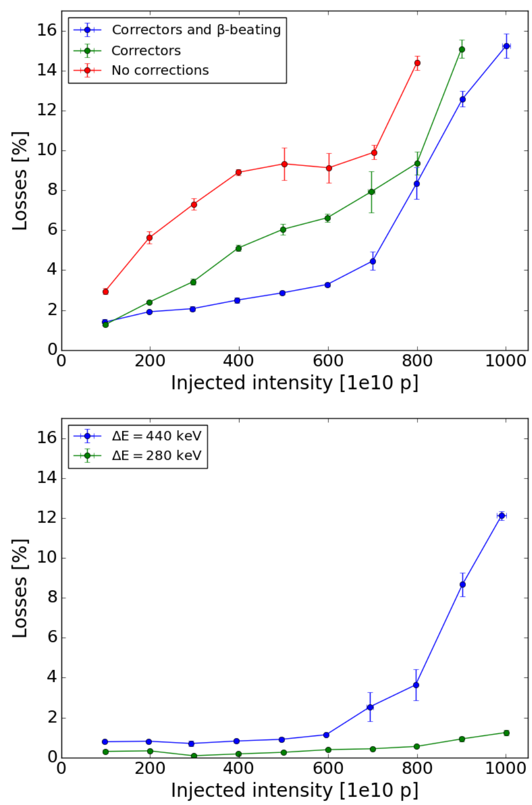

Figure 3: Total losses for the ISOLDE user versus the injected intensity for an injection working point of $Q_x, Q_y = (4.22, 4.45)$ (top) and $Q_x, Q_y = (4.22, 4.35)$ (bottom). The losses are calculated with or without resonance compensation and including the $\beta-$beating corrections [2] (top) and different energy spread (bottom).

situation keeping the losses below the 10% level for the nominal setting of 800×10^{10} ppr, which is the operational loss budget for the high intensity beams in the PSB. Moreover, the correction of the injection chicane induced β-beating [2] further reduces the losses.

Different working points were also investigated. The best option was a working point of $Q_x, Q_y = (4.22, 4.35)$ at injection with the same tune change to $Q_x, Q_y = (4.17, 4.23)$ from 450 ms to 500 ms. In this configuration only the 4th order resonances, $4Q_y = 17$ and $2Q_x + 2Q_y = 17$ and the 3rd order skew resonance, $3Q_y = 13$, are crossed allowing for a better correction, as seen in Fig. 3 (bottom). It should be noted that in this case the β-beating at injection is not corrected as the vertical tune is far from the vertical half integer resonance $2Q_y = 9$. The ultimate improvement reducing the losses below the 2% level was the reduction of the energy spread from LINAC4 to $\Delta E = 280$ keV. This allowed reducing the longitudinal halo and the impact of the periodic resonance crossing, that dominates losses from resonances in the presence of space charge [10, 19]. Even though, the longitudinal line density and hence space charge are increased, the emittance preservation is not a requirement for this user and some blow-up can be tolerated. In addition, the optimization of the extraction and the trajectories at the transfer line [20] minimized the losses, even for the higher emittance, and allowed the implementation of this solution.

TOF

The production of the TOF beam in the PSB is similar to the ISOLDE one, as similar intensity is needed for both beams. The main difference between the users is the energy, as TOF is extracted at 2 GeV and only from one ring (R2). The higher energy revealed a new instability that caused large losses just before arrival to the flat top and blocked operations, since it was not cured by the Transverse Feedback. The intrabunch motion of this new instability, as shown in Fig. 4, is different from the expectations including the effect of the kicker termination [16]. Linear coupling was used to stabilize the beam similar to past operations in the PS [21]. The tunes are set at the same value ($Q_{x,y} = 4.17$) while skew quadrupole magnets are powered to further excite the linear coupling. The beam was stabilized up to 1000×10^{10} ppr, which was more than the requirements from the user.

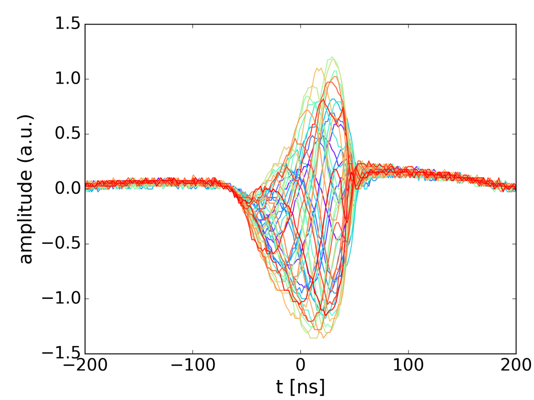

Figure 4: Intrabunch motion of the instability measured for the TOF user.

CONCLUSION

After the completion of the LIU project several studies were done to explore the intensity limitations for the beams for ISOLDE and n-TOF. Loss map studies revealed betatronic resonances up to 4th order, which were suppressed to a large extent using appropriate corrector magnets allowing for higher brightness and intensities. In addition, optimizations of the working point and the longitudinal characteristics reduced the losses to the percent level for intensities up to 1000×10^{10} ppr. Finally, a new instability was revealed at high energy that was cured using the linear coupling.

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