MEASUREMENT AND COMPENSATION OF SECOND AND THIRD ORDER RESONANCES AT THE CERN PS BOOSTER

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Abstract

Space charge effects at injection are the most limiting factor for the production of high brightness beams in the CERN PS Booster. The beams for LHC, CNGS and ISOLDE feature incoherent tune spreads exceeding 0.5 at injection energy and thus cover a large area in the tune diagram. Consequently these beams experience the effects of transverse betatron resonances and efficient compensation is required. Several measurements have been performed at the PS Booster in 2003, aiming at a detailed analysis of all relevant second and third order resonances and an optimisation of the compensation scheme. Special attention was paid to the systematic $3Q_y = 16$ resonance. To avoid this particularly dangerous resonance an alternative working point was tested. A comparison of resonance driving terms and compensation settings for both working points was made and important differences in the strengths of the resonances were found. The peculiarities when measuring third order coupling resonance driving terms are also mentioned.

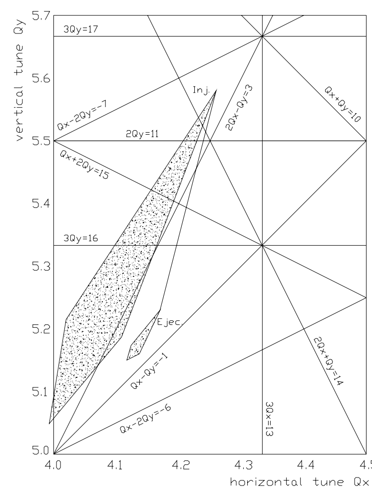

Figure 1: *PSB tune diagram for high intensity beams.*

INTRODUCTION

The PS Booster (PSB) accelerates protons from 50 MeV to 1.4 GeV. For injection of a high intensity beam, the working point of the PSB is displaced from the nominal tune values $Q_x \approx 4.17$, $Q_y \approx 5.23$ up to $Q_x \approx 4.26$, $Q_y \approx 5.58$. The large "necktie" shaped area due to incoherent space charge tune spread ($\Delta Q_x \approx 0.25$, $\Delta Q_y \approx 0.5$) shown in Fig.1 contains all the individual particles of the beam and covers several resonances. With increasing beam energy the working point is moved towards smaller tune values which is possible due to the decreasing space charge. According to the tune diagram a multitude of different resonances have to be considered to establish a complete resonance compensation scheme. The presently used scheme covers the second order $2Q_y = 11$, the systematic third order $3Q_y = 16$ as well as the third order sum resonances $2Q_x + Q_y = 14$ and $Q_x + 2Q_y = 15$ [1]. The third order difference resonance $2Q_x - Q_y = 3$ was not compensated so far.

MEASUREMENTS AND RESULTS

To measure resonance driving terms, a new multi-turn acquisition system was installed [2]. All relevant resonances up to third order were analysed in ring 1 (of the four PSB rings). Resonance driving term measurements for the bare (uncorrected) machine and for a deliberate excitation with a defined multipole, to calibrate the acquisition system, were performed. For each measurement only a single resonance was considered. A more detailed description on how to determine resonance driving terms in the PSB can be found in Reference [2]. The correlation between amplitudes and phases of spectral lines and resonance strengths and phases of Hamiltonian (driving) terms is described in [3].

Second order resonance

The vertical second order resonance $2Q_y = 11$, driven by the Hamiltonian term h_{0020}, is covered by particles and has to be compensated in standard operation. For the measurements, the vertical tune Q_y was adjusted to 5.48, the vertical chromaticity was not corrected[1]. In Fig. 2, the elliptic shape of the normalised vertical phase space and the large amplitude of the (0,-1) resonance line clearly indicate the bare machine resonance excitation. From the measured resonance strength $|h_{0020}| = 7.0 \pm 0.4 \cdot 10^{-3}$ and phase $\psi_{0020} = 269.8^\circ \pm 8.2^\circ$ of the driving term, the compensation currents are calculated to:

- $I_{QNO412L3} = +6.27 \pm 0.55$ A
- $I_{QNO816L3} = -2.82 \pm 0.93$ A

Fig. 3 demonstrates the successful application of these settings. The normalised phase space is free from perturbations and the (0/-1) resonance line is clearly reduced.

[1] Beam off-sets in the chromaticity correction sextupoles give rise to additional quadrupolar contributions.

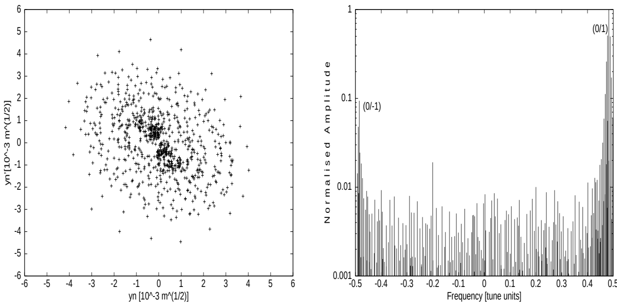

Figure 2: *Normalised vertical phase space and Fourier spectrum for the bare machine close to the $2Q_y = 11$ resonance condition.*

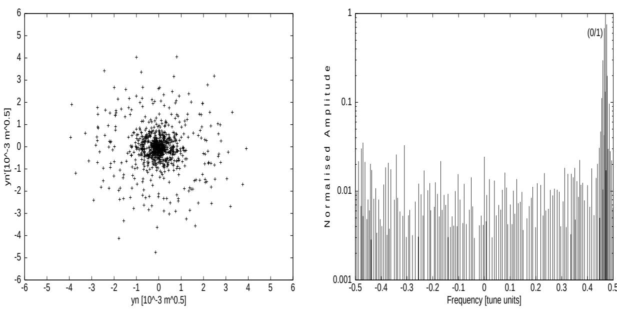

Figure 3: *Normalised vertical phase space and Fourier spectrum with compensation currents on.*

Systematic third order resonance

The PSB consists of 16 identical periods, hence the vertical third order $3Q_y = 16$ resonance is systematic and the most perturbing in this working area. For the measurements the vertical tune was set close to resonance condition ($Q_y \approx 5.345$) and the vertical chromaticity was corrected. Figs. 4 to 6 compare the bare machine with the compensated case. For the bare machine, the triangular phase space deformation, the corresponding resonance line (0,-2) and the particle losses are clearly visible. When compensated, the phase space is quasi free from perturbing terms and no resonance line and particle losses occur.

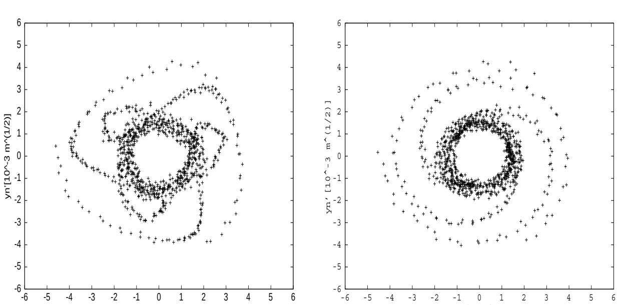

Figure 4: *Normalised vertical phase space of the bare machine (left) and with compensation (right) for Q_y close to the resonance condition.*

The measured strength and phase of the bare machine

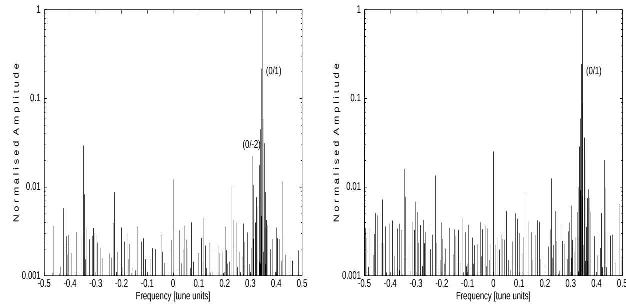

Figure 5: *Vertical Fourier spectra for the bare machine and with compensation.*

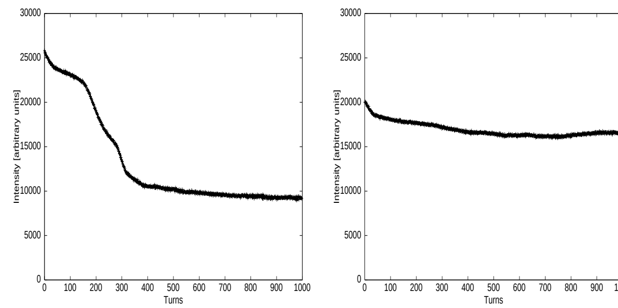

Figure 6: *Beam intensity over the first 1000 turns after injection into the machine.*

excitation

- $|h_{0030}| = 9.0 \pm 0.6 \cdot 10^{-3} mm^{-\frac{1}{2}}$
- $\psi_{0030} = -21.4° \pm 13.9°$

was successfully compensated with two independent skew sextupoles: $I_{XSK2L4} = -12.3$ A, $I_{XSK9L1} = +15.3$ A.

Third order coupling resonances

From the tune diagram of the PSB (Fig. 1) one notes that three third order coupling resonances are covered by particles at injection. In standard operation the sum resonances $2Q_x + Q_y = 14$ and $Q_x + 2Q_y = 15$ are compensated, the difference resonance $2Q_x - Q_y = 3$ was not compensated so far. Measurements for all these resonances were made to determine the corresponding driving terms. Tune and resonance lines in Fourier spectra can only be measured during the coherent oscillations of the beam in both planes. Unfortunately, large residual chromaticities (only one family of chromaticity sextupoles in the PSB) induce a rapid decoherence of the beam oscillations. As a result the measured FFT spectra do not show the expected resonance lines.
In case of the difference resonance $2Q_x - Q_y = 3$ it is possible to adjust the chromaticities in both planes in a way that the horizontal resonance line (-1/1) does not vanish. For this the chromaticity was adjusted to be equal in both planes. With this setting, a line for the bare machine excitation is visible in the horizontal Fourier spectrum. In the vertical plane the resonance line is covered by the background (Fig.7).

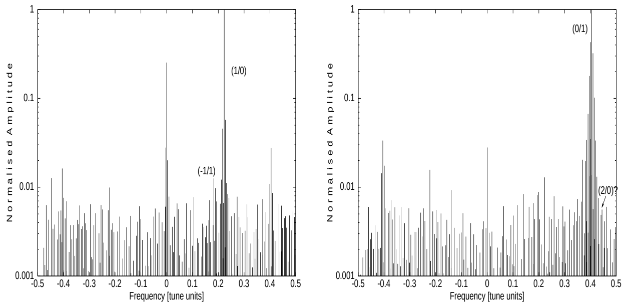

Figure 7: *Horizontal and vertical Fourier spectrum for tunes close to the* $2Q_x - Q_y = 3$ *resonance condition.*

Alternative working point

At the end of the run 2003 a "lower" working point for the PSB was tested to avoid the $3Q_y = 16$ systematic resonance and potentially increase the beam intensity and brightness. The vertical tune was shifted one integer down to 4.23, thus only non-systematic resonances have to be considered. Measurements for the most important resonances were done, showing significantly less bare machine excitation for this working point. Fig. 8 shows the Fourier spectra for tunes close to the $2Q_y = 9$ and $3Q_y = 13$ resonance condition respectively. The resonance spectral lines are clearly smaller than the corresponding resonance lines for $2Q_y = 11$ and $3Q_y = 16$ (Figs. 2 and 5) of the standard working point. Table 1 presents the measured strengths of

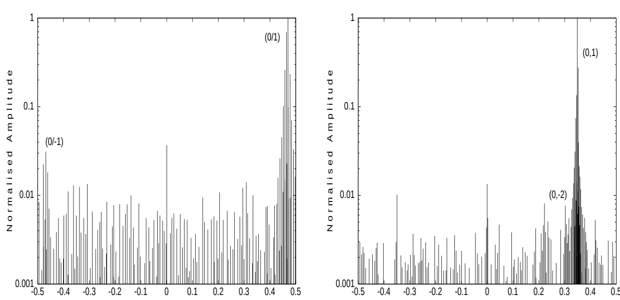

Figure 8: *Vertical Fourier spectra for the bare machine for tunes close to the* $2Q_y = 9$ *respectively* $3Q_y = 13$ *resonance condition.*

Driving Term	standard WP	lower WP
h_{0020}	7.0 ± 0.4	3.2 ± 0.1
h_{0030}	$9.0 \pm 0.6\ mm^{-\frac{1}{2}}$	$2.2 \pm 0.4\ mm^{-\frac{1}{2}}$

Table 1: *Measured resonance strengths in* 10^{-3} *for both working points.*

the resonance driving terms for both working points. The obtained results indicate a decrease in resonance strengths about a factor 2 respectively a factor 4. Table 2 summarizes the calculated compensation currents for these resonances[2]. When considering only the measurement results, the lower working point is definitely favourable. More detailed results on the various measurements can be found in [4, 5].

Comp. Elements	standard WP	lower WP
QNO412L3	+6.3 A	-1.4 A
QNO816L3	-2.8 A	-2.7 A
XSK2L4	-12.3 A	0.0 A
XSK9L1	+15.3 A	+31.0 A

Table 2: *Calculated compensation currents for the standard and lower working point.*

CONCLUSIONS

It has been shown that the new multi-turn acquisition system in the PS Booster allows efficient determination and compensation of 2nd and 3rd order resonances. Restrictions were encountered in the case of coupling resonances due to the lack of a second chromaticity sextupole family. Furthermore, comparative resonance driving term measurements with different lattice settings led to the conclusion that, from the resonance excitation point of view, a "lower" working point is preferable to the one used in standard operation.

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[5] P. Urschütz, *Measurement and Compensation of Resonance Driving Terms at the CERN PS Booster Synchrotron by Harmonic Analysis of Turn-by-turn Beam Position Data*, CERN, Thesis.

[2] The XSK2L4 skew sextupole is located in a high β_y region compared to the XSK9L1 and is therefore approx. 10 times stronger.