

WORKING POINT AND RESONANCE STUDIES AT THE CERN PS

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Abstract

The increase of luminosity demanded by the High Luminosity LHC (HL-LHC) requires an increase of beam intensity, which might result in instabilities appearing at injection energy in the CERN PS. Transverse head-tail instabilities have already been observed on operational LHC beams and a stabilizing mechanism as an alternative to linear coupling is currently being studied. It consists of reducing the mode number of the transverse oscillation by changing linear chromaticity and in succession completely suppressing the instability by a transverse damper system with appropriate bandwidth. Therefore, a chromaticity correction scheme at low energy exploiting the intrinsic possibilities offered by special circuits mounted on top of the main magnet poles, the Pole Face Windings (PFW), has been examined. The presence of destructive betatron resonances, which restrict the choice of the injection working point and the maximum acceptable tune spread, forms an additional limitation for high-brightness and high-intensity beams in the CERN PS. To improve the current working point control scheme, the influence of the PFW on the machine resonances is presented in this paper.

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The presence of destructive betatron resonances, which restrict the choice of the injection working point and the maximum acceptable tune spread, forms an additional limitation for high-brightness and high-intensity beams in the CERN PS. To improve the current working point control scheme, the influence of the PFW on the machine resonances is presented in this paper.

CONTROL OF THE WORKING POINT

When the CERN PS was put into operation in November 1959, it was the world's first synchrotron based on the alternating gradient principle. This was realized by using 100 combined function main magnets, each of them consisting of a focusing and a defocusing half unit. This design provided the advantage of constructing the machine in a compact way, but came along with the drawback of requiring additional means to adjust the working point.

Therefore, the machine tune is controlled by two different groups of magnets, their use depending on the energy of the circulating particles. From injection kinetic energy at 1.4 GeV up to approximately 3.5 GeV the focusing and defocusing families of the Low Energy Quadrupoles (LEQ) are used, while the PFW and the Figure of 8 Loop (F8L) take over at higher energy. In each half unit of the main magnet the PFW are divided into a so-called narrow and wide circuit, the names indicating whether the air gap of the magnet is small or large at their respective positions. Contrary to the PFW, the F8L is only a single winding, that crosses in the center of the main magnet, having the form of a figure of eight [1, 2].

Altogether, the PFW and the F8L constitute five independent circuits and, therefore, theoretically offer means to control both tunes as well as the linear and one of the second order chromaticities.

The bare machine at 2 GeV

In the absence of any active auxiliary magnets or circuits the working point of the CERN PS is fully determined by the momentum of the beam, as the main magnets account for the dipole and the quadrupole field at the same time. The available radial steering allows to measure the dependency of the tune on the momentum error, revealing a completely linear behavior ($\xi_x=-0.83$, $\xi_y=-1.12$, see Fig. 1a). This measurement and the upcoming ones were conducted at 2 GeV, corresponding to the future injection kinetic energy.

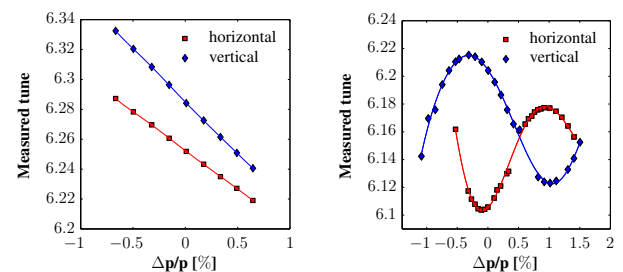
The machine is obviously only rarely operated in this configuration as there is no freedom in choosing the tunes. However, even by powering the LEQ the observed linearity is not altered. These additional magnets account for a change of the tunes, inducing β -beating in the order of 10%, without introducing any magnetic effects of higher order.

The non-linear machine at 2 GeV

In order to correct linear chromaticity at energies above 3.5 GeV, the PFW and the F8L are today used in 3 current mode (3CM), meaning that the narrow and wide circuits of each half unit of the main magnet are powered with the same current. This approach only allows to control 3 parameters, namely both tunes and chromaticity in one plane, leaving no means to influence chromaticity in the other.

However, the implementation of a chromaticity correction scheme at injection aims for reducing the mode number of transverse head-tail instabilities and, therefore, control of linear chromaticities in both planes is desired. This requires to operate the PFW and the F8L in 4CM, fixing, e.g., the current in the F8L to zero.

To examine the influence on the linearity of the machine the working point was moved from the one of the bare machine (6.25, 6.28) to (6.10, 6.20) by the PFW in 4CM and the measured dependence of the tune on the momentum deviation is shown in Fig. 1b. The appearing non-linearities



(a) Bare machine.

(b) Tune control with PFW.

Figure 1: Influence of auxiliary coils on the linearity of the machine.

and their correction were studied in detail [3] and the unbalancing of currents in the narrow and wide windings was understood to be the cause, most likely due to the asymmetric alignment of the PFW.

The next step was to examine the feasibility of influencing the sextupole and octupole component of the magnetic field and to, ideally, linearize the observed non-linearities. Therefore, the matrix correlating the parameters of interest and the currents of the available circuits, corresponding to the equation

$$\begin{pmatrix} \Delta Q_x \\ \Delta Q_y \\ \Delta \xi_x \\ \Delta \xi_y \\ \Delta Q''_{x,y} \end{pmatrix} = \mathbf{M}_{5 \times 5} \begin{pmatrix} \Delta I_{FN} \\ \Delta I_{FW} \\ \Delta I_{DN} \\ \Delta I_{DW} \\ \Delta I_{F8L} \end{pmatrix},$$

was measured [4]. By inversion, one obtains $\mathbf{M}_{5 \times 5}^{-1}$, which is then used to calculate the desired correction currents. An example of successful correction of horizontal linear chromaticity is shown in Fig. 2a, where the different curves correspond to the different offsets $\Delta \xi_x$ as defined in the matrix equation above. The dashed line in Fig. 2b refers to the theoretically expected evolution of ξ_x , constant as $\Delta \xi_y$ remains unchanged and following $\Delta \xi_x$ in the horizontal plane, which is in good agreement with the measurements.

Contrary to this result, using the matrix approach to correct the octupole components Q''_x or Q''_y with the PFW was found to produce non-predictable results, making an operational implementation at low energy unlikely. The reason for this is not yet understood but under investigation.

Instead, the current of 6 octupoles distributed around the ring, the ODEs, was varied and the measurements in Fig. 3

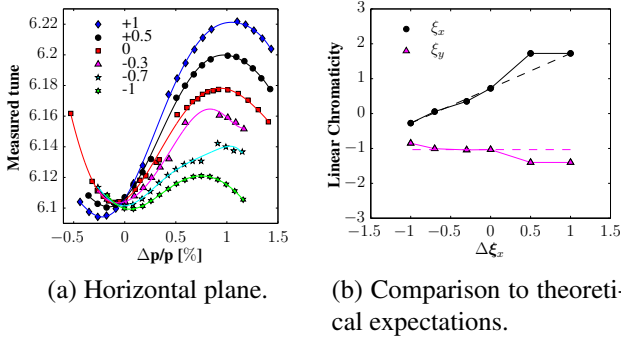


Figure 2: Modification of ξ_x .

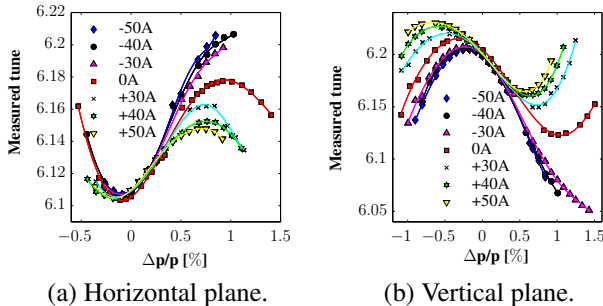


Figure 3: Correction of Q'' with the ODEs.

prove the expected influence of the octupoles on Q'' , while ξ_x and ξ_y remained almost constant.

IDENTIFICATION OF RESONANCES

Controlling the working point and eventually linear chromaticity requires to use the PFW in 4CM. Due to this fact, betatron resonances that are not present for the bare machine could be excited and, depending on the chosen working point, degrade the beam quality. Therefore, beam loss based measurements, inspired by the technique used in [5], have been conducted to identify destructive resonances (see [3]).

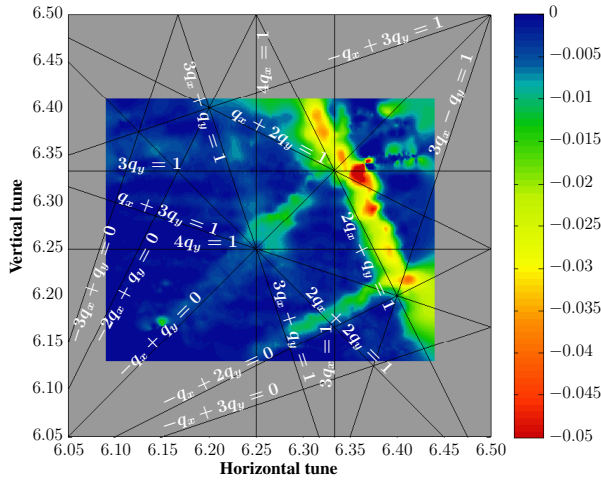
A single bunch of $1.2 \cdot 10^{12}$ protons with transverse normalized emittances (1σ) of $\varepsilon_x \approx 10$ mm-mrad and $\varepsilon_y \approx 8$ mm-mrad, was stored for 1.3 seconds at either 1.4 or 2 GeV, keeping the tune in one plane constant while changing it dynamically in the other. Due to the large beam size particles are quickly lost once the tunes enter into the stop band of an excited resonance. This allows to roughly estimate the relative strength and the width of all resonances by calculating the derivative of a beam current transformer signal. In order to take the resulting reduction of intensity along the cycle into account, each peak of the derivative is normalized by the intensity of the beam right before crossing this respective resonance. A two-dimensional illustration of the working point plane is then obtained by repeating the measurement for different constant tunes and interpolating the data points on an equidistant grid.

For this beam the Laslett tune spread was calculated to be $\Delta Q_x = -0.05$ and $\Delta Q_y = -0.07$, sufficiently small to neglect multiple resonance crossing due to a large space charge neck tie, making the identification of single resonance lines possible.

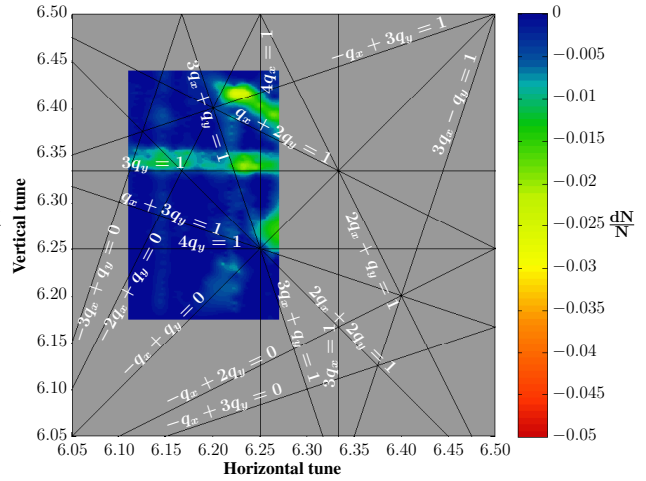
Figures 4a and 4b show measurements at injection energy, where the tunes were controlled by the LEQ only and the color scale represents beam loss. The strongest detected resonance is clearly the $2q_x + q_y = 1$, while the most interesting line concerning machine operation is the $3q_y = 1$ (q being the fractional tune). The peculiarity of the measurement technique is that resonances are most efficiently detected when the scan is conducted perpendicular to the line. This causes the resonance $3q_y = 1$ to be visible in Fig. 4b but not in Fig. 4a.

In contrast to [6], where a hybrid working point using the LEQ and the PFW was set up, a series of measurements was conducted using only the PFW (the current in the F8L being set to zero). An extract of the results is shown in Figs. 4c and 4d. Most importantly, no additional resonances can be observed, the line $3q_y = 1$ remains equal in strength and width and the $2q_x + q_y = 1$ even seems to be slightly reduced. Within the red highlighted area in Fig. 4d no resonances seem to be excited and these measurements therefore suggest this area to be the most beneficial within the working point plane, limited by the vertical integer and third order resonances. This would allow to inject beams with a maximum tune spread of $\Delta Q_y \approx -0.33$.

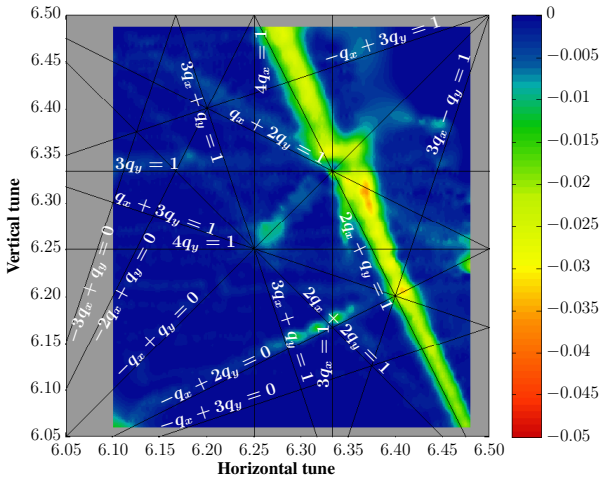
However, the tune spread based on the demands of the



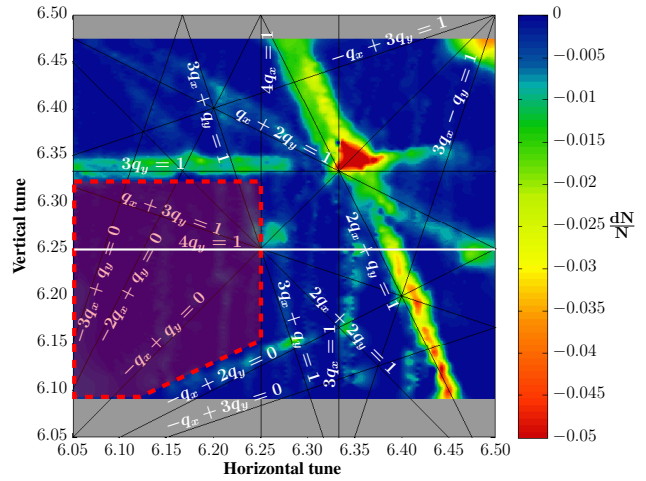
(a) Horizontal scan at 1.4 GeV using the LEQ.



(b) Detail of a vertical scan at 1.4 GeV using the LEQ.



(c) Horizontal scan at 2 GeV using the PFW in 4CM.



(d) Vertical scan at 2 GeV using the PFW in 4CM. The highlighted area appears to be free of severe resonances; the vertical 4th order is indicated by the white line.

Figure 4: Several graphical representations of the working point plane.

HL-LHC is supposed to be $\Delta Q_y = -0.34$ or even larger, which is not reachable with a machine in this configuration unless the third order resonance $3q_y = 1$ is compensated.

CONCLUSION

A chromaticity correction scheme at injection energy requires the working point to be controlled by the PFW in 4CM. This mode of operation was observed to create highly non-linear magnetic fields and it was shown that Q'' can be influenced by octupoles as expected.

Despite these non-linearities the same betatron resonances were found to be excited as in the bare machine, which also led to the understanding, that the observed resonances are mainly caused by magnetic errors within the main magnets. Based on this, a compensation scheme for resonances has recently been successfully tested and even allowed to completely compensate the $3q_y = 1$ [7].

However, the resonance $4q_y = 1$, which is not visible on

the presented measurements, seems to be excited by the beam itself in the presence of high space charge. Therefore, $Q_y = 6.25$ is currently considered being the upper limitation for high-brightness beams unless means of compensating the $4q_y = 1$ or an alternative working point are found [8].

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