NEW WORKING POINT FOR CERN PROTON SYNCHROTRON

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Abstract

The LHC High-luminosity project requests high brightness and intensity beams from the CERN Proton Synchrotron (PS). Currently, the generation of such beams is limited due to resonance effects at injection. The impact of resonances can be minimized by performing appropriate correction with dedicated magnets and by optimizing the tune working point. Currently the tune working point at injection is naturally set by the quadrupolar component generated by the one hundred combined function normal conducting magnets installed in the PS. In this paper, a study is presented exploiting the use of the available five auxiliary individually powered circuits to adjust the quadrupolar and higher-order multipole components for changing the tune working point at injection. Due to the non-linear contribution of each circuit to the magnetic field distribution a finite-element magnetic model was prepared to predict the required currents in the auxiliary coils. The magnetic model was benchmarked with magnetic measurements and then tested in the PS machine during dedicated machine development times.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN is the largest particle collider ever designed and built for scientific research. Today, in order to exploit the LHC discovery potential an upgrade is planned to further increase its luminosity.

Within the LHC Injectors Upgrade (LIU), the role of the Proton Synchrotron (PS) is of particular importance; the PS in fact is the machine in the LHC Injector Chain where the longitudinal characteristics of the LHC beam are determined [1].

The PS was designed on the principle of alternating gradient, using 100 combined function main magnets, each of them consisting of a focusing and defocusing half. To adjust the working point, auxiliary magnetic circuits are used: the figure-of-eight loop and the pole-face windings, see Figure 1.

As it will be further explained, one limitation of the PS for high-brightness and high-intensity beams is the presence of beam betatron resonances, which restrict the choice of the injection working point and create instabilities [2]. Another limitation is the fact that the variation of one current affects all multipoles, being combined function magnets. In the effort of finding a better working point than the one in use, a way to link the five different auxiliary circuits to the resulting tunes has been searched for.

This paper presents the methodology, the identification of the model and its application and finally the verification on the real machine.

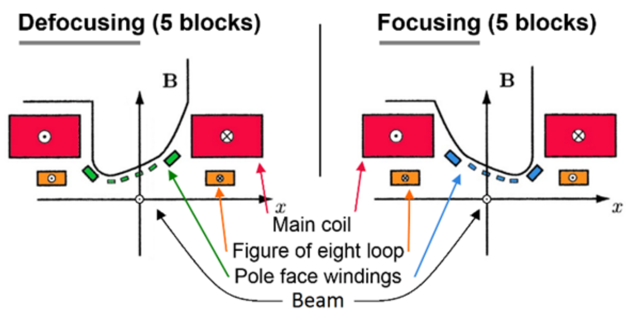

Figure 1: PS coils scheme (beam turning clock-wise) [3].

Considering the bare machine (magnetic field produced only by the main coil), the working point at injection corresponds to the tunes $Q_x = 6.24$ and $Q_y = 6.28$. The corresponding surrounding area in the tune diagram is crossed by many resonance lines, as it can be seen in Figure 2 (R. Wasef, private communication, 2015).

The resonance condition in a circular accelerator can be written as $aQ_x + bQ_y = p = mN$, where m is the super-periodicity of the lattice and $a+b$ the order of resonance: only harmonics p integer multiple of m can take place [4].

The PS has a super-periodicity of 10, which makes the beam particularly sensitive to harmonics 10, 20 and 50: these harmonics correspond to the structural or systematic resonances. In Figure 2 they are represented by the thick lines (respectively red, orange and blue). The thin lines represent instead the non-structural resonances coming from sextupolar and octupolar errors.

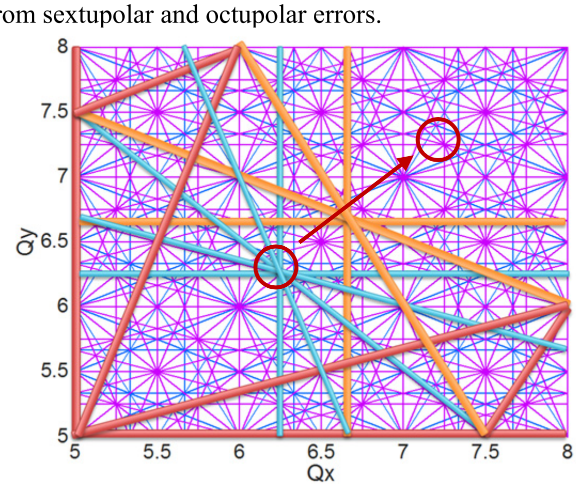

Figure 2: Tune diagram of the PS.

The purpose of this study is to increase both tunes of one integer, to $Q_x = 7.24$ and $Q_y = 7.28$, a better suited area due to its limited presence of systematic resonances.

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METHODOLOGY

In the following section the methodological approach is presented, introducing the tools used for this study.

MAD-X

MAD-X is a general-purpose tool for charged-particle optics design and studies in alternating-gradient accelerators and beam lines, developed at CERN more than 20 years ago [5].

In MAD-X it is possible either to feed the field coefficients K_n of a magnet and obtain the machine optics parameter, or to do the opposite: in this case the tunes and chromaticities were set to obtain the values of K_n.

For this study, the model of the PS lattice was used to obtain the values of the field coefficients and therefore of the field multipoles corresponding to the desired tunes. These values were then considered as a reference to find the corresponding currents to obtain the said tunes.

Component Responses

For each half of the magnet, focusing and defocusing, a corresponding set of multipoles for the two working points was calculated using MAD-X, see Table 1. All the field values are expressed in the Taylor notation $\left(B_y(z)+iB_x(z)=\sum_{n=1}^{\infty} B_n \cdot \frac{(n-1)!}{r_0^{(n-1)}} \cdot \left(\frac{x+iy}{r_0}\right)^{(n-1)}\right)$ and integrated over the magnetic length.

Table 1: Multipoles Values Calculated with MAD-X

	Tune	B_1 [Tm]	B_2 [Tm/m]	B_3 [Tm/m^2]	B_4 [Tm/m^3]	B_5 [Tm/m^4]
Focusing	6.24, 6.28	0.224	0.886	-0.025	0.381	5.725
Focusing	7.24, 7.28	0.224	1.064	-0.025	0.381	5.725
Defocusing	6.24, 6.28	0.225	0.890	0.038	-0.544	-36.40
Defocusing	7.24, 7.28	0.225	-1.069	0.038	-0.544	-36.40

The function $B(i_{\mathrm{MC}})$ is not linear for high levels of current and it was therefore considered a working point limited to $i_{\mathrm{MC}} = [390; 430]$ A. Regarding the figure-of-eight loop and the pole face windings, i_{f8} and i_{PFW}, the ranges were: $i_{\mathrm{f8}} = [0; 150]$ A and $i_{\mathrm{PFW}} = [0; 55]$ A.

Considering these ranges, the multipoles have been calculated and linearized both for the focusing and the defocusing part as function of the currents by using the 3D Opera model [6].

IDENTIFICATION OF THE MODEL

The 3D Opera model has been validated regarding both the local and integral values of B_1 (dipole) and B_2 (quadrupole) comparing the results with magnetic measurements carried out on one bare magnet unit during this work.

Running the said 3D model starting with the main coil current, the focusing and defocusing multipoles from B_1 to B_5 (decapole) corresponding to the lowest and the highest value of i_{MC} have been obtained. Then, the coefficients of the straight line passing through these two points have been calculated for all the multipoles: m_{MC}^{Bn} and q_{MC}^{Bn} represent the gradient and the B-intercept of the line $B_n(i_{\mathrm{MC}}) = m_{\mathrm{MC}}^{Bn} i_{\mathrm{MC}} + q_{\mathrm{MC}}^{Bn}$ in the specified range.

The same was done for the figure-of-eight loop and pole face windings, using an average main coil current equal to 410 A to take into account the remanent magnetization of the yoke [7].

With these coefficients it has been possible to calculate the needed current to obtain the desired multipoles values.

Applying the Model

The conditions imposed by MAD-X, and shown in Table 1, were considered. The multipoles, for both focusing and defocusing parts, written as functions of the six currents have the form:

$$B_n(i_k) = \sum_{k=1}^{6} m_n(i_k) \cdot i_k + q_n(i_k)$$

The resulting system could be expressed in matrix form:

$$\mathbf{M} \cdot \mathbf{I} + \mathbf{Q} = \mathbf{B}$$

where **M** and **Q** are the coefficients matrix and vector, **I** is the currents vector and **B** is the given multipoles vector.

The system appeared to have more variables than equations: due to this, some hypothesis had to be made in order to solve it. It was decided to consider the dipolar and quadrupolar components separated in focusing and defocusing part, while the higher multipoles (sextupole B_3, octupole B_4, B_5) as an integral along the entire magnet.

The linear system of equation was then solved in MATLAB using matrices and manually assigning different weights to the equations. This method resulted efficient (Set 2 was obtained), but left the doubt that the found solution was not necessarily the optimum (see Table 3). A second script was therefore made, to find the minimum of a constrained multivariable function. It was quickly found out that it is very difficult to minimize at the same time B_3, B_4 and B_5: the function to be minimized was then decided to be the sum of their absolute values. The dipolar and quadrupolar components were considered as equalities, while the sextupolar and octupolar components as inequalities (their absolute value had to be lower or equal to the wanted value). Finally, the decapolar components were not individually considered, but only in the said sum of absolute values. Set 1 was obtained in this case. The two sets of currents are presented in Table 2.

Table 2: Solutions Found with the New Model

	i_{MC} [A]	i_W^{F} [A]	$i_{\mathrm{N}}^{\mathrm{F}}$ [A]	i_W^{D} [A]	$i_{\mathrm{N}}^{\mathrm{D}}$ [A]
Set 1	420.00	63.27	19.64	62.98	19.63
Set 2	423.27	92.98	23.19	92.03	22.66

Using these values as an input to calculate the corresponding multipoles, gave the results in Table 3.

Table 3: Integrated Multipoles Values Calculated with MAD-X and with the New Model

	B_{1F} [Tm]	B_{1D} [Tm]	B_{2F} [Tm/m]	B_{2D} [Tm/m]
MAD-X	0.224	0.225	1.064	-1.069
Set 1	0.224	0.225	1.016	-1.021
Set 2	0.224	0.225	1.064	-1.069

	B_3 [Tm/m^2]	B_4 [Tm/m^3]	B_5 [Tm/m^4]
MAD-X	0.013	-0.164	-30.68
Set 1	0.694	0.011	9164.5
Set 2	0.013	0.0004	14544.8

For the first set, it can be noticed that B_2 was not exactly matching the values from MADX, it was ~4% lower.

With the second set that had been obtained, B_2 was exactly matching the values from MADX, B_3 and B_4 were in the limits and only B_5 was bigger than the wanted one.

VERIFICATION IN THE PS

The two sets of currents were tested at injection in the PS by using them to excite a field in the main magnets. The injection bump, the orbit corrections and the acquisition system are normally optimized for the tune integers 6, 6: for this experiment, they had to be adjusted to be able to inject at 7, 7.

With the first set, the Q_x reached the integer 7, but the residual rms horizontal orbit needs further optimization (about 30 mm peak-to-peak excursion, see Figure 3). The beam was lost after approximately 1s, as it can be seen in Figure 4. The fractional tune could not be measured using the standard tune measurement approach (large beam losses, rapid decoherence of the betatron oscillations).

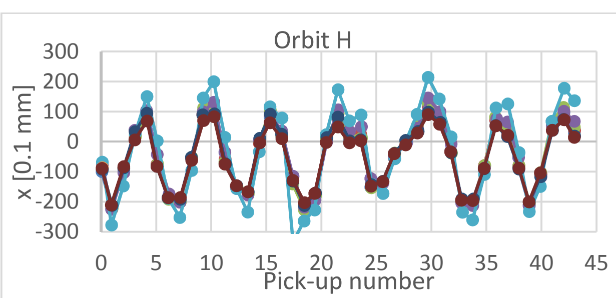

Figure 3: Orbit of the beam on the horizontal axis, for the first set of currents.

The second set of currents has also been tried out, but it has not been possible even to inject the beam in the machine because no time was available to reset the injection bump.

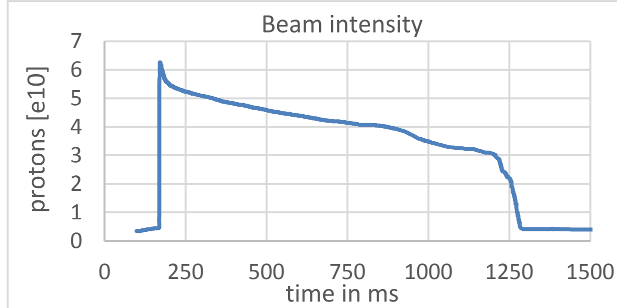

Figure 4: Protons over time during the first test in the PS.

CONCLUSION

A mathematical model relating currents and multipoles of the PS has been developed, based on the finite elements model of the magnet. This model was used to calculate the currents setting needed to move the PS working point to the desired one.

Two different sets of current have been tried out in the machine: many challenges were encountered, due to the fact that the injection bump and the orbit corrections in the PS are normally set for the tune integers 6, 6. Despite the unavailability of a study on the injection bumps at 7, 7, it has been possible to optimize some optics parameters and inject, as shown inFigure 3. However, injecting at 7, 7 in a machine optimized for 6, 6 resulted in the impossibility to keep the beam circulating or to accelerate it. Additionally, in the second case the machine had been set for the first set of currents and was then highly sensitive to any tried change in the tunes. All this highlighted the need of a study of a fine-tuned general optics model for the desired tune.

This work was a first try to see if the working point can be conveniently changed by using the existing magnets and power converters. The presented data will be used as a starting point for a more comprehensive study of all the mechanisms linking the currents to the tunes in the PS, which may provide the additional constraints needed to determine a successful set of currents.

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