CERN PROTON SYNCHROTRON WORKING POINT MATRIX FOR EXTENDED POLE FACE WINDING POWERING SCHEME

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Abstract

The CERN Proton Synchrotron has been continuously improving its beam performances since 1959. The working point parameters of the accelerator are mainly controlled by dedicated windings installed on the poles of the main combined function magnets. In 2007, the power supplies of these windings were renovated and extended from three to five independent groups, allowing exploration of new working point settings. This configuration offers the flexibility of several adjustment strategies such as leaving one current free or to control an additional physical parameter, like Q''_h. A non-linear chromaticity measurement campaign, at different beam momenta, resulted in matrices defining the relationship between the five pole face winding currents and the four beam parameters Q_h, Q_v, ξ_h, and ξ_v. Each cell of these matrices was fitted against momentum. The final result is a single matrix as a function of beam momentum, which is now used by the operational software to trim the working point. This paper summarises this measurement campaign by presenting the resulting matrix with a brief overview of the adjustment tools and strategy. Furthermore a few future possible benefits of this control enhancement will be discussed.

INTRODUCTION

The PS ring is made of a hundred combined function magnets. Their poles have a particular shape in order to generate a quadrupolar field in addition to the main dipolar field as illustrated in figure 1. Each magnet consists of two parts, one half with a focusing and the other half with a defocusing pole design. Extra magnetic elements, the so called Pole Face Windings (PFW) and figure of eight loop (8L), have been added to control quadrupolar, sextupolar and octupolar field components. This complex magnetic configuration governs the betatronic motion (i.e. the physical parameters tune, linear and non-linear chromaticitiy), which is principally controlled by the currents delivered to these PFW's and the 8L.

Pole face windings and figure of eight loop

The PFWs (figure 2) are divided into four independent circuits. Two of them are mounted on poles of the focusing (F) part of the main magnets, and the two others on the defocusing (D) part. The F and D circuits are each divided into a wide and a narrow circuit. The wide circuit winding (W) covers the whole magnet poles, while the narrow circuit winding (N) only covers the poles where the gap is narrow. The individual circuits are named DN, DW, FN, and FW. The 8L is a winding describing a figure of eight around the poles of both halfs of the magnet and therefore crosses between the focusing and defocusing part.

Before 2007 the PFW and 8L were powered by three independent power converters, each controlled by their own current function generator. The circuits were connected in series and parallel, which had the advantage to partly cancel the currents induced by the main magnetic field variations [1]. This mode of operation was called the three-currents mode. The 2007 renovation led to one independent power supply per PFW and 8L, the five-current mode. In this new configuration the induced currents do no longer cancel partly, but it requires the regulation to reject them, making use of new regulation technologies to increase bandwidth and stability [1], [2].

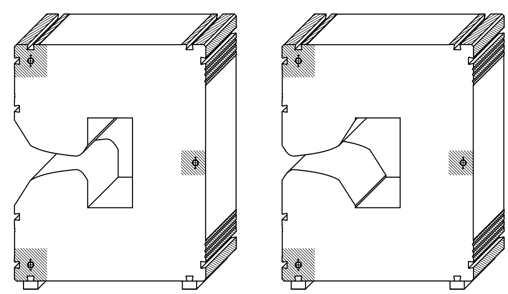


Figure 1: Main yoke.

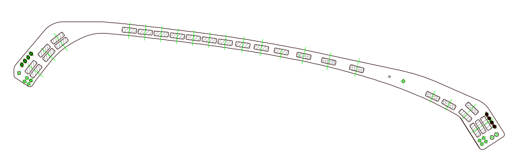


Figure 2: Pole Face Windings.

MATRIX MEASUREMENT

In 1995, three 20$^{\text{th}}$ order polynomials where established that define the PFW and 8L currents as a function of momentum. $I_j = \sum_{n=0}^{20} a_n p^n$ where j = each PFW and 8L. An iterative approach was use to define them allowing acceleration of a beam with an intensity of up to 10^{13} protons with minimum losses. These same polynomials were used to generate the initial functions of PFW and 8L currents for the measurement campaign. At any momentum, the behavior of the physical parameters Q_h, Q_v, ξ_h and ξ_v

is supposed to vary linearly with respect to small current variations around the initialized reference currents. Every physical parameter variation can be defined as a linear combination of the current variations in each circuit, i.e. $\Delta par_i = \sum_{j=1}^{5} b_j I_j$ where $\Delta par_i = Q_h, Q_v, \xi_h, \xi_v$ and j identifies the circuit of PFW and 8L. The coefficients b_j are momentum dependent and have to be determined by measurements. At each momentum, a working point reference is measured for the initial current functions. Then a well defined variation on each current is programmed and the working point is re-measured. In this way, for every momentum, a 4×5 matrix can be built (1), of which an example is given in table 1.

$$\begin{pmatrix} Q_h \\ Q_v \\ \xi_h \\ \xi_v \end{pmatrix}_p = M(4 \times 5)_p \begin{pmatrix} I_{FN} \\ I_{FW} \\ I_{DN} \\ I_{DW} \\ I_{8L} \end{pmatrix} \qquad (1)$$

Measurement procedure

The measurements were done at seven different momenta using distinct magnetic cycles for each momentum. A single bunch of 5.10^{11} protons was accelerated up to the desired plateau and used to perform the tune measurements.

On the measurement plateau of approximately hundred milliseconds, positive and negative offsets were applied on the currents of each of the 4 PFW and 8L independently in order to measure the resulting offsets on the tune and chromaticity.

Chromaticity measurement

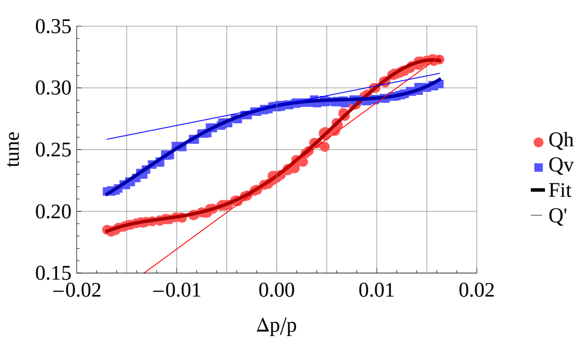


Figure 3: Example of chromaticity determination from tune measurements.

The tune values were obtained from the tune measurement system, while the non-linear chromaticity was determined by the tune variation caused by different programmed momentum offsets. The tune values were then fitted against the momentum offset using an n^{th} order polynomial: $Q_{(h,v)} = \sum_{i=1}^{n} a_i (\frac{\Delta P}{P})^i$, as illustrated in figure 3. The order n of this polynomial function was chosen to obtain the best fit.

Measurement results

Table 1 represents the measurements done for a beam momentum of 2.12 GeV/c. Each cell contains the value of the current offset on a circuit over the offset measured on a physical parameter. The same measurements were repeated for all momenta mentioned in table 2.

	ΔQ_h	ΔQ_v	$\Delta \xi_h$	$\Delta \xi_v$
ΔI_{FN}	0.02149	-0.00923	0.79164	-0.52457
ΔI_{FW}	0.02958	-0.01905	-0.06723	0.05509
ΔI_{DN}	-0.01991	0.03870	0.47934	-0.69336
ΔI_{DW}	-0.01781	0.02586	-0.10773	0.13304
ΔI_{8L}	-0.00739	0.00794	0.00098	0.00106

Table 1: 2.12 GeV/c transfer matrix.

p	2.12	3.5	10	14	20	24	26

Table 2: Measurement momenta in GeV/c.

Results per couple parameter - circuit

To obtain a single matrix that can be used over the entire momentum range of the PS, each value in each matrix cell for the seven matrices was fitted using an exponential equation (2) where B represents the global dipolar field (B) in Tesla. Figures 4(a), 4(b), 4(c) and 4(d) represent the measurement points corresponding to each cell of the seven matrices together with the exponential fit.

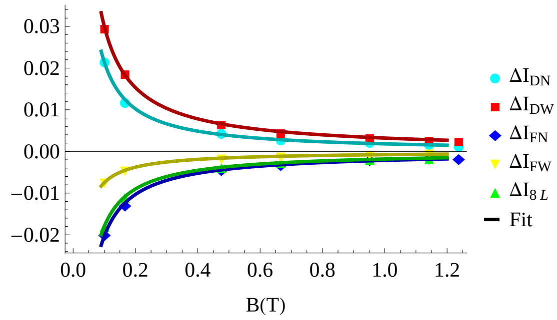
$$\frac{\Delta par_i}{\Delta I_j} = aB^b \qquad (2)$$

FINAL RESULTS

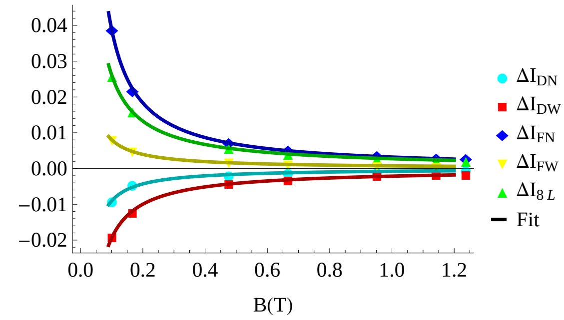
Table 3 presents the parameters a and b in (2) for each cell of the matrix.

Matrix cell	a	b
$\Delta Q_H \Delta I_{FN}$	34.99689	-1.07076
$\Delta Q_H \Delta I_{FW}$	24.64516	-0.97139
$\Delta Q_H \Delta I_{DN}$	-17.3456	-0.97714
$\Delta Q_H \Delta I_{DW}$	-17.4251	-0.99547
$\Delta Q_H \Delta I_{8L}$	-6.80339	-0.98612
$\Delta Q_V \Delta I_{FN}$	-15.2404	-1.07551
$\Delta Q_V \Delta I_{FW}$	-14.6549	-0.95949
$\Delta Q_V \Delta I_{DN}$	69.07055	-1.08337
$\Delta Q_V \Delta I_{DW}$	22.68724	-0.97956
$\Delta Q_V \Delta I_{8L}$	9.662390	-1.02653
$\Delta \xi_H \Delta I_{FN}$	1024.789	-1.03632
$\Delta \xi_H \Delta I_{FW}$	-15.9811	-0.76467
$\Delta \xi_H \Delta I_{DN}$	414.5541	-0.97748
$\Delta \xi_H \Delta I_{DW}$	-37.0519	-0.83247
$\Delta \xi_H \Delta I_{8L}$	0.015882	-0.40170
$\Delta \xi_V \Delta I_{FN}$	-626.882	-1.02394
$\Delta \xi_V \Delta I_{FW}$	865.5609	-1.30197
$\Delta \xi_V \Delta I_{DN}$	-613.057	-0.97968
$\Delta \xi_V \Delta I_{DW}$	560.6163	-1.12489
$\Delta \xi_V \Delta I_{8L}$	6.23 E+12	-5.26391

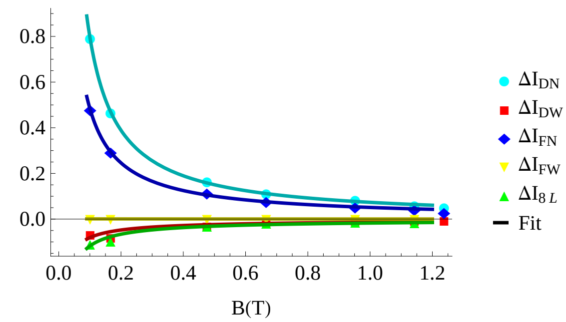
Table 3: Final matrix values.



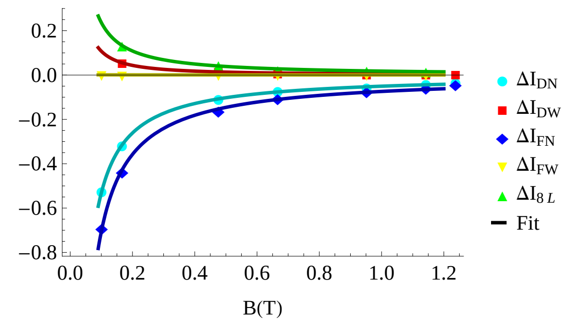
(a) $\Delta Q_h/\Delta I_j$.



(b) $\Delta Q_v/\Delta I_j$.



(c) $\Delta \xi_h/\Delta I_j$.



(d) $\Delta \xi_v/\Delta I_j$.

Figure 4: Physical parameters offset / circuits offets, as function of B-field.

Adjustment tools

The final resulting matrix is used by the adjustment software in two different ways. It used directly to estimate the offsets on physical parameters when PFW and 8L currents are adjusted.

On the other hand, the inverted matrix is used to calculate the offset to be applied on the PFW and the 8L currents for a given adjustment of one or more of the physical parameters. The strategy used at present is to fix one of the currents in order to obtain a 4×4 matrix.

OUTLOOK

The presented scheme is now fully operational and all working points for each beam accelerated in the PS are calculated using the obtained matrix. The configuration with five independent currents provides the means to control an additional parameter. (e.g, rms current in one of the power converters, Q''_h to minimize the detuning with amplitude, etc.)

Following the new control of the PS working point a high intensity beam was setup to be accelerated up to 26 GeV/c with minimum losses. The currents of each of the PFW and 8L circuits were fitted with a polynomial as a function of the magnetic field in order to obtain new initialization functions that require little adjustment to accelerate high intensity beams.

The working point up to approximately 4 GeV/c is presently controlled by dedicated quadrupoles, leaving the chromaticity to the natural value of about -1 in both planes. With the obtained tools it can now be envisaged to control the working point, tune and chromaticity, also at low energy using the PFWs and the 8L.

Imbalancing the narrow and wide windings seems to enhance the non-linear field components. A measurement campaing is required to determine if these non-linearities do not restrict the dynamical aperture.

REFERENCES

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