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PS-Booster Ejection Correction Dipoles: ppm-Operation at 1 and 1.4 GeV

M. Benedikt

Abstract

From 1999 the maximum ejection energy of the PS-Booster will be raised to 1.4 GeV in view of LHC operation. However, there are other clients who will continue to take a 1 GeV beam (e.g. ISOLDE). Therefore, the PS-Booster has to operate in ppm-mode between 1 and 1.4 GeV. This note describes the required modifications for ppm operation of the ejection correction dipoles. This system makes it possible to adjust the beam position and angle at the ejection septum independently for all four Booster rings.

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24. February 1999

Introduction

One problem inherent to the PS-Booster is that the closed orbits are generally different in all four rings. It is therefore necessary to seperately adjust the positions and angles of each of the four beams at the ejection septum. For this, two pairs of independently controlled dipoles (horizontal and vertical) are used in each ring. The design and specifications of the system and the choice of the positions for the correction magnets is described in detail in [1]. The main motivations for this note were the lack of up-to-date documentation and the fact that the values quoted in [1] are valid only for 800 MeV.

Principle of the method

For the adjustment of position and angle at a certain element in a circular machine at least two correction dipoles are required. A single dipole kick δ_1 leads to a change of the closed orbit at some reference position according to

$$(\Delta \mathrm{co}_{\mathrm{ref}})_1 = \mathrm{A}\delta_1 \quad \text{and} \quad (\Delta \mathrm{co}'_{\mathrm{ref}})_1 = \mathrm{C}\delta_1 \ , \tag{1}$$

where the constants A and C depend on the lattice. The effect of a second dipole kick δ_2 is described similarly,

$$(\Delta \mathrm{co}_{\mathrm{ref}})_2 = \mathrm{B}\delta_2 \quad \text{and} \quad (\Delta \mathrm{co}'_{\mathrm{ref}})_2 = \mathrm{D}\delta_2 \ . \tag{2}$$

The resulting total change of the closed obit is the superposition of (1) and (2) and is conveniently expressed in matrix-form as:

$$\begin{pmatrix} \Delta \mathrm{co}_{\mathrm{ref}} \\ \Delta \mathrm{co}'_{\mathrm{ref}} \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \cdot \begin{pmatrix} \delta_1 \\ \delta_2 \end{pmatrix} . \tag{3}$$

The effectiveness of such a correction, based on two dipole kicks, is dependent on the orthogonality of the kicks and it is an advantage to choose the locations of the two dipoles such that one changes mainly the position whereas the other changes mainly the angle.
It should be noted that such an orbit adjustment leads to a residual orbit distortion everywhere else in the machine. This is not the case when using a local four magnet bump.

Booster Ejection Dipoles - Geometry

In the PS-Booster, the adjustment of position and angle of the beam at the entrance to the ejection septum is performed with the correction dipoles located in Sections 4L1 and 11L1. Each dipole is used for horizontal (DHZ) and vertical (DVT) corrections. The exact locations of the dipole magnets (physical centre) are:

- BE.DHZ 4L1 and BE.DVT 4L1 — 426 mm upstream of centre 4L1.
- BE.DHZ 11L1 and BE.DVT 11L1 — 950 mm upstream of centre 11L1.

The reference position, where the correction is required, is the entrance to the horizontal ejection septum in Section 15L1:

- BE.SMH 15L1 — 800 mm upstream of centre 15L1.

For the further analysis, it is assumed that the horizontal and vertical tunes of the Booster at ejection are $Q_x = 4.17$ and $Q_z = 5.23$.

Figure 1 shows the horizontal closed-orbit distortions along the machine circumference resulting from a 1 mrad kick in the dipole BE.DHZ 4L1 (a), and from the same kick applied via the dipole magnet BE.DHZ 11L1 (b).

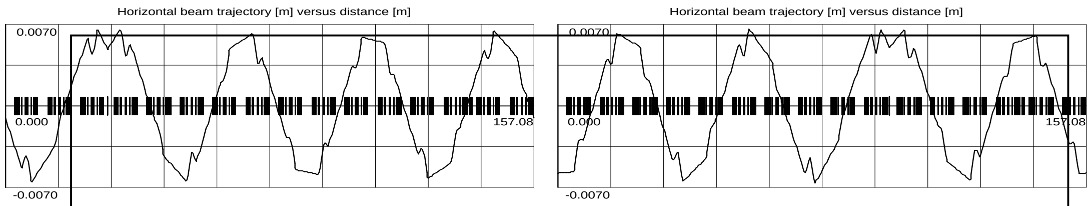

Figure 1: Horizontal closed-orbit distortion in the PS-Booster due to 1 mrad dipole kicks of BE.DHZ 4L1 (a) and BE.DHZ 11L1 (b)

The geometrical relations between the kicks in Section 4L1 or 11L1 and the resulting horizontal orbits at the entrance to the ejection septum are:

<u>Kick 4L1</u>: $\Delta x_{ES}[\text{mm}] = 0.760 \cdot \text{DHZ 4L1}[\text{mrad}]$, $\Delta x'_{ES}[\text{mrad}] = 0.947 \cdot \text{DHZ 4L1}[\text{mrad}]$ (4)

<u>Kick 11L1</u>: $\Delta x_{ES}[\text{mm}] = 5.615 \cdot \text{DHZ 11L1}[\text{mrad}]$, $\Delta x'_{ES}[\text{mrad}] = 0.104 \cdot \text{DHZ 11L1}[\text{mrad}]$ (5)

Inspection of Figure 1 and Equations (4, 5) shows that a horizontal kick, applied in Section 4L1, changes mainly the angle of the closed orbit at the ejection septum and leaves the position unchanged, whereas it is just the opposite for a kick applied in Section 11L1.
Figure 2 shows the vertical closed-orbit distortions along the machine circumference resulting from a 1 mrad kick in the dipole BE.DVT 4L1 (a), and from the same kick applied via the dipole magnet BE.DVT 11L1 (b).

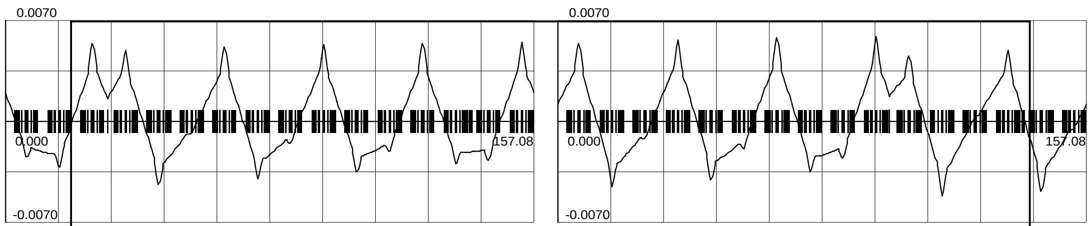

Figure2: Vertical closed-orbit distortion in the PS-Booster due to 1 mrad dipole kicks of BE.DVT 4L1 (a) and BE.DVT 11L1 (b).

The effects of these kicks on the vertical orbit at the ejection septum are found to be:

<u>Kick 4L1</u>: $\Delta z_{ES}[\text{mm}] = -2.122 \cdot \text{DVT 4L1}[\text{mrad}]$, $\Delta z'_{ES}[\text{mrad}] = 0.021 \cdot \text{DVT 4L1}[\text{mrad}]$ (6)

<u>Kick 11L1</u>: $\Delta z_{ES}[\text{mm}] = 0.669 \cdot \text{DVT 11L1}[\text{mrad}]$, $\Delta z'_{ES}[\text{mrad}] = -0.793 \cdot \text{DVT 11L1}[\text{mrad}]$ (7)

It can be seen that, in the vertical plane, the dipole magnet BE.DVT 4L1 is mainly responsible for a position change at the ejection septum whereas the magnet BE.DVT 11L1 affects the angle.
The overall effect of each pair of dipoles on the horizontal and vertical orbits at the ejection septum can now be calculated by adding Equations (4), (5) and Equations (6)

and (7) respectively. The horizontal and vertical orbits at the septum can then be written as a function of the kicks applied by the dipoles in matrix form:

Horizontal Orbit:
$$\boxed{\begin{pmatrix} \Delta x_{ES}\ [\mathrm{mm}] \\ \Delta x'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} 0.7600 & 5.6150 \\ 0.9470 & 0.1040 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DHZ\ 4L1[mrad]} \\ \mathrm{DHZ\ 11L1[mrad]} \end{pmatrix}.} \tag{8}$$

Vertical Orbit:
$$\boxed{\begin{pmatrix} \Delta z_{ES}\ [\mathrm{mm}] \\ \Delta z'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} -2.1220 & 0.6690 \\ 0.0210 & -0.7930 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DVT\ 4L1[mrad]} \\ \mathrm{DVT\ 11L1[mrad]} \end{pmatrix}.} \tag{9}$$

Equations for control and acquisition:

The matrix-equations (8, 9) give the geometrical relations between the horizontal and vertical closed orbits at the ejection septum and the kicks applied via the ejection dipoles. However, for the control of the power supplies and also for the acquisition, the deflection of each dipole magnet has to be expressed in terms of its current. All the ejection dipoles are of the same physical type and therefore a single factor describes the deflection as a function of the current for all of them (at a fixed energy). From 1999 onwards, the PS-Booster will be operated in ppm-mode with ejection energies of 1 and 1.4 GeV. Due to the different beam-rigidity, the relation between deflection and current will be a function of the beam energy. The factor quoted in [1] was valid for 800 MeV operation and has to be scaled with the beam rigidities for 1 and 1.4 GeV according to

$$(\mathrm{mrad/A})_{E1} = \frac{(B\rho)_{E0}}{(B\rho)_{E1}} (\mathrm{mrad/A})_{E0} \ .$$

Table 1 lists the beam rigidities and deflection-per-current-factors for the relevant ejection energies.

Energy [GeV]	**Magnetic Rigidity [Tm]**	**Deflection/Current [mrad/A]**
0.8	4.881	0.165
1.0	5.657	0.142
1.4	7.144	0.113

Table 1: Deflection-per-current for the ejection dipoles as function of beam energy.

Equations (8, 9) can now be rewritten with the currents on the right-hand side by multiplying the matrix-elements with the factors quoted in Table1.

$$\left.\begin{array}{ll} 0.8\ \mathrm{GeV\ (hor.)}: & \begin{pmatrix} \Delta x_{ES}\ [\mathrm{mm}] \\ \Delta x'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} 0.1254 & 0.9265 \\ 0.1563 & 0.0172 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DHZ\ 4L1[A]} \\ \mathrm{DHZ\ 11L1[A]} \end{pmatrix} \\ 1.0\ \mathrm{GeV\ (hor.)}: & \begin{pmatrix} \Delta x_{ES}\ [\mathrm{mm}] \\ \Delta x'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} 0.1082 & 0.7993 \\ 0.1348 & 0.0148 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DHZ\ 4L1[A]} \\ \mathrm{DHZ\ 11L1[A]} \end{pmatrix} \\ 1.4\ \mathrm{GeV\ (hor.)}: & \begin{pmatrix} \Delta x_{ES}\ [\mathrm{mm}] \\ \Delta x'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} 0.0857 & 0.6330 \\ 0.1068 & 0.0117 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DHZ\ 4L1[A]} \\ \mathrm{DHZ\ 11L1[A]} \end{pmatrix} \end{array}\right\} \tag{10}$$

$$0.8\ \mathrm{GeV\ (vert.)}: \quad \begin{pmatrix} \Delta z_{ES}\ [\mathrm{mm}] \\ \Delta z'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} -0.3501 & 0.1104 \\ 0.0035 & -0.1308 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DVT\ 4L1[A]} \\ \mathrm{DVT\ 11L1[A]} \end{pmatrix}$$

$$\left.\begin{array}{ll}
\text{1.0 GeV (vert.):} & \begin{pmatrix} \Delta z_{ES}\ [\mathrm{mm}] \\ \Delta z'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} -0.3021 & 0.0952 \\ 0.0030 & -0.1129 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DVT\,4L1[A]} \\ \mathrm{DVT\,11L1[A]} \end{pmatrix} \\[2ex]
\text{1.4 GeV (vert.):} & \begin{pmatrix} \Delta z_{ES}\ [\mathrm{mm}] \\ \Delta z'_{ES}\ [\mathrm{mrad}] \end{pmatrix} = \begin{pmatrix} -0.2392 & 0.0754 \\ 0.0024 & -0.0894 \end{pmatrix} \cdot \begin{pmatrix} \mathrm{DVT\,4L1[A]} \\ \mathrm{DVT\,11L1[A]} \end{pmatrix}
\end{array}\right\} \quad (11)$$

Equations (10, 11) are used for the acquisition of the position/angle correction of the horizontal and vertical closed orbits at the ejection septum. The inputs are the acquisition values of the currents in the correction dipoles.

For the control of the power supplies, Equations (10, 11) have to be rewritten such that the wanted position/angle corrections act as input on the right-hand-side. This is done by matrix inversion and gives for the horizontal control-equations (12):

$$\left.\begin{array}{ll}
\text{0.8 GeV (hor.):} & \begin{pmatrix} \mathrm{DHZ\,4L1[A]} \\ \mathrm{DHZ\,11L1[A]} \end{pmatrix} = \begin{pmatrix} -0.1203 & 6.4964 \\ 1.0956 & -0.8793 \end{pmatrix} \cdot \begin{pmatrix} \Delta x_{ES}\ [\mathrm{mm}] \\ \Delta x'_{ES}\ [\mathrm{mrad}] \end{pmatrix} \\[2ex]
\text{1.0 GeV (hor.):} & \begin{pmatrix} \mathrm{DHZ\,4L1[A]} \\ \mathrm{DHZ\,11L1[A]} \end{pmatrix} = \begin{pmatrix} -0.1395 & 7.5296 \\ 1.2699 & -1.0191 \end{pmatrix} \cdot \begin{pmatrix} \Delta x_{ES}\ [\mathrm{mm}] \\ \Delta x'_{ES}\ [\mathrm{mrad}] \end{pmatrix} \\[2ex]
\text{1.4 GeV (hor.):} & \begin{pmatrix} \mathrm{DHZ\,4L1[A]} \\ \mathrm{DHZ\,11L1[A]} \end{pmatrix} = \begin{pmatrix} -0.1761 & 9.5085 \\ 1.6037 & -1.2870 \end{pmatrix} \cdot \begin{pmatrix} \Delta x_{ES}\ [\mathrm{mm}] \\ \Delta x'_{ES}\ [\mathrm{mrad}] \end{pmatrix}.
\end{array}\right\} \quad (12)$$

In the same way the vertical control-equations (13) are derived:

$$\left.\begin{array}{ll}
\text{0.8 GeV (vert.):} & \begin{pmatrix} \mathrm{DVT\,4L1[A]} \\ \mathrm{DVT\,11L1[A]} \end{pmatrix} = \begin{pmatrix} -2.8801 & -2.4298 \\ -0.0763 & -7.7070 \end{pmatrix} \cdot \begin{pmatrix} \Delta z_{ES}\ [\mathrm{mm}] \\ \Delta z'_{ES}\ [\mathrm{mrad}] \end{pmatrix} \\[2ex]
\text{1.0 GeV (vert.):} & \begin{pmatrix} \mathrm{DVT\,4L1[A]} \\ \mathrm{DVT\,11L1[A]} \end{pmatrix} = \begin{pmatrix} -3.3382 & -2.8162 \\ -0.0884 & -8.9328 \end{pmatrix} \cdot \begin{pmatrix} \Delta z_{ES}\ [\mathrm{mm}] \\ \Delta z'_{ES}\ [\mathrm{mrad}] \end{pmatrix} \\[2ex]
\text{1.4 GeV (vert.):} & \begin{pmatrix} \mathrm{DVT\,4L1[A]} \\ \mathrm{DVT\,11L1[A]} \end{pmatrix} = \begin{pmatrix} -4.2155 & -3.5564 \\ -0.1116 & -11.2804 \end{pmatrix} \cdot \begin{pmatrix} \Delta z_{ES}\ [\mathrm{mm}] \\ \Delta z'_{ES}\ [\mathrm{mrad}] \end{pmatrix}.
\end{array}\right\} \quad (13)$$

Coefficients for LINC modules

In the control system of the PS-Booster, the control of the ejection dipoles is performed via equipment-modules called LINC. Such a module allows the control and acquisition of up to four power supplies in a way that is similar to that described above. However, in the case of the Booster ejection dipoles only a single pair of power supplies is controlled by one module. The information that needs to be provided for LINC is basically the matrix coefficients of the control (12, 13) and acquisition-equations (10, 11).

The control coefficients (matrix coefficients of Equations 12 and 13) are stored in ADR1 of LINC, the acquisition coefficients (matrix coefficients of Equations 10, 11) in ADR2. Both ADR1 and ADR2 consist of 16 coefficients but only the first four are non-zero in the case of the Booster ejection dipoles (due to the fact that only two power supplies need to be controlled).

Writing the coefficients in LINC ADR1 as ADR1:={ L1, L2, L3, L4, L5,..., L15, L16} and the matrices in the control-equations (12, 13) in the form: $C = \begin{pmatrix} c1 & c2 \\ c3 & c4 \end{pmatrix}$,

gives the following relations between the coefficients in ADR1 and the control-equations (12,13):

$$L1 \equiv c3,\ \ L2 \equiv c4,\ \ L3 \equiv c1,\ \ L4 \equiv c2 \qquad (14)$$

Table 2 contains the coefficients for LINC ADR1 (control of the ejection dipoles) which are found via the relation (14) and Equations (12, 13) [†].

LINC ADR1 horizontal					**LINC ADR1 vertical**			
	0.8 GeV	**1.0 GeV**	**1.4 GeV**			**0.8 GeV**	**1.0 GeV**	**1.4 GeV**
L1	1.0956	1.2699	1.6037		L1	-0.0763	-0.0884	-0.1116
L2	-0.8793	-1.0191	-1.287		L2	-7.7070	-8.9328	-11.2804
L3	-0.1203	-0.1395	-0.1761		L3	-2.8801	-3.3382	-4.2155
L4	6.4964	7.5296	9.5085		L4	-2.4298	-2.8162	-3.5564
L5 - L16	0	0	0		L5 - L16	0	0	0

Table 2: Coefficients for LINC ADR1 (horizontal/vertical ejection dipole control) as function of beam energy

Writing the coefficients in ADR2 as ADR2:={L1*,L2*,L3*,L4*,L5*,....,L15*,L16*}

and the matrices in the acquisition-equations (10, 11) in the form: $C^* = \begin{pmatrix} c1^* & c2^* \\ c3^* & c4^* \end{pmatrix}$,

gives the following relations between the coefficients in ADR2 and the acquisition-equations (10,11):

$$L1^* \equiv c2^*,\ \ L2^* \equiv c1^*,\ \ L3^* \equiv c4^*,\ \ L4^* \equiv c3^*. \qquad (15)$$

Table 3 contains the coefficients for LINC ADR1 (acquisition of the ejection dipoles) which are found via the relation (15) from Equations (10, 11) [†].

LINC ADR2 horizontal					**LINC ADR2 vertical**			
	0.8 GeV	**1.0 GeV**	**1.4 GeV**			**0.8 GeV**	**1.0 GeV**	**1.4 GeV**
L1*	0.9265	0.7993	0.6330		L1*	0.1104	0.0952	0.0754
L2*	0.1254	0.1082	0.0857		L2*	-0.3501	-0.3025	-0.2392
L3*	0.0172	0.0148	0.0117		L3*	-0.1308	-0.1129	-0.0894
L4*	0.1563	0.1348	0.1068		L4*	0.0035	0.0030	0.0024
L5*-L16*	0	0	0		L5*-L16*	0	0	0

Table 3: Coefficients for LINC-ADR2 (horizontal/vertical ejection dipole acquisition) as function of beam energy

[†] It should be noted that the relations ($L1 \equiv c3$, $L2 \equiv c4$, $L3 \equiv c1$, $L4 \equiv c2$) mean that LINC ADR1 performs exactly the algebra of the control-equations (12, 13), but with the two power supplies exchanged. This reflects itself in an exchange of the matrix rows in (12, 13). The same argumentation applies for LINC ADR2 and the acquisition-equations (10, 11); it is straightforward to show that in this case the matrix columns in (10, 11) have to be exchanged.

Modifications in LINC for ppm-operation:

In total there are 8 pairs of ejection dipoles in the PS-Booster (one pair horizontal and one pair vertical per ring, 4 rings). Each of these is controlled via a LINC module. Up to now, the Booster ejection dipoles were operated in non-ppm mode. Therefore the arrays ADR1 and ADR2 in LINC were of the dimension {1 x 16} to store the control and acquisition coefficients for one specific ejection energy (see Tables 2, 3). These coefficients were then valid for all the 24 PSB-users.
In order to permit ppm-operation between 1 and 1.4 GeV, a third dimension will be added to ADR1 and ADR2 resulting in an array size {1 x 16 x 24}. This makes it possible to define specific control and acquisition coefficients for every single PSB-user out of the 24. However, it should be noted that all 1 GeV users will use the same coefficients and the same is true for all 1.4 GeV users.

Historical remarks:

It is interesting to note that the control/acquisition-equations (10 to 13) had to be scaled when the extraction energy of the PS-Booster was raised from 800 MeV to 1.0 GeV in 1986. At that time, the scaling of both control and acquisition matrices was made in the wrong direction. This means that corrections applied by the operating team were in fact reduced by 26 % in strength. The acquisition, however, was hiding this problem since the incorrect scaling in the acquisition-equations just canceled the error introduced by the wrong control-equations.

Acknowledgements:

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References:

[1] J.P.Delahaye, *Ajustment individuel par anneau de l' orbite fermee a l' ejection*, PS/BR Note/77-19, 1977.

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