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PROPOSAL FOR A QUADRUPOLE CORRECTION MAGNET IN THE BOOSTER RECOMBINATION SECTION

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Abstract

The vertical recombination of the four PS-Booster rings results in small differences in the optics for the four rings. These differences are due to the edge-focusing of the vertical bending magnets. The predicted emittance blow-up in the PS due to these optical differences is about 5 %, depending on which ring is being considered.
Up to now, no correction elements have been required, since the resulting inter-ring mismatch was not considered as being significant. However, in view of LHC operation it is desirable to minimise all possible sources of beam blow-up. In this note, a quadrupole correction magnet, to reduce the above effects, is proposed. With this relatively simple solution, the emittance blow-up can be decreased to about 1 %. A magnet design and cost estimate are presented.

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Introduction

The PS-Booster consists of four identical synchrotrons that are stacked on top of each other with a vertical spacing of 36 cm. After ejection, the beams from the four rings are recombined at the level of the PS which is the level of the Booster ring III. The recombination geometry, including the main vertical bending elements, is shown schematically in Figure 1. The three fast kicker magnets (BT1.KFA10, BT4.KFA10, BT.KFA20) have a negligible effect on the optics due to their small bending angle and are not considered further.

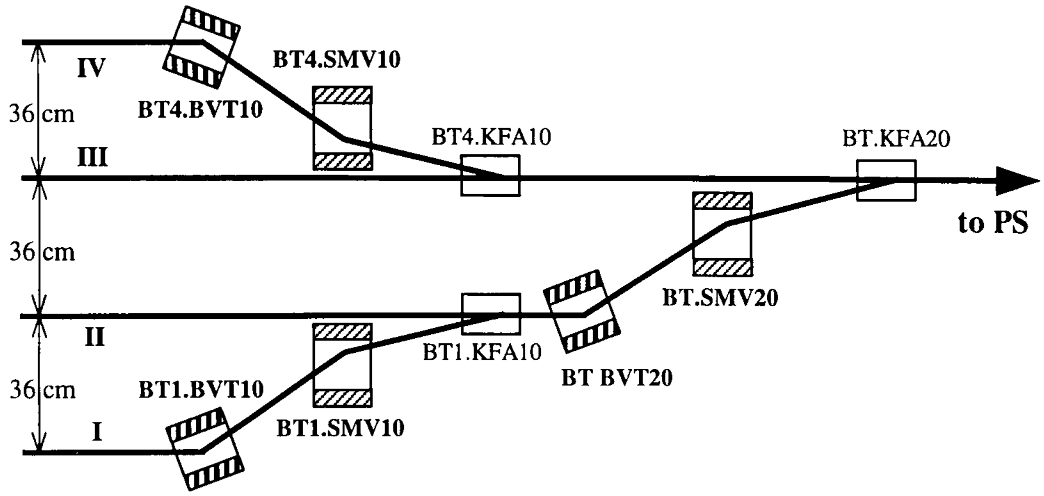

Figure 1: Vertical recombination geometry of the four Booster rings.

The recombination results in small differences in the Twiss functions for the beams coming from the four rings [1]. These differences are due to edge-focusing effects in the vertical bending (BT1.BVT10, BT4.BVT10 and BT.BVT20) and septum magnets (BT1.SMV10, BT4.SMV10 and BT.SMV20). These elements are built as rectangular magnets and thus act as focusing elements in the horizontal plane while being transparent for the vertical plane. As a result, the horizontal Twiss and dispersion functions for the beams from the four rings are different at injection to the PS, which consequently leads to a mismatch and emittance blow-up.

Optical functions

Figure 2 shows the Twiss functions in the recombination section for the beam coming from ring I with the positions of the vertical bending and septum magnets. As already mentioned, the optical functions for the other rings are almost identical apart from the small perturbations due to the edge-focusing. The edge-focusing effect at the entry or exit of a vertically deflecting magnet perturbs the Twiss-functions in the horizontal plane at a point "1" downstream from the considered element "0" according to

$$\begin{pmatrix} \Delta\beta/\beta \\ \Delta\alpha - \alpha\cdot\Delta\beta/\beta \end{pmatrix}_1 = \beta_0 \cdot \begin{pmatrix} \sin(2\Delta\mu) \\ \cos(2\Delta\mu) \end{pmatrix} \cdot \frac{\tan(\varphi)}{\rho}, \qquad (1)$$

where ρ is the bending radius of the element considered, φ is the edge angle and $\Delta\mu$ is the phase advance between the edge focusing element and the downstream position*.

* It should be noted that in general there will be two contributions, one for the entry and another one for the exit of the magnet.

As can be seen from (1), the perturbation is proportional to the beta-function at the bending magnet. In the Booster recombination line, all relevant elements have approximately the same ρ. The sum of the edge focusing from entry and exit is also roughly identical for all the magnets. So the size of the resulting error depends mainly on the local horizontal beta-functions at the single magnets. Inspection of Figure 2 shows that the largest perturbation is therefore introduced by the magnet BT.BVT20.

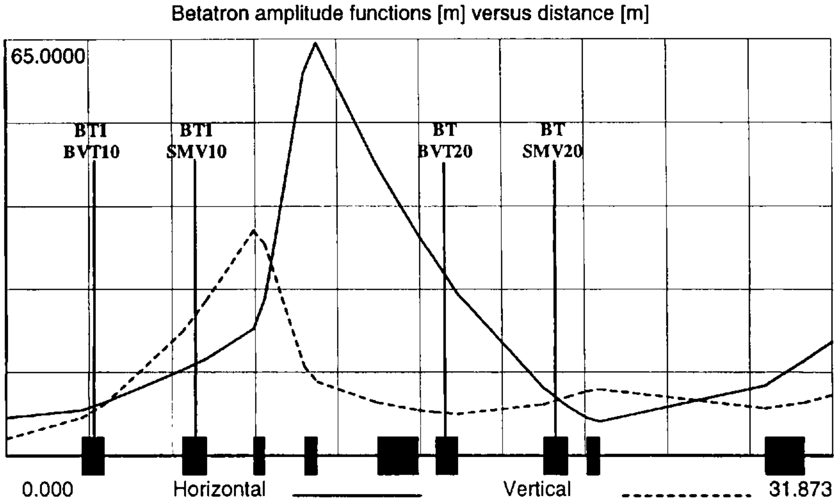

Figure 2: Twiss functions in the recombination section for the beam ejected from ring I.

The betatron mismatch can be corrected with a quadrupole magnet. The action of a quadrupole is described with an equation similar to (1) by replacing the edge focusing term $(\tan\varphi)/\rho$ by the integrated gradient kl,

$$\begin{pmatrix} \Delta\beta/\beta \\ \Delta\alpha-\alpha\cdot\Delta\beta/\beta \end{pmatrix}_1 = \pm\beta_0\cdot\begin{pmatrix} \sin(2\Delta\mu) \\ \cos(2\Delta\mu) \end{pmatrix}\cdot kl\,, \qquad (2)$$

where the sign depends on the plane that is considered.
Since a quadrupole affects both planes, unlike a bending magnet with edge focusing, there will be an unwanted effect in the vertical plane. The choice of the corrector position should be optimised by two criteria:

- The perturbation propagates with twice the betatron phase advance along the transfer line (cf. Equation 1), thus correctors should be placed at multiples of $\pi/2$ in phase downstream of the perturbation.
- To maximise the correction while keeping the unwanted effect in the vertical plane small, the beta-function in the horizontal plane should be large while the vertical one should be small.

Correction of Booster recombination scheme

The geometry of the Booster recombination section has a certain symmetry. This allows the problem to be separated into two parts (cf. Figure 1). The first part consists of the edge effects introduced by BT1.BVT10, BT1.SMV10 (ring I) and symmetrically BT4.BVT10, BT4.SMV10 (ring IV), the second part concerns the perturbations of BT.BVT20 and BT.SMV20 (rings I and II). Whatever the case, the correction element would have to be placed upstream of the relevant septum magnet, where the beams can still be acted on separately.

Corrections for BT1.BVT10, BT1.SMV10 and BT4.BVT10, BT4.SMV10:

The edge focusing of these magnets affects the beams coming from rings I and IV. However, no corrections have been foreseen for the reasons quoted below:

- The horizontal beta-functions at the locations of BT1.BVT10, BT1.SMV10 and BT4.BVT10, BT4.SMV10 are relatively small, thus the mismatch due to the edge-focusing is also small (see Figure 2 and Equation 1).
- Figure 2 shows that the horizontal and vertical beta-functions upstream of the septum magnets BT1.SMV10 and BT4.SMV10 are de-facto identical, thus a correction quadrupole for the horizontal plane would introduce a large unwanted perturbation in the vertical plane.
- Due to a lack of physical space upstream of the septum magnets, the simple addition of a correction quadrupole is not possible.

Correction for BT.BVT20 and BT.SMV20:

The edge focusing of these magnets affects the beams coming from rings I and II. In this case a correction is proposed for the following reasons:

- The horizontal beta-function at the BT.BVT20 is large compared to all other relevant elements (see Fig 2 and Equation 1), therefore this element creates the largest mismatch.
- An element-free straight section in between BT.BVT20 and BT.SMV20 provides space for the installation of a correction element.
- Due to the large horizontal beta-function the phase advance is slow in the vicinity of BT.BVT20 and therefore a corrector adjacent to this magnet is positioned ideally according to the phase considerations above.
- From Figure 2 it can be also seen that the vertical beta-function is small at the position considered, so that a corrector would act mainly on the horizontal plane as desired.

Estimation of correction efficiency

Assuming that ring III is matched perfectly to the PS, the horizontal rms-emittance blow-up due to the betatron mismatch of the other 3 rings can be calculated from

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{1}{2}\cdot\frac{\beta}{\beta+\Delta\beta}\begin{pmatrix}\Delta\beta/\beta \\ \Delta\alpha-\alpha\cdot\Delta\beta/\beta\end{pmatrix}^{T}\begin{pmatrix}\Delta\beta/\beta \\ \Delta\alpha-\alpha\cdot\Delta\beta/\beta\end{pmatrix}, \tag{3}$$

where α and β are the Twiss parameters at a given point in the machine and $\Delta\alpha$ and $\Delta\beta$ are the deviations from these values [2]. The calculated rms emittance blow-up $\Delta\varepsilon/\varepsilon$ for all rings is quoted in Table 1.

To determine the best position and optimum strength for the correction quadrupole acting on rings I and II, a numerical matching was performed with WinAgile [3]. As a result, the best position was found to be just downstream of BT.BVT20, with a normalised integrated correction gradient of $kl = 0.011\ \mathrm{m}^{-1}$. The residual blow-up after correction is summarised in Table 2. It should be mentioned that a more equal distribution of the remaining errors between inner (II, III) and outer (I and IV) rings can be achieved with the quadrupole magnets in the common part of the lines. This would result in a horizontal emittance blow-up of about 0.3 % for all rings.

To illustrate the usefulness of the proposed correction, the horizontal emittance blow-up due to the mismatch has been compared to an equivalent injection steering error (position only) for the nominal LHC-beam ($\varepsilon_{rms} = 1.1\ \pi\ \mu m$) at the injection point of the PS (60 cm downstream the quadrupole BTP.QNO60, with $\beta = 23.8$ m and $\alpha = 1.53$). For such a comparison, it should be remembered that a betatron-mismatch causes a fractional emittance blow-up, independent of the absolute emittance value, whereas a steering error causes a blow-up depending on the initial emittance according to

$$\frac{\Delta\varepsilon}{\varepsilon} = \frac{1}{2\cdot\varepsilon}\begin{pmatrix} \Delta x/\sqrt{\beta} \\ \Delta x'\sqrt{\beta} + \alpha\cdot\Delta x/\sqrt{\beta} \end{pmatrix}^T \begin{pmatrix} \Delta x/\sqrt{\beta} \\ \Delta x'\sqrt{\beta} + \alpha\cdot\Delta x/\sqrt{\beta} \end{pmatrix}, \tag{4}$$

where Δx, $\Delta x'$ and α, β are the steering errors and the horizontal Twiss functions at the injection point.

	Ring 1	Ring 2	Ring 3	Ring 4
Blow-up horiz.	5.2 %	3.0 %	0 %	0.9 %
Blow-up vert.	0.0 %	0.0 %	0 %	0.0 %

Table 1: Horizontal rms emittance blow-up without correction quadrupole.

	Ring 1	Ring 2	Ring 3	Ring 4
Blow-up horiz.	1.0 %	0.0 %	0 %	0.9 %
Blow-up vert.	0.2 %	0.3 %	0 %	0.0 %

Table 2: Emittance blow-up with the proposed correction quadrupole.

	Ring I	Ring II	Ring III	Ring IV
Before correction.	0.9 mm	0.7 mm	0 mm	0.4 mm
After correction	0.4 mm	0.0 mm	0 mm	0.4 mm

Table 3: Equivalent horizontal position error for LHC nominal beam at injection point with and without quadrupole corrector.

From Table 3 it can be seen that the present situation with the uncorrected mismatch results in an emittance blow-up for ring I of the LHC beam that is equivalent to an injection steering error of 0.9 mm. This error can be reduced by the proposed correction down to an equivalent of 0.4 mm, which is of the order of the maximum tolerable injection mis-steering between the four rings [4]. It should be noted, that a position error of 0.9 mm at the injection point (uncorrected situation) causes a coherent oscillation with an amplitude of 1.7 mm seen by the PS trajectory measurement system (CODD).

Dispersion functions

The differences in the horizontal dispersion functions due to the edge focusing are negligible both before and after correction. The vertical bending magnets create a finite vertical dispersion at injection to the PS ($D_{z,max} = 38$ cm occurring in ring 2). However, the emittance blow-up due to this is less than 1 % for the LHC beam described above.

Magnet design

The magnet yoke is built laminated to enable pulsed operation. As the required field levels are low and the field in the return yoke is far from saturation, standard transformer steel (Si steel) of thickness 0.7 mm can be used. The yoke is built from two halves and can be separated. This has the advantage that no vacuum intervention is necessary for the installation.

The pole profile has a hyperbolic central part, followed by a straight line that is a tangent to the hyperbola and a radius as transition to the coil window. The linear part acts as shim to adjust the transverse gradient homogeneity. It is dimensioned so that the central field compensates the transverse fall off of the gradient of the end field.

The coils can be built air cooled. Due to the low field levels in the yoke, the poles can be built non-tapered and consequently the coils have a racetrack shape which is the simplest and cheapest coil type.

Table 4 lists the magnetic and yoke characteristics. The required normalised integrated correction gradient of $kl = 0.011\ m^{-1}$ corresponds to an $\int Gdl$ of about 0.079 Tm/m at 1.4 GeV. The gradient for an aperture of 104 mm diameter and an iron length of 200 mm (effective length 236 mm) is about 0.33 T/m.

Magnet characteristics	
G	0.33 T/m
$\int Gdl$	0.079 Tm/m
Aperture diameter	104 mm
Iron length	200 mm
Effective length	236 mm
Total length	280 mm
Total width	320 mm
Total height	330 mm

Table 4: Magnet and yoke characteristics of the proposed correction quadrupole.

The coil design (see Table 5) has been studied for different conductor cross sections. The solution best adapted to an existing power supply (see below) can be chosen. As the magnet yoke is laminated, pulsed operation is possible. However, the heat-up of the coils is low enough so that the magnet could deliver the required correction gradient even in DC mode. The current quoted in Table 5 corresponds to the nominal gradient of 0.33 T/m.

Coil characteristics			
Parameter	**Version 1**	**Version 2**	**Version 3**
I_{nom} (G =0.33 T/m)	6.4 A	4.5 A	3.3 A
R at 20 °C	0.50 Ω	1.27 Ω	2.70 Ω
L	22 mH	45 mH	82 mH
Conductor height	1.5 mm	1.0 mm	0.8 mm
Conductor width	3.5 mm	3.0 mm	2.5 mm
Layers	8	10	12
Turns per layer	7	8	9
ΔT (DC-operation)	14 ° C	18 ° C	21 ° C

Table 5: Coil characteristics of the proposed correction quadrupole.

A specification and specification drawings have been prepared [5]. Figure 3 shows side view and end view of the magnet assembly, taken from the specification drawings.

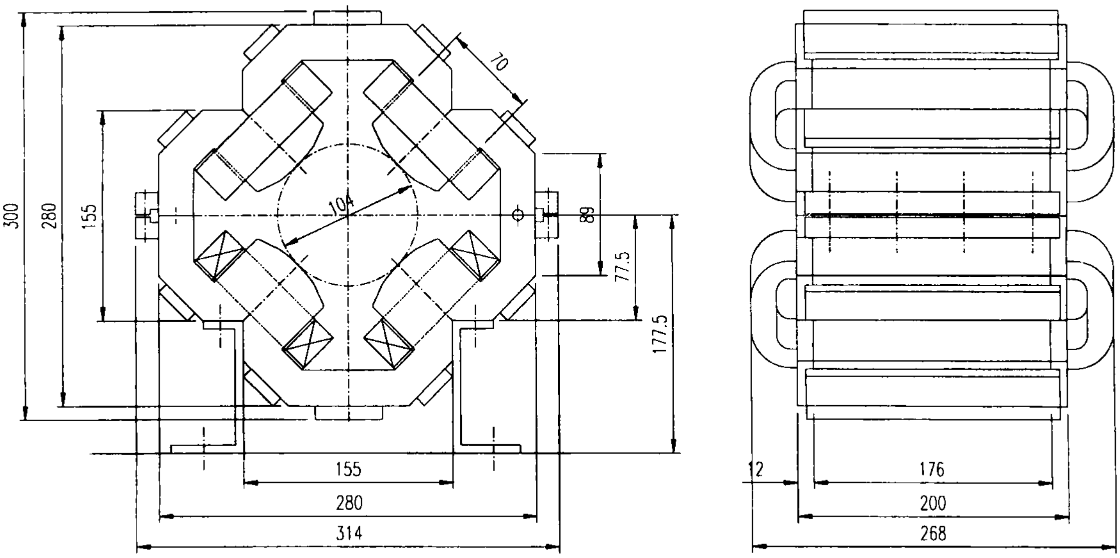

Figure 3: Side and front view of the proposed corrector quadrupole.

Power supply and control

The power supply foreseen for the correction quadrupole is of the type "capacitive discharge" and should allow ppm-operation. Presently, power supplies with similar requirements are being developed at CERN for the dipole correction magnets in the BTP line [6]. In order to avoid extra development cost it is foreseen to use such a supply. For this, the coil design version 2 (see Table 5) is best suited, resulting in the power supply parameters summarised in Table 6. As can be seen, the safety margin for the current (gradient) is about 30 %.

Power supply parameters	
load inductance (coil vers.2)	45 mH
load resistance (coil vers.2)	1.27 Ω
capacitance	200 μF
rise time (1/4 period)	5 ms
resonance frequency	50 Hz
max. voltage	100 V
max. current	6 A

Table 6: Power supply parameters (cf. coil version 2 in Table 5).

The control card mil1553 is included in the power supply chassis. Therefore, no additional cost is to be foreseen for controls, provided the power supply is located in the vicinity of the new supplies for the BTP-line correction dipoles.

Cost estimate

An approximate cost estimate for the construction and installation of the proposed quadrupole correction magnet and the power supply is given in Table 7 below.

Cost estimate	
part/unit	estimated cost CHF
magnet	13,000
magnet toolings	5,000
study support [7]	5,000
support [7]	10,000
power supply [6]	9,000
power supply installation [6]	2,000
cabling [8]	1,800
total	**45,800**

Table 7: Cost estimate for the correction quadrupole.

Conclusions

In this note, a solution for the correction of the mismatch between the PS-Booster rings at injection to the PS is proposed. It consists of a quadrupole correction magnet with power supply and control equipment. The cost of the whole arrangement would be approximately 46,000 CHF and it should reduce the rms emittance blow-up due to the inter-ring mismatch from 5 % to 1 %.

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References:

[1] A.Jansson, M.Lindroos, M.Martini, K.Schindl, *Study of emittance blow-up sources between the PS-Booster and the 26 GeV PS*, Proc. of EPAC 98, Stockholm, 1998.

[2] D.A.Edwards, M.J.Syphers, *An Introduction to the Physics of High Energy Accelerators,* ISBN: 0-471-55163-5, Wiley, 1993.

[3] P.Bryant, *WinAgile, a program for the design of alternating gradient lattices,* http://nicewww.cern.ch/~bryant

[4] G.R.Lambertson, *Summary of the working group on emittance control,* Particle Accelerators, Vol. 58, 33-38, 1997.

[5] SL/Spec, *A corrector quadrupole for the PSB-CPS transfer line,* to be issued.

[6] J.-M. Cravero and J.P. Royer, *private communication.*

[7] P.Bourquin, *private communication.*

[8] H. Friedel, *private communication.*

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