A NOVEL ALIGNMENT PROCEDURE FOR THE FINAL FOCUS OF FUTURE LINEAR COLLIDERS

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Abstract

An algorithm for the simultaneous optimization of orbit, dispersion, coupling and beta-beating in the final focus of future linear colliders is presented. Based on orbit and dispersion measurements the algorithm determines the optimal corrector settings in order to simultaneously minimize the r.m.s orbit, the r.m.s dispersion, the r.m.s coupling, the r.m.s. beta-beating and the r.m.s strength of the dipoles correctors. A number of different options for error handling of beam position monitors, weighting, and correction have been introduced to ensure the stability of the algorithm. A sextupole tuning procedure is also applied to further optimize the beam parameters at the interaction point. Preliminary results for the beam delivery systems of CLIC are presented.

INTRODUCTION

Static element misalignments and unwanted beam position monitor offsets induce emittance dilution that can severely reduce the performances of a linear collider. Emittance blow up due to such causes is traditionally cured using beam-based alignment techniques. During the last decades several beam-based alignment techniques, such as 1-to-1 correction and dispersion free steering, have been studied and have been successfully applied to linacs and rings (see for instance [1] and [2]). Nevertheless, the situation is somehow more complicated in the final focus systems of the next generation of linear colliders. Two reasons justify this increased difficulty: the strongly non-linear behavior of the system, due to multipolar magnetic fields (sextupoles, octupoles), and the synchrotron radiation emission from the strong quadrupoles and sextupoles in the beamline. Although extensive experience on final focus alignment has been gained at SLC [3, 4], the tiny beamsize at the interaction point of future linear colliders (more than three orders of magnitude smaller than at SLC) require the development of new more sophisticated algorithms, such as the one presented in this paper.

THE ALIGNMENT PROCEDURE

The alignment procedure presented in this paper proceeds in four steps subdivided in three phases. The first phase, when the beam trajectory is supposedly very far from the ideal orbit, is run with multipolar magnets switched off. This allows to avoid complicated non-linear behaviors in the beam dynamics. In this phase, a step of 1-to-1 correction and a step of dispersion free steering are applied. The second phase, that constitutes the third step of the alignment procedure, tries to center each multipole magnets with respect to the beam orbit. In this phase each multipolar magnet is individually powered and it's aligned using a technique similar to quad-shunting. The third phase, that corresponds to the fourth and the last step of the alignment procedure, runs with all the multipolar magnets on and consists in the simultaneous correction of orbit, dispersion, coupling and beta-beating. Table 1 summarizes the whole procedure.

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Table 1: The Four Steps of the Alignment Procedure

Phase / Step	Multipoles	Alignment technique
I / 1-2	switched off	1-to-1 and dfs
II / 3	powered indiv.	multipole-shunting
III / 4	switched on	orbit - dispersion - coupling - beta-beating

Phase I: Multipoles Switched Off

1) 1-to-1 Correction. The principle of 1-to-1 correction consists of the simultaneous zeroing of the beam position monitor (BPM) readings, using a standard correction algorithm. Minimizing the BPM readings guarantees the flatness of the orbit, because it steers the beam as close as possible to the center of the monitors (thus, supposedly, to the center of the magnets too). 1-to-1 correction is also known as "orbit" correction. More details about this technique can be found for instance in [2].

If the beam positions are measured with a N monitors distributed along the final focus, the beam position at the BPMs is represented by a vector $\mathbf{b}$,

$$\mathbf{b} = (b_1, b_2, \ldots, b_N).$$

The orbit is corrected by a set of M correctors (kickers, dipole magnets) represented by the vector θ,

$$\theta = (\theta_1, \theta_2, \ldots, \theta_M).$$

Given an arbitrary trajectory $\mathbf{b}$, the task of 1-to-1 correction is to find a set of corrector kicks θ that minimizes the equation

$$\mathbf{b} + \mathbf{R}\theta = 0 \tag{1}$$

where $\mathbf{R}$ is the *response matrix* of the system (dimension $N \times M$) to the corrector θ. Considering that 1-to-1 correction must be applied to both axes, x and y, the Eq. (1) can be rewritten as

$$\begin{pmatrix} \mathbf{b}_x \\ \mathbf{b}_y \end{pmatrix} = -\begin{pmatrix} \mathbf{R}_{xx} & 0 \\ 0 & \mathbf{R}_{yy} \end{pmatrix} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix}. \tag{2}$$

It can be demonstrated that 1-to-1 correction is not enough to cure emittance blow up because the uncorrected residual dispersion can lead to emittance dilution through beam size increase. A better correction technique is Dispersion Free Steering (DFS).

2) Dispersion Free Steering. This technique attempts to correct orbit and dispersion simultaneously [2, 5]. The dispersion is measured, then the correctors are solved in order to match the nominal dispersion of the system. Dispersion along the beamline can be measured by sending two test beams with different energies through the system, and evaluating the difference in their respective vector of BPM readings:

$$\eta = \frac{\mathbf{b}_{+\delta} - \mathbf{b}_{-\delta}}{2\delta}$$

where δ is the relative energy difference of the two test beams, relative to the nominal beam. Energy differences of the order of a few per-mille are usually sufficient. If η_0 is the nominal dispersion, the system of equation that must be solved for θ, is an extension of Eq. (2). The extended linear system of equations is

$$\begin{pmatrix} \mathbf{b}_x \\ \mathbf{b}_y \\ \eta_x - \eta_{0,x} \\ \eta_y - \eta_{0,y} \end{pmatrix} = - \begin{pmatrix} \mathbf{R}_{xx} & 0 \\ 0 & \mathbf{R}_{yy} \\ \mathbf{D}_{xx} & 0 \\ 0 & \mathbf{D}_{yy} \end{pmatrix} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix} \tag{3}$$

where $\mathbf{D}_{xx}$ and $\mathbf{D}_{yy}$ are the *dispersion response matrices* of the system to the correctors θ. As $\eta_{0,x}$ is usually different than zero, this technique is often referred to as "Target Dispersion Steering".

Phase II: Multipoles Powered Individually

3) Multipole-Shunting. This technique consists of centering each multipolar magnet around the beam by measuring the change in beam trajectory induced by controlled transverse offsets applied to the magnet. It is similar to quad-shunting with the difference that it considers *all* BPM downstream the magnet instead of only the first one—as in the traditional implementation of this technique. A detailed and instructive explanation of quad-shunting can be found for instance in [6].

A response matrix $\mathbf{S}$ is constructed –from the beamline optics– in order to model the response of the beam to dipole kicks located at the multipoles. Then the procedure starts. In turn, each multipole is powered to its nominal current and a scan of its transverse position is executed. Based on the resulting change in beam trajectory $\Delta\mathbf{b}$, the kick θ given by each multipole is calculated solving for θ the following system of equations

$$\Delta\mathbf{b} = -\mathbf{S}\theta.$$

Then, the kicks obtained for each position are fitted in order to locate the minimum. The location of the minimum coincides with the magnetic center of the multipole. For sextupole magnets, for instance, the relation between offsets dx and dy and the resulting deflecting kick is well known,

$$\begin{aligned} \theta_x &= -\frac{1}{2}\frac{S_N}{B\rho}\left(\mathrm{d}x^2 - \mathrm{d}y^2\right), \\ \theta_y &= +\frac{S_N}{B\rho}\,\mathrm{d}x\,\mathrm{d}y, \end{aligned}$$

where S_N is the integrated sextupole strength and $B\rho$ the beam magnetic rigidity. The same principle is applied to octupoles and decapoles, when such elements are present in the lattice.

Phase III: Multipoles On

4) Simultaneous Orbit – Dispersion – Coupling – Beta-beating Correction. In the last phase of the alignment procedure, all multipoles are powered at their nominal strength. In this configuration the last step of optimization attempt to correct orbit, dispersion, coupling and the beta-beating simultaneously.

Quantities like coupling and beta-beating can be measured as follows: initially, the first corrector of the beamline is activated to excite a betatron oscillation in the positive direction of the x axis. Then, the beam trajectory is measured and the vector of BPM readings is called $\mathbf{b}_{x,y|\theta_{1,+x}}$. Subsequently, the same corrector is used to excite an opposite betatron oscillation in the negative direction of the x axis. The beam trajectory is measured again and the vector of BPM readings is called $\mathbf{b}_{x,y|\theta_{1,-x}}$. The same procedure is repeated in the vertical direction, exciting two opposite betatron oscillations in the two directions of the y axis. The two trajectories are called $\mathbf{b}_{x,y|\theta_{1,+y}}$ and $\mathbf{b}_{x,y|\theta_{1,-y}}$. The horizontal and vertical beta-beating and coupling, $\beta_{x,y}$ and $\mathbf{c}_{x,y}$, are defined by the following expressions:

$$\beta_x = \frac{b_{x|\theta_{1,+x}} - \mathbf{b}_{x|\theta_{1,-x}}}{2\Delta\theta_{1,x}}, \qquad \beta_y = \frac{b_{y|\theta_{1,+y}} - \mathbf{b}_{y|\theta_{1,-y}}}{2\Delta\theta_{1,y}}, \tag{4}$$

$$\mathbf{c}_x = \frac{\mathbf{b}_{x|\theta_{1,+y}} - \mathbf{b}_{x|\theta_{1,-y}}}{2\Delta\theta_{1,y}}, \qquad \mathbf{c}_y = \frac{\mathbf{b}_{y|\theta_{1,+x}} - \mathbf{b}_{y|\theta_{1,-x}}}{2\Delta\theta_{1,x}}. \tag{5}$$

The value of these quantities for the ideal machine (i.e. the model) can be measured, numerically, using a tracking code. The nominal beta-beating and couplings are called $\beta_{0,x}$, $\beta_{0,y}$, $\mathbf{c}_{0,x}$ and $\mathbf{c}_{0,y}$.

To find the optimal set of correctors we need to calculate the beta-beating and coupling response matrices, $\mathbf{B}$ and $\mathbf{C}$. These matrices are the response of Eq. (4) and (5) to the correctors θ. The linear system of equations that must be solved for θ is an extension of Eq. (3),

$$\begin{pmatrix} \mathbf{b}_x \\ \mathbf{b}_y \\ \eta_x - \eta_{0,x} \\ \eta_y - \eta_{0,y} \\ \beta_x - \beta_{0,x} \\ \beta_y - \beta_{0,y} \\ \mathbf{c}_x \\ \mathbf{c}_y \end{pmatrix} = - \begin{pmatrix} \mathbf{R}_{xx} & 0 \\ 0 & \mathbf{R}_{yy} \\ \mathbf{D}_{xx} & 0 \\ 0 & \mathbf{D}_{yy} \\ \mathbf{B}_{xx} & 0 \\ \mathbf{B}_{yx} & 0 \\ 0 & \mathbf{C}_{xy} \\ 0 & \mathbf{C}_{yy} \end{pmatrix} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix} \tag{6}$$

This system is solved in a least-squares sense using the singular value decomposition (SVD), see for instance [2].

FINAL SYSTEM OF EQUATIONS AND WEIGHT FACTORS

For the sake of simplicity in the previous sections it has been omitted that each contribution in Eq. (3) and (6) must be weighted by an appropriate weight factor. The weights should be such that any change in θ has the same impact on the vector of observables at the left-hand side of the system.

In the case of this alignment procedure at least three weights are necessary: two, ω_1 and ω_2, for the dispersion terms in Eq. (3) and (6) one, ω_3, for the coupling and beta-beating term of Eq. (6). An additional weight β should be added for the SVD to limit the amplitude of the correctors. The actual form of the two systems of equations is therefore the following:

1. Dispersion free steering:

$$\left(\begin{array}{ccc} & & \mathbf{b} \\ \omega_1 & \cdot & (\eta-\eta_0) \\ & & \mathbf{0} \end{array}\right) = -\left(\begin{array}{ccc} & & \mathbf{R} \\ \omega_1 & \cdot & \mathbf{D} \\ \beta & \cdot & \mathbf{I} \end{array}\right)\left(\begin{array}{c} \theta_x \\ \theta_y \end{array}\right)$$

2. Coupling and beta-beating correction:

$$\left(\begin{array}{ccc} & & \mathbf{b} \\ \omega_2 & \cdot & (\eta-\eta_0) \\ \omega_3 & \cdot & (\beta-\beta_0) \\ \omega_3 & \cdot & \mathbf{C} \\ & & \mathbf{0} \end{array}\right) = -\left(\begin{array}{ccc} & & \mathbf{R} \\ \omega_2 & \cdot & \mathbf{D} \\ \omega_3 & \cdot & \mathbf{B} \\ \omega_3 & \cdot & \mathbf{C} \\ \beta & \cdot & \mathbf{I} \end{array}\right)\left(\begin{array}{c} \theta_x \\ \theta_y \end{array}\right)$$

where the four weights factors are: ω_1, ω_2, ω_3 and β. The optimal values for these four coefficients can be found analytically. Alternatively they can also be found by running a computer simulation.

APPLICATION TO THE CLIC BDS

During the last years several efforts have been made to cure static misalignments of the CLIC BDS but none of them has resulted conclusive [7]. The alignment technique presented in this paper has been applied to computer simulations of the CLIC Beam Delivery System (BDS). Results are still preliminary but already they are very encouraging. The simulation setup consisted of: CLIC BDS lattice $L^\star = 3.5$ m, random –Gaussian distributed– transverse misalignment 10 μm r.m.s., BPM resolution 10 nm. Single-particle (bunch core) tracking was used for the calculation of the response matrices and during the optimization procedure, whereas a full particle tracking with 100'000 macro-particles was used for the evaluation of beamsize and emittance. Synchrotron radiation emission, that seems to be the most detrimental factor in the CLIC BDS alignment, was not taken into account. Figure 1 shows the final vertical beam size for 1000 random misalignment seeds during the three phases of the alignment. The average final vertical beam size at the interaction point, after the complete alignment procedure, is $\sigma_y = (2.6 \pm 1.3)$ nm.

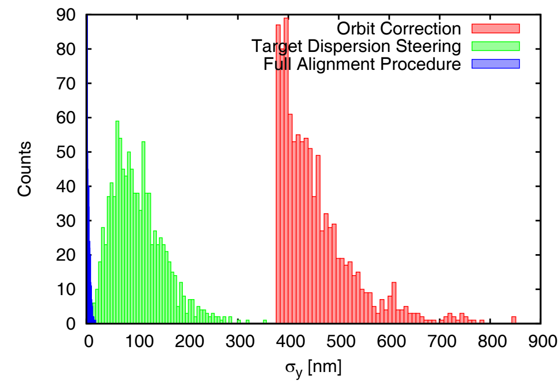

Figure 1: Histogram of the vertical beam sizes of 1000 seeds in the CLIC BDS. The three phases of the alignment procedure are shown in red, green and blue, respectively. Final vertical beamsize at the interaction point is (2.6 ± 1.3) nm.

CONCLUSIONS

A new technique for the static alignment of final focus systems of future linear colliders has been presented. It consists of the simultaneous correction of orbit, dispersion, beta-beating and coupling as well as the centering of the multipolar magnets with an advanced multipole-shunting technique. This alignment procedure has been applied to the CLIC BDS with extremely promising results. Further studies must be performed in order to consolidate it and possibly improve it. Future steps of this work will include its application to the alignment of the ATF2 test facility for its experimental validation.

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