Application of Kick Minimization to the RTML "Front End"

P. Tenenbaum

January 30, 2007

1 Introduction

The "front end" of the ILC RTML constitutes the sections of the RTML which are upstream of the first RF cavity of the first stage bunch compressor: specifically, the SKEW, COLL, TURN, SPIN, and EMIT sections. Although in principle it should be easy to transport the beam through these sections with low emittance growth, since the energy spread of the beam is relatively low, in practice it is difficult because of the large number of betatron wavelengths and strong focusing, especially in the TURN section.

We report here on the use of the Kick Minimization Method for limiting the emittance growth in the "front end" of the RTML. Kick Minimization (KM) is a steering method which balances two optima: minimization of the RMS measured orbit on the BPMs (often called 1:1 steering), and minimization of the RMS corrector strength [1]. The simulation program used for these studies is Lucretia [2].

2 Kick Minimization Algorithm Used in This Study

Consider a situation in which the quads of the RTML "front end" are vertically misaligned with respect to the survey line with an RMS of σ_q, while the BPMs are vertically misaligned from their respective quad magnetic centers with an RMS of σ_B; this is the situation which typically occurs after quad-shunting has been used to measure the BPM-to-quad offsets. The minimum emittance growth occurs when the beam trajectory is straight in an absolute sense, ie, there is no kinking of the trajectory by correctors or quads. In a system with nonzero misalignments, this will occur when the setting of a corrector θ_i is exactly equal-and-opposite to the product of the quad integrated strength and its offset from the survey line, or $\theta_i = (K_1L)_i y_i$.

Unfortunately, the quad misalignments with respect to the survey line, y_i, are not known. However, it is known that the BPM offsets with respect to the quad centers are close to zero, with RMS error σ_B as mentioned above. For a quad with a zero BPM reading ($B_i \approx 0$), and a zero corrector strength θ_i, we can therefore be sure that the beam is passing close to the magnetic center of the quad and is not being kicked by that quad. More generally, if the BPM reading and the corrector are not zero, then the "no-kicking" condition occurs when the BPM reading and the corrector reading balance one another:

$$B_i + \theta_i/(K_1L)_i \approx 0. \quad (1)$$

In principle, one could achieve an unkicked beam passing through the entire beamline by measuring the BPM readings and solving Equation 1 for θ_i such that it is satisfied at all BPMs. In practice, the solution is not stable in the presence of errors, since a large BPM reading at a given location can be "corrected" either by changing the upstream orbit such that the BPM reading is reduced, or else by increasing the corrector setting at that location. The latter option results in an increased BPM reading at the next location, which will demand an increased corrector strength at that point; and so on throughout the beamline. Thus, it is necessary to also use the knowledge of the absolute misalignments and absolute orbit to constrain the solution. Just to complicate matters further, the "front end" includes an area with significant xy coupling, so simultaneous steering in both planes is necessary for any procedure to converge.

2.1 The Matrix Equation and its Solution

Let us define $\vec{B}_x$ as the vector of horizontal BPM readings, and $\vec{B}_y$ as the vector of vertical BPM readings. We can then define vectors of BPM readings which have been adjusted to take into account the strength of the nearby corrector magnets: $\vec{C}_x \equiv \vec{B}_x - \vec{\theta}_x/\vec{KL}$, $\vec{C}_y \equiv \vec{B}_y + \vec{\theta}_y/\vec{KL}$, where we take the usual convention that positive KL values are horizontally focusing and where the division is array division (ie, the resulting vector components are $\theta_i/(KL)_i$).

Now define the usual steering response matrices: matrix M_{xx} is the response of the horizontal BPMs to the horizontal correctors; M_{xy} is the response of the horizontal BPMs to the vertical correctors; and so on. Now let us define a set of steering matrices which are modified by the quad strengths: for example, N_{xx},

$$\begin{aligned} N_{xx,ij} &\equiv -\frac{1}{KL_i} + M_{xx,ij},\ i = j, \\ &\equiv M_{xx,ij},\ i \neq j. \end{aligned} \tag{2}$$

The matrix N_{yy} is similarly defined except that the $1/KL$ term comes in with a positive sign and not a negative sign. The matrices N_{xy} and N_{yx} are identically equal to M_{xy} and N_{yx}, respectively.

We can now put this together into a matrix equation as follows:

$$\begin{bmatrix} \vec{B}_x \\ \vec{B}_y \\ \vec{C}_x \\ \vec{C}_y \end{bmatrix} = -\begin{bmatrix} M_{xx} & M_{xy} \\ M_{yx} & M_{yy} \\ N_{xx} & N_{xy} \\ N_{yx} & N_{yy} \end{bmatrix} \begin{bmatrix} \vec{\Delta\theta}_x \\ \vec{\Delta\theta}_y \end{bmatrix}, \tag{3}$$

where $\vec{\Delta\theta}_{x,y}$ is the vector of corrector *changes* which are needed, relative to their current settings.

The Equation 3 is solved as follows: the beam is tracked through the lattice, and the current BPM values and corrector values are measured and used to construct the $\vec{B}$ and $\vec{C}$ vectors of observables. Equation 3 is solved in a weighted least-squares sense to obtain the changes to the correctors, $\vec{\Delta\theta}_{x,y}$. The changes are then added to the existing corrector settings and the procedure is, if necessary, iterated. The weights should be set such that increasing one element of $\vec{B}$ by an amount equal to $\sqrt{\sigma_q^2 + \sigma_B^2}$ has the same impact on the χ^2 as increasing one element of $\vec{C}$ by an amount equal to σ_B (ie, the solver should work harder to minimize the components of $\vec{C}$ than the components of $\vec{B}$).

3 Dispersion Bumps

After iterating KM to convergence, the simulations apply dispersion bumps. The bumps are constructed out of combinations of skew quad settings in the turnaround. The skew quads are set in $-I$ pairs, so that exciting the skew quads in a pair with equal-and-opposite strengths causes the resulting betatron coupling to cancel and the dispersion coupling to add.

One refinement to the basic procedure is that it was found that each skew quad pair is about 45° away, in betatron phase, from the most useful wires in the EMIT section. It was also found that, with this arrangement, the dispersion knobs would not converge properly when each one was applied in turn. After some mathematics we managed to convince ourselves that this was a consequence of having a large nonzero α_y at the location of the wire scanners – a large α_y coupled with a non-ideal phase advance from the knob to the wires led to a situation in which the procedure converges on the wrong answer. To fix this, we changed the knob setup to have the correct phases. Specifically, the first dispersion knob has coefficients $1/\sqrt{2}$ for SQ1, $-1/\sqrt{2}$ for SQ2 (which is $-I$ away from SQ1), $1/\sqrt{2}$ for SQ3, and $-1/\sqrt{2}$ for SQ4; the knob which is orthogonal to this has coefficients $1/\sqrt{2}$, $-1/\sqrt{2}$, $-1/\sqrt{2}$, $1/\sqrt{2}$ for these 4 skew quads, respectively.

4 Simulations

A number of simulations were performed with different sets of errors, specifically:

- Simulations which included only misalignments, specifically 150 μm RMS horizontal and vertical misalignments of the quads with respect to the survey line, and 7 μm RMS horizontal and vertical misalignments of the BPMs with respect to the quad centers
- The misalignments, plus 0.25% RMS quad strength errors
- The misalignments and quad strength errors, plus 0.5% RMS bend strength errors
- The misalignments, quad, and bend strength errors, plus 300 μrad RMS quad roll errors
- The misalignments, strength errors, and quad rolls, plus 300 μrad RMS bend roll errors.

For each set of errors, 100 seeds were generated, and the results after 2 iterations of KM were collected, as well as 2 iterations of KM followed by 2 iterations of dispersion knobs. Table 1, below, shows the mean emittance growth for all of these simulations.

Table 1:

Errors	After KM	After KM + Knobs
X/Y Offsets	2.13 nm	0.37 nm
Add Quad Strength	5.36 nm	3.20 nm
Add Bend Strength	6.12 nm	3.25 nm
Add Quad Rolls	23.22 nm	7.60 nm
Add Bend Rolls	23.31 nm	7.61 nm

Note that 0.37 nm is the emittance growth that the beam will experience in the “front end” RTML when a perfect beam is injected into a perfect lattice. This is due to the large chromaticity of the matching regions, especially the matching regions into and out of the COLL section. Table 1 shows that, in the presence of simple misalignments, KM and knobs can reduce the emittance growth from errors to zero, but the addition of other errors increases the emittance growth to over 7 nm in the mean (recall that the emittance budget for the RTML as a whole is about 4 nm).

Fortunately, there are other techniques which can be used to break down the resulting emittance growth even further:

- Injection of a beam with zero energy spread allows the exact emittance growth from xy coupling to be deduced
- Injection of a beam with zero horizontal emittance allows the exact emittance growth from dispersion and chromaticity to be deduced

- By comparing the zero-horizontal-emittance beam's normal mode and projected emittances, the dispersion and chromaticity contributions can be deduced.

Table 2 shows the breakdown of the emittance growth into these sources (dispersion, coupling, chromaticity) after KM and knobs for the various simulations.

Table 2:

Errors	All Aberrations	Chromaticity	Dispersion	Coupling
X/Y Offsets	0.37 nm	0.37 nm	0.00 nm	0.00 nm
Add Quad Strength	3.20 nm	0.82 nm	0.01 nm	2.39 nm
Add Bend Strength	3.25 nm	0.82 nm	0.06 nm	2.39 nm
Add Quad Rolls	7.60 nm	1.49 nm	0.00 nm	6.08 nm
Add Bend Rolls	7.61 nm	1.49 nm	0.02 nm	6.08 nm

Table 2 suggests the following:

- The combination of KM and dispersion knobs can completely eliminate dispersion as a source of emittance growth in the RTML "front end", presumably limited only by the resolution of the BPMs and the wire scanners (which were not modeled in this study)
- After dispersion correction the most serious problem is coupling correction, which is not addressed by any of the tuning methods in this simulation
- The chromaticity of the matching regions is a serious problem which is not addressed by the linear dispersion or coupling corrections; we should examine the possibility of redesigning the matching regions to correct this problem.

5 Acknowledgements

These studies would not have been possible without many excellent ideas and discussions with K. Kubo and J. Smith. The work reported in this note was supported by the US Department of Energy under Contract DE-AC02-76SF00515.

References

[1] K. Kubo, "Emittance Dilution Due to Misalignment of Quads and Cavities of ILC Main Linac," `http://lcdev.kek.jp/~kkubo/reports/MainLinac-simulation/lcsimu-20050310.pdf` (2005).

[2] `http://www.slac.stanford.edu/ilc/codes/Lucretia/` (2006).