Dispersion and Betatron Matching into the Linac

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Abstract

In high energy linear colliders, the low emittance beam from a damping ring has to be preserved all the way to the linac, in the linac and to the interaction point. In particular, the Ring-To-Linac (RTL) section of the SLAC Linear Collider (SLC) should provide an exact betatron and dispersion match from the damping ring to the linac. A beam with a non-zero dispersion shows up immediately as an increased emittance, while with a betatron mismatch the beam filaments in the linac. Experimental tests and tuning procedures have shown that the linearized beta matching algorithms are insufficient if the actual transport line has some unknown errors not included in the model. Also, adjusting quadrupole strengths steers the beam if it is offset in the quadrupole magnets. These and other effects have lead to a lengthy tuning process, which in the end improves the matching, but is not optimal. Different ideas will be discussed which should improve this matching procedure and make it a more reliable, faster and simpler process.

1 Theoretical Considerations

A mismatch in betatron functions of the beam (α, β) and the lattice ($\tilde{\alpha}$, $\tilde{\beta}$) and a non-zero dispersion (η or $\eta' \neq 0$) at the beginning of the linac enlarges the effective emittance (ϵ_{eff}). A dispersion η causes different beam positions for different energies $\Delta x = \eta \Delta E/E$. This effect can be estimated by the following example. For an energy spread $\frac{\sigma_E}{E} = \delta \approx 1\,\%$, a dispersion of $\eta = 10\,\text{mm}$ will lead to an emittance growth of roughly 10 % (at a beam size of $\sigma_0 = \sqrt{\epsilon\beta} = 316\,\mu\text{m}$):

$$\epsilon_{eff}\beta = \sigma^2 = \epsilon\beta + \eta^2\delta^2 = (0.1 + 0.01)\,\text{mm}^2, \qquad (1)$$

if there is a similar disturbance in the angular component with η'. Otherwise the full expression has to be recognized:

$$\epsilon_{eff} = \epsilon\sqrt{1 + [\eta^2 + (\beta\eta' + \alpha\eta)^2] < \delta^2 > /(\epsilon\beta)}, \qquad (2)$$

which corresponds to a bigger (and additionally mismatched [1]) ellipse in phase space.

A betatron mismatch has no immediate effect on the emittance, but will increase the emittance by the filamentation of the phase space ellipse induced by an energy spread. This magnification due to the betatron mismatch is given by:

$$\beta_{mag} = \frac{1}{2}\left(\frac{\tilde{\beta}}{\beta} + \frac{\beta}{\tilde{\beta}}\right) + \frac{1}{2}\left(\alpha\sqrt{\frac{\tilde{\beta}}{\beta}} - \tilde{\alpha}\sqrt{\frac{\beta}{\tilde{\beta}}}\right)^2 . \qquad (3)$$

e.g.: $\alpha = \tilde{\alpha} = 0$

$(\beta - \tilde{\beta})/\tilde{\beta}$	$\beta_{mag} - 1$
0.5	0.08
1.0	0.25
2.0	0.67
4.0	1.60
$n > 10$	$\approx n/2$

Fig. 1 shows the beam in real space for β, η-mismatch and also higher order contributions. Besides the theoretical considerations, the observed practical problems during the actual minimization process will be described.

2 Dispersion Match

Although the dispersion adjustment should be performed only after the betatron match is done, it will be described first.

2.1 Measurement

There are two different techniques to determine the influence of the dispersion term:

1. The emittance, determind by wire scanners (or screens), is compared for the two cases: a) with the normal 1 % energy spread (compressor in RTL is on) and b) with no energy spread (compressor off).
2. By changing the phase and amplitude of the compressor to provide an acceleration, no acceleration or deceleration, it will lead to an offset Δx at the BPMs (beam position monitors), if dispersion term are present.

Additionally, a skewness in the beam distribution measured by a wire (screen) indicates higher order energy dependencies (T_{166} [4]), which can be determined by the BPM-data: For lower and higher energies Δx has the same sign.

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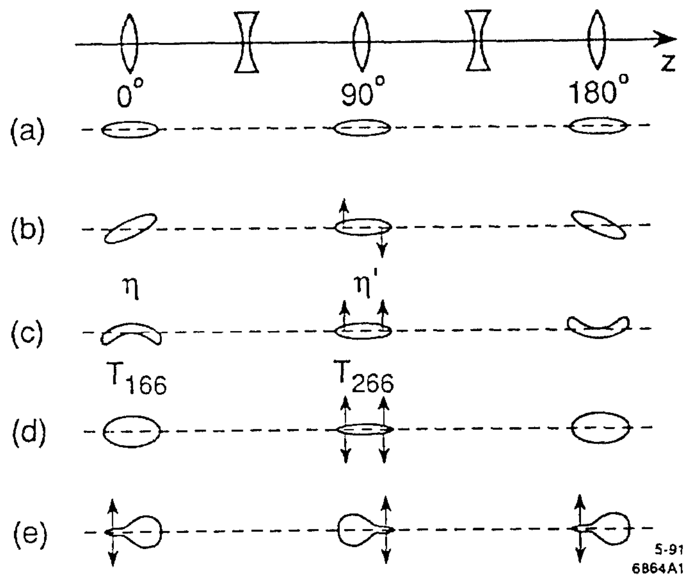

Figure 1: Beam Mismatches.

The beam response in x,z-space is shown for different mismatches. The beam has a longitudinal energy correlation introduced by a compressor and follows a 90° per cell lattice (arrows indicate additional x'): a) Matched beam, b) dispersion in space ($\eta = R_{16}$) and angle ($\eta' = R_{26}$), c) higher order dispersion (or dispersive chromaticity): T_{166}, T_{266}, d) betatron mismatch ($\tilde{\beta} \approx 4\beta$), e) (betatron-) chromaticity is different focusing for different energies and resultant betatron match within the beam for not fully compressed bunches.

2.2 Correction

A combination of quadrupoles (η, η'–knobs) is changed, which should not influence the betatron match. Depending on the measurement techniques either the overall effect is decreased by minimizing the emittance or spot sizes, or the actual dispersion and higher orders are measured and can be compensated by a right amount of the η, η'–knobs and sextupole adjustments. Here some of the main techniques and their advantages are discussed:

1. The emittance is minimized and checked with wires at the beginning (or end) of the linac: The precise measurement leads to a more direct minimization of the important quantity, a residual dispersion may compensate rf-kicks and wakefields.

2. The two-dimensional spots on two screens are minimized by finding two good settings per screen $(\eta, \eta') = (\eta_1, 0)$ and $(0, \eta'_1)$ and set to common solution: It is a quick method, but not necessarily the most accurate one.

3. Calculate and/or iterate BPM-data: The dispersion alone is minimized, residuals from rf-kick or wakefields remain. This method gives quantitative results for dispersion and also for higher orders.

For the higher order in dispersion, e.g. the betatron chromaticity, two methods have to be combined: At different energies, set by the compressor, the betatron matching (see below) is measured with the wires.

3 Betatron Match

The twiss parameters α and β of the beam have to be measured and compared to the design $\tilde{\alpha}$, $\tilde{\beta}$.

3.1 Measurement

The measurement is done by either a quadrupole scan or by multiple wire measurements. For the first method, the beam size on a screen or wire is recorded for different quadrupole settings. The second method needs at least three wires (screens), which measure the beam size at different phase advances giving α, β and ϵ (emittance) of the beam [2, 3]. From the mismatch of the beam with respect to the design the beta-magnification β_{mag} (see eq. 3) is calculated.

3.2 Correction

With the known lattice, α and β of the beam can be tracked back to the beginning of the RTL and the corresponding beta-knobs changed by the appropriate amount. Most often the knobs are empirically tuned to minimize β_{mag}.

3.3 Difficulties with Betatron Adjustment

A variety of problems, such as measurement inaccuracies, magnetic hysteresis and RTL focusing errors, makes the minimization of β_{mag} below a value of 1.2 difficult. Some problems, their origin and their effects are summarized below:

1. Measurement error: Wire vibrations, photo multiplier saturation, bad timing of the gate (or nonlinearities of screens) may cause a wrong matching minimum.

2. Hysteresis in magnets: β_x, β_y knobs become nonorthogonal, especially if quadrupole trims have different signs in respect to common power supply.

3. Lattice: (i) Nearly degenerated matching knobs using only four quads require big changes, which steer the beam. (ii) Nonlinear knobs. (iii) Vertical focusing depends on steering through sextupoles.

4. Changing only one quad: Then less change is necessary. The measured hysteresis gap is $\approx 1\,\%$, while a $0.6\,\%$ change gives already $\beta_{mag} = 2$ (see Fig. 2).

5. Not stable over days: With a different steering near the nonlinear septum or a vertical steering, the adjustment changes.

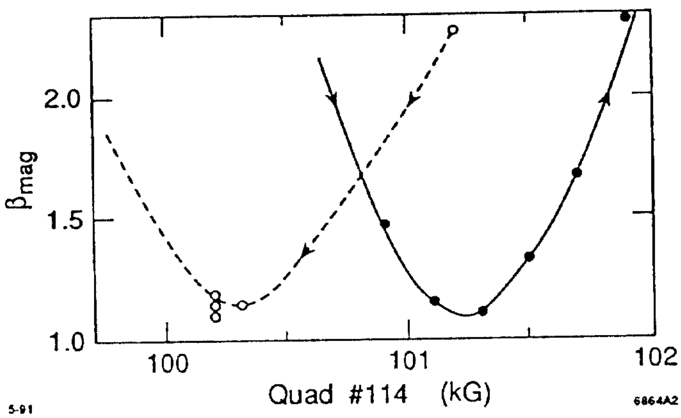

Figure 2: Betatron Match Sensitivity.

Here one of the "matching" quadrupoles (number 114) in the RTL is changed by a few percent. For a 0.4 % change of the magnetic field the betatron magnification (corresponding to an emittance growth after filamentation) is 1.5. The difference going up or down the hysteresis loop (see arrows) is about 1 % in field strength, which makes it difficult to adjust combinations of magnets.

4 Precise Adjustment

It should be mentioned that a coarse adjustment is achieved quite quickly and keeps the emittance blow-up below 30–50 % of the $1.6 \cdot 10^{-5}$ m rad normalized damping ring emittance. A precise adjustment can also be obtained, but usually only in one plane (x or y).

4.1 Adjustment Procedures

Over the years several betatron matching "knobs" have been generated using four matching quadrupoles. They are configured to change orthogonally one component of β_x, α_x, β_y, α_y or more precisely, they control the cosine-like, $\tilde{\beta}/\beta$, and sine-like, $\tilde{\alpha} - \alpha\tilde{\beta}/\beta$, components of a beta-beat.

Historically the first set of knobs failed, since the power supply of one quad couldn't regulate well at the desired low amount. Then a second set was made using a small trim power supply for that quad. The difficulty with these knobs is that small misalignments of the strong matching quads cause a big steering of the beam. A third set uses only one matching quad and three pairs of quads in the dispersive region of the RTL. They require only small changes (less steering), but they have quite a large cross-talk between the x and y plane.

A different technique uses the four matching quads but with dynamic knobs. This means the measured response of the knobs is used to calculate the desired coefficients for the four quads. A potential problem is the hysteresis of the magnets. Another method tries to avoid the hysteresis by calculating the desired change and trimming the magnets to these values after standardization. This requires quite a long time, steers the beam and seems to have a poor convergence.

The simplest way is taking only the most sensitive quad for the desired change and taking care of the normal standardization direction on the hysteresis loop. This is not totally orthogonal and therefore insufficient for a complete betatron match.

4.2 New Ideas

A number of ideas have been generated during discussions, but haven't been tried yet. One is to use more than four quads and minimizing the sum of changes to get the desired effect. This will be less degenerat, so less quad changes and therefore less beam steering will occur. Also the x–y cross-talk might be less, but no hysteresis of the magnets are considered. To avoid hysteresis knobs may be used which always have the quads going in the standardization direction (or against for resetting). A variation might be a knob which brings a quadrupole current (if tweaked against hysteresis) far beyond the required value and then back following the standardization direction (quasi-standardized). Also a different standardization method [5] might be considered, which is insensitive against tweaks around an optimal setting. Together with dynamic knobs, a fast procedure has to be found, since drifts of 20-30 % in emittance over a few days have been observed.

5 Conclusion

Dispersion and betatron matching into the SLC-linac can reduce the emittance growth below about 30 %. For a further reduction, different procedures are needed, which deal with the problems of hysteresis in the magnets, measurement errors, sensitivity of the lattice and long-term stability.

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