A RECIPE FOR LINEAR COLLIDER FINAL FOCUS SYSTEM DESIGN

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Abstract

The design of Final Focus systems for linear colliders is challenging because of the large demagnifications needed to produce nanometer-sized beams at the interaction point. Simple first- and second-order matrix matching have proven insufficient for this task, and minimization of third- and higher-order aberrations is essential. An appropriate strategy is required for the latter to be successful. A recipe for Final Focus design, and a set of computational tools used to implement this approach, are described herein. An example of the use of this procedure is given.

INTRODUCTION

The new compact final focus system [1], based on local chromaticity correction in the final doublet, is now being adopted for all of the linear collider designs because of its superior performance over the traditional final focus design. At the same time, we are receiving an increasing number of requests for a more detailed recipe for the optical design of such a system. A brief, spontaneously written recipe was discussed at the recent Nanobeam workshop [2]. A more detailed treatment is given here.

Some traditional FF systems have been designed using the FFADA (Final Focus Automatic Design and Analysis) program [3]. Although FFADA automates the generation of different solutions for the final telescope, the most tedious part of the design process, minimization of the third-order U3466 aberration (the notation of TRANSPORT [4] is used here and below) still required a trick - one needed to use FFADA to generate a system with certain demagnifications Mx and My, check U3466, change Mx and/or My, recheck U3466, and iterate until the aberration vanished.

This process can be expressed as a recipe: while preserving the desired linear and second-order properties of the system under consideration, scan possible solutions along particular degrees of freedom (Mx or My in this case), find the optimum, scan along other degrees of freedom, and continue iterating until a proper solution is found. Sometimes no satisfactory solution can be found, either because you are stuck in a local minimum or because the requested performance cannot be achieved. In these cases you must use your intuition to know when you need to go back and change something.

A similar approach can be used for designing a compact FF system. In this case, there are many more free parameters that can be changed, but the basic procedure is the same.

A TUNING RECIPE

The following steps were used to design a compact FF system, which will be presented in the next section. The procedure has been implemented as a semi-automatic design tool based on Matlab. As with any recipe, this one should be considered a guide more than a detailed map. It may be necessary to change the strategy or add more steps, depending on the situation (e.g. how far you are from a solution) or depending on the tools being used. The FF system presented in [1] was designed entirely using TRANSPORT. In the following, it is assumed that the basic matching is done with MAD [5]. The element names correspond to those shown in Figure 1. Only those steps of the design which involve variables ($knobs$) important for aberration tuning are highlighted.

0) Design the betatron and energy collimation systems.

1) Work backwards from the IP starting with design values for β^*, η'^*, and L^*. Choose reasonable lengths for the Final Doublet (FD) quadrupoles QD0 and QF1 and the separation between them. At a later stage the quadrupole lengths and their separation can be varied to trade synchrotron radiation in the FD against FD vibration tolerances. Make a linear match, varying the strengths of QD0 and QF1, to obtain certain values for α_x and α_y at the exit of QF1 (going away from the IP). These values will later be used to optimize 3rd order aberrations (such as U3246, U1226, etc.).

2) Make a linear match, varying the strength of QD2A, QF3, QD2B, QD4, QF5, QD6, and QF7, to obtain the following conditions: a) "pseudo -I" transform between SD0 and SD4 (all Rii=-1, R12=V_1, and R34=V_2); b) "pseudo +I" transform between SF1 and SF6 (all Rii=1, R12=V_3, and R34=V_4); c) horizontal and vertical waists ($\alpha_{x,y} = 0$) at the center of QF7. These V_i are knobs to be used for further aberration tuning (usually for geometric terms such as U1222, U3224, U3444, etc.).

3) Make a linear match, varying the bending angles of B1, B2, and B5, to obtain zero dispersion ($\eta = 0$ and $\eta' = 0$) at the end of the system, with a certain nonzero value of dispersion at SF5. This dispersion value becomes another tuning knob (affects geometric and chromo-geometric terms).

4) Make a linear match, varying the strengths of six beta-matching quadrupoles (labelled "QM" in Figure 1) to obtain a telescopic transformer (diagonal) matrix for the system with certain demagnifications Mx and My.

5) Reverse the system and start from the FF entrance. Make a second-order match, varying the strengths of all sextupoles, to zero the T126, T122, T166, T346, and T324 aberrations. At a later stage, when one is close to a solution, SF5 or SF6 can be excluded from the match and left for

later hand/automated tuning.

Further minimization of higher-order aberrations involves both computation of the higher-order transfer matrices for the system and manipulation of beam properties determined by tracking. Implementation will depend on the available tools. In our example, we use the complementary programs TRANSPORT and TURTLE [6] to minimize higher-order aberrations. TRANSPORT calculates matrices up to third-order, while TURTLE is a six-dimensional particle tracking code. Note that it is important to do the tracking and higher-order matrix calculation with codes that are consistent with one another. Using DI-MAD [7] for the tracking is also a good choice.

6) Convert the matched optics from MAD to a TRANS-PORT/TURTLE deck (using a conversion program developed at SLAC). For convenience of further evaluation of aberrations, calculate the inverse of the total first-order matrix of the FF system and insert this matrix at the beginning of the beamline, so that the overall first-order matrix becomes the identity matrix.

7) Run TRANSPORT to calculate the second- and third-order matrices, as well as the beam matrix with energy offset $+\Delta$ and $-\Delta$. The higher-order chromatic aberrations can be determined from the off-energy matrices.

8) Using the same TRANSPORT beamline, track the beam to the IP using TURTLE. Either the aberrations or the tracked beam sizes could be used as criteria for automatic minimization. In addition the bandwidth of the system, or the variation of the tracked IP beam sizes with energy, is an important quantity to optimize.

Remember this state, then return to the beginning and change the value of some knob. In essence you are computing numerical derivatives of the important aberrations and beam properties with respect to each knob and with respect to energy. Do this for all the knobs. Some knobs affect several aberrations, but differently, eventually allowing all of the major aberrations to be minimized (if in principle a solution exists for the requested parameters). In general all lengths, especially the lengths of the bends B1 and B2 and the drifts surrounding them, are additional knobs (in particular for U3466). Select the best set of knob values, keeping in mind that iteration of this process will be required due to the nonlinearity of the response of the aberrations to knob changes.

Repeat until an acceptable solution is found. Use knobs appropriate to the situation. Most of the steps in this procedure can be performed automatically. For example, Matlab-based scripts are used in our example to generate the TRANSPORT/TURTLE files, run these programs, read, analyze, and present the results, and then to search for an optimal solution using Matlab's optimization routines.

When a solution is close to optimum, and most of aberrations are small, use octupoles OC10 and OC1 near QD10 and the FD, respectively, for fine tuning of U3246 and U3244.

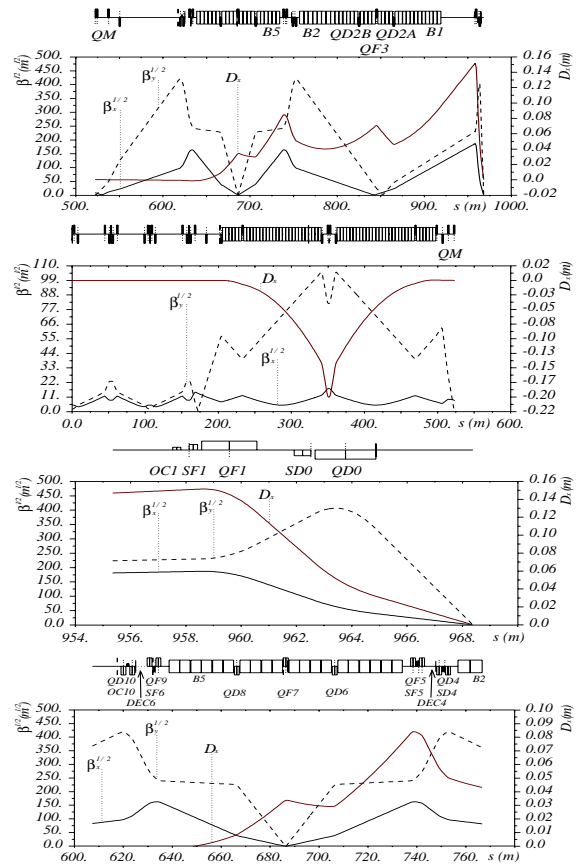Typically the third-order aberrations can be made small and the bandwidth of the system is limited by fourth or-

Figure 1: Preliminary optics for the NLC low energy BDS, $L^* = 3.51$ m, $\eta'^* = 0.009$. Final focus proper, collimation section, final doublet region, aberration correction region.

der terms, in particular V32246 (observed in the way that U3224 changes with energy). Use decapoles DEC6 and DEC4 (see Figure 1) with equal strengths to cancel this aberration. For better cancellation of V32446, use a sum of aberrations as a minimization criterion, constraining U3244$_{+\Delta E}$ and U3244$_{-\Delta E}$ to be asymmetric (as in Figure 4). In our case, since TRANSPORT and TURTLE do not handle decapoles, it was necessary to use DIMAD tracking to optimize the strength of these elements.

The authors wish to note here that we do not know of a single optics code that can do all that we need, e.g. TURTLE/TRANSPORT do not handle decapoles or synchrotron radiation, while MAD does not calculate or allow matching of higher-order aberrations. Clearly, there is a need for a more complete beam optics design code.

BDS FOR THE SECOND IR OF NLC

The methods and tools described above have been used to design a Beam Delivery System (BDS) for a second, low energy, Interaction Region (IR) for NLC. This BDS must be somewhat shorter than the primary, high energy, IR BDS (which is 1.4 km long), to allow space for the transport lines that provide the necessary separation between the two IRs (see [8] for more discussion of this configuration). The optics for this preliminary design are shown in Fig-
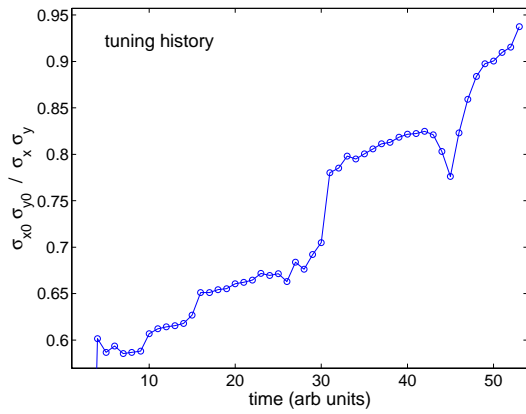
Figure 2: Tuning history for the low energy NLC BDS design. σ_{x0} and σ_{y0} are the nominal linear IP spot sizes.

ure 1. The nominal input beam parameters are: energy E = 250 GeV/beam, emittances $\gamma\varepsilon_{x,y} = (3.6, 0.04) \, 10^{-6}$m, energy spread $\sigma_E = 0.25\%$, bunch length $\sigma_z = 0.11$ mm. At the IP $\beta^*_{x,y} = (8, 0.11)$ mm and $\sigma^*_{x,y} = (243, 3)$ nm.

The optics shown is optimized for 250 GeV/beam. For the 500 GeV/beam case (and for 650 GeV/beam, available with reduced beam current), the final doublet will be replaced with a longer version in order to reduce synchrotron radiation in the FD ("long doublet" version), and the angle of the B1, B2, and B5 bends will be reduced by approximately a factor of two (with simultaneous adjustment of the bends in the energy collimation section to keep the IP location fixed) to reduce synchrotron radiation in the bends.
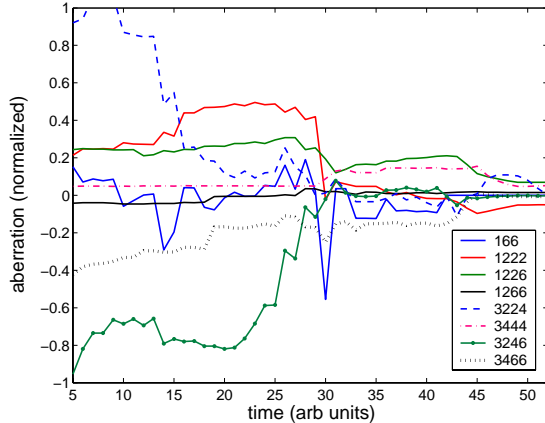

Figure 3: Predominant second and third order aberrations during tuning (normalized to the nominal beam sizes).
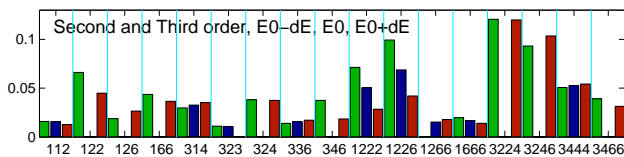

Figure 4: Predominant second and third order aberrations (for the on-energy beam and for $+\Delta E$ and $-\Delta E$) at the final stage of tuning (absolute values, normalized to the nominal beam sizes). Note the symmetry of U3244$_{+\Delta E}$ and U3244$_{-\Delta E}$ terms.
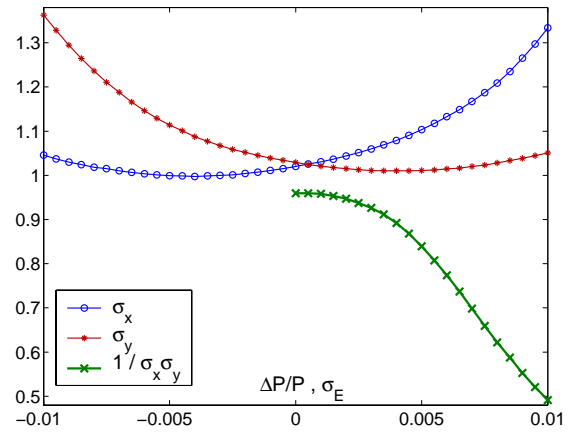

Figure 5: DIMAD tracking results for the final system. Luminosity equivalent IP beam sizes versus energy offset, and $1/\sigma_x\sigma_y$ (normalized) versus energy spread. Hour-glass, beam-beam effects, and synchrotron radiation are not included.

Figures 2 and 3 show the history of the tuning process. The quantity plotted in Figure 2 is equivalent to fractional luminosity. Note that not all intermediate steps are shown. Both hand tuning and automatic optimization with Matlab were used during this process.

Figure 4 shows the predominant second- and third-order aberrations remaining after tuning (absolute values, normalized to the nominal IP beam parameters) for both the on-energy beam and for beams with $\pm 0.2\%$ energy offset. Observation of these aberrations can aid in the creation of additional tuning knobs. Matrix elements for the off-energy beams and their asymmetry give information about fourth- and fifth-order chromatic aberrations. Figure 5 shows the resulting bandwidth of the system, obtained by tracking.

Finally, we note that in spite of the seeming tediousness of this approach to FF design, this method is almost directly applicable for tuning a real final focus during commissioning and operation.

CONCLUSION

A recipe for the optical design of a compact final focus system is presented and illustrated with an example of a preliminary design for the low energy NLC beam delivery system.

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