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Brief Review of Linear Collider Beam-Based Alignment for Linacs

Tor Raubenheimer and Peter Tenenbaum

Stanford Linear Accelerator Center
Stanford University
2575 Sand Hill Road
Menlo Park, CA

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Abstract

All next generation linear collider designs rely heavily on beam-based alignment and emittance tuning techniques. This paper describes the different techniques proposed for the linear collider linacs and discusses some of the operational experience with the different approaches.

All of the linear collider designs rely heavily on beam-based alignment (BBA) techniques to preserve the small beam emittances necessary to attain the desired luminosity [1, 2, 3, 4]. This note will summarize the three different beam based alignment approaches proposed for linear collider: quadrupole shunting, Dispersion Free steering (DFS), and Ballistic Alignment (BA), and some of the possible limitations of these approaches. An attempt will be made to consider systematic and operational limitations as well as the more straight-forward statistical performance limits. It should be noted that many of these comments are subjective because we either do not have experience with the different algorithms or the experience is not definitive. It should also be noted that many of the limitations that are noted here may be overcome with some innovative thinking and dedicated work and should not be taken as the final word!

Beam-based alignment techniques have been used for decades in accelerators, but much of this experience may be difficult to apply. Many of the early applications used relatively poor diagnostics and were primarily interested in beam steering – for example, quad-shunting was used to steer the beam through the SLAC linac and beam switchyard before diagnostics were added. In addition, many techniques have been used in storage rings where the beams tend to be much more stable than in a pulsed linear accelerator where an entirely different set of systematic limitations may apply. Here, we will only consider studies performed at the SLC and at the FFTB – other experience could and should be compiled.

In general, the BBA techniques attempt to 'measure' the alignment by varying some component and measuring the difference between trajectories before and after the change. Thus, provided the quantity being varied accurately represents the source of the dilution, the performance of the BBA techniques relies on the 'precision' of the diagnostics, usually Beam Position Monitors (BPMs), where, by precision, we mean the pulse-to-pulse statistical noise of the beam measurements. For example, the expected performance of the quad-shunting and Dispersion-Free Steering (DFS) algorithms scale as: $\Delta Y = 1 \sim 2\, \sigma_{prec}$, where σ_{prec} is the reading-to-reading measurement jitter. Of course, because the BPMs measure the centroid response to the applied change and do not measure the actual emittance dilution of the beam, the BBA algorithms are sensitive to systematic errors and can converge on solutions that actually increase, rather than reduce, the emittance dilution.

Quad-shunting:

Quad-shunting is a technique for determining the quadrupole magnetic center by varying the quadrupole strength and measuring the resulting deflection on downstream BPMs. If a BPM is located in the center of the quadrupole being shunted, the relative quad-to-BPM alignment can be determined. The statistical resolution can be improved by using a number of upstream BPMs to fit the incoming betatron oscillation and multiple downstream BPMs to fit the outgoing oscillation.

The quad-shunting technique has been used many places but we will discuss the experience at the FFTB [5,6]. Here, 30 quadrupole were aligned using the quad-shunting technique. Typical strength variations were about 25% and the stripline BPMs had a precision of 1 μm. The incoming beam jitter was relatively large, as much as 40 μm in places and had to be fitted out. The residuals of the fits on the quadrupole centers varied from less than 1 μm to more than 50 μm. The large residuals occurred close to the IP – such a dependence is not unexpected in a final focus system where both the optics becomes less optimal for BBA and the number of downstream BPMs decrease as one approaches the IP. In the upstream beta matching region, where the optics is more similar to a linac optics, the fit residuals were less than 3 μm. In addition, dispersion measurements can be used to set an upper bound on the alignment of these quadrupoles of roughly 7 μm. It is expected that with more favorable beam optics, improved BPMs, and smaller beam jitter, the results might be better.

Of all BBA methods, this technique is the least sensitive to systematic errors. It is a nulling technique where knowledge of the detailed beam optics is only needed to fit out the incoming beam jitter. The primary source of systematic error is believed to be shifts of the quadrupole center during changes in the magnet excitation [7]. Very roughly this will set a limit on the effective alignment of $\Delta Y / \Delta K/K$, where ΔY is the shift of the magnetic center and $\Delta K/K$ is the fractional change in strength. Measurements of an NLC-like electromagnet with a radius of 0.63 cm, shows a center shift of roughly 1 μm after a 20~30% strength [8] change implying a ~4 μm systematic alignment error – it might be expected that the shift scales with the bore of the magnet. A similar level of systematic alignment errors is found by scaling the magnetic measurements of the FFTB quadrupoles with a pole tip radius of 1.1 cm to the NLC [7]. In addition, the ~7 μm limit set by the dispersion measurements in the FFTB are consistent with these estimates.

One disadvantage of the quad-shunting technique is that it is relatively slow. With advanced software, multiple magnets, separated by 10~20 BPMs, could be measured at the same time although care would need to be taken to ensure that the beam trajectory stays reasonably close to the axis and the beam size does not grow excessively due to beta-beats. It is thought that the quad-shunting could be completed in one shift (8 hrs) for the NLC without measuring multiple magnets at the same time – this is roughly 15 times faster than at the FFTB. It is hoped that the technique could be implemented as quickly as 1 to 2 hours when measuring multiple magnets at the same time.

Dispersion-Free Steering:
The Dispersion-Free Steering (DFS) [9] attempts to correct the dispersion and the trajectory at the same time, thereby reducing the dispersive emittance growth. The dispersion is 'measured' by varying the beam energy or the magnetic field strengths. Then, both the trajectory and the difference between the on- and off-energy trajectories are minimized using weights that are based on their respective accuracies. For the trajectory, the weight should be equal to the expected misalignments σ_{BPM} while for the difference trajectory the weight would be equal to $1.4\sigma_{prec}$, where σ_{prec} is the BPM precision (reading-to-reading jitter). The technique is relatively easy and fast to implement although, for reasonable changes in the effective energy, it will be invasive to luminosity operation. The statistical limit of the residual dispersion will be roughly equal to $1.4\sigma_{prec}$ [10] and, although the trajectory may make large excursions, over distances comparable to the betatron wavelength, the trajectory should be locally smooth. It should be noted that, even without systematic errors, the DFS technique does not correct wakefield dilutions due to the beam trajectory, in fact, it can actually increase the emittance dilution due to wakefields [11].

Unfortunately, the DFS technique is quite sensitive to systematic errors and the sensitivity scales with both $1/\Delta E$, where ΔE is the effective energy change used to 'measure' the dispersion, and the ratio of $\sigma_{BPM} / \sigma_{prec}$. This later ratio can be quite large. Systematic errors include rf deflections or stray magnetic fields, magnetic hysteresis, quadrupole center variation, BPM errors, beam jitter, and transverse wakefields. Variations of the basic DFS technique have been developed to reduce the sensitivity to the different error sources. For example, changing the beam energy instead of the quadrupole strength reduces the sensitivity to quadrupole center shifts and only varying the rf structures upstream of the region to be corrected enables one to 'measure' the rf deflections and wakefields from structure misalignments [4].

Many groups have studied Dispersion-Free Steering extensively but it can be quite difficult to properly include all of the relevant effects into the simulations. As a simple example, consider the effect of beam jitter on the off-energy trajectory measurement. Typically the incoming jitter is fitted out. However, if the jitter causes a y-z correlation due to wakefields or dispersion or if there is a modeling or an energy scaling error such that the model phase advance is not correct, the trajectory will appear to grow as the beam propagates down the linac. In this case, the DFS algorithm may add a betatron oscillation to the final corrected trajectory – not a good solution!

There were four attempts to implement DFS in the SLAC linac: spring of 1991, spring of 1992, fall of 1993, and 1995. To model a future linear collider, the bunch charge was reduced to 1e10, making the effect of the wakefields similar to that in NLC or CLIC. The effective energy was changed by scaling the quadrupole magnets by 10%, 20%, and 30%. The algorithm appeared to converge in each of the four studies, but the residual dispersion was roughly 4 larger than that expected from simulation implying an effective quadrupole alignment of roughly 60 microns. Measurements of the beam emittance did not show any improvement. Possible sources of error include: rf deflections, beam jitter in transverse and longitudinal phase space, shifts of the quadrupole centers during shunting, and BPM errors. Attempts were made to understand the poor solutions. A paper was written in 1995 [12] summarizing the final attempt with some suggestions as to the sources of the error; these ideas were never confirmed.

Subsequently, a version of DFS was implemented and found to improve the performance of the SLC [13]. The approach, referred to as Two-Beam DFS, used information from both the co-accelerated positron and electron beams. This reduces the sensitivity to many systematic errors because the effective energy change is 200% and the quadrupole strengths are not changed. There is, however, an additional error from the systematic BPM reading differences between the electron and positron beams. Detailed comparisons were not made between the expected and observed performance. It would be difficult to implement this technique in a future linear collider because of the two beam requirement.

A technique very similar to the Two-Beam DFS had been used since 1989 in the SLAC linac to find quadrupole and BPM misalignments [14]. The approach used position data from both the electron and positron beams to find the BPM and quadrupole misalignments – the DFS algorithm uses the same information to reduce the dispersion. It was believed that the resolution of this technique, i.e. the residual quadrupole and BPM errors, was roughly 4 ~ 6 times the BPM resolution. In the SLC, the BPM resolution was between 15 and 25 microns and the residual statistical quadrupole and BPM errors were roughly 100 microns [15]. This residual is roughly 2 times larger than what would be expected from simulations [10].

In conclusion, it would seem that the DFS algorithm works quite well although the performance is not as good as simulations indicate. Unfortunately, the algorithm is relatively sensitive to systematic errors and it is not presently clear how these errors will limit the performance as one scales from the SLC to the future colliders. Error estimates of the impact of the systematic errors [9] do not explain the residuals observed during tests at the SLC.

Ballistic alignment:

Ballistic alignment [16] is analogous to DFS except the energy change ΔE is 100%, i.e. the magnets are turned off. In this case, the algorithm is much less sensitive to shifts of the magnetic center which was the primary motivation for developing the technique. However, the algorithm is very sensitive to rf deflections as well as stray or remnant magnetic fields. For example, the ½ Gauss field of the Earth or tilts of the rf cavities that are a fraction of a milli-radian are enough to confuse the algorithm. Estimates of the remnant dipole fields in electromagnets range from 20 mGauss to a few Gauss. Using careful turn-off procedure but not using a bipolar supply to de-Gauss the magnets, measurements of remnant poletip fields of iron dominated quadrupoles at SLAC range from 3 to 40 Gauss. However the variation from pole-to-pole, which determines the remnant dipole field, was not checked. No estimates of the remnant fields due to persistent currents in the TESLA superconducting quadrupoles have been made [17].

Finally, at this time, there is little or no operational experience with true ballistic alignment. Because the quadrupoles and the rf acceleration must be turned off in the alignment region, some difficulties will likely arise when trying to transport the beam through the alignment region and downstream. The procedure would probably be operationally more time consuming than the DF steering but less than the quad-shunting techniques.

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