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# Benchmarking/Crosschecking DFS in the ILC Main Linac

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**Abstract**

In an effort to compare beam dynamics and create a "benchmark" for Dispersion Free Steering (DFS) a comparison was made between different ILC simulation programs while performing DFS. This study consisted of three parts. First, a simple betatron oscillation was tracked through each code. Secondly, a set of component misalignments and corrector settings generated from one program was read into the others to confirm similar emittance dilution. Thirdly, given the same set of component misalignments DFS was performed independently in each program and the resulting emittance dilution was compared. Performance was found to agree exceptionally well in all three studies.

## 1 Introduction

There have been previous comparisons of the performance of ILC simulations codes [1, 2, 3, 4]. These have found good agreement when comparing emittance growth due to betatron oscillations, wakefields and off-energy nonlinearities. The general conclusion is that BMAD [5], LIAR [6], Merlin [7], PLACET [8] and MAD [9] all simulate the emittance dilution in the ILC main linac equally well. However, these simulations never directly compared the performance of a main linac Beam-Based Alignment (BBA) algorithm. Instead, they implicitly studied the performance by studying various components of emittance dilution separately. The purpose of this study was to extend the simulation crosschecking to include the explicit performance of a specific static Beam-Based Alignment algorithm. DFS was chosen as it is the most complex and widely used of the BBA currently being studied.

Potential sources of error include incomplete or incorrect models of imperfections and instrumentation performance, conceptual errors in the correction procedures and "simple" programming bugs. In order to avoid these, strong interaction with the relevant other working groups is essential as well as comparisons between the different codes. This paper is the next step in the continuing endeavor to compare simulation codes.

## 2 BBA Simulation Codes

Since the last set of simulation comparisons, there have been some changes to the simulation codes actively used. MAD is no longer used for alignment purposes due to its limited functionality. Three new codes

| Parameter | unit | value |
|---|---|---|
| Energy | GeV | 5.0 |
| $\sigma_\delta$ | % | 3.0 |
| $\sigma_z$ | mm | 300 |
| Charge | $10^{10}$ e | 2.0 |
| $\gamma\epsilon_x$ | nm | 8000 |
| $\gamma\epsilon_y$ | nm | 20 |
| $dP_z/d_z$ | $m^{-1}$ | 0.0 |

Table 1: Initial Main Linac Beam Parameters

have become active, these are CHEF [10], Lucretia [11] and SLEPT [12]. One of these new codes, SLEPT, has been included in the following analysis. The other two are in different stages of crosschecking. Any discrepancies between these and the fully reviewed codes are currently being studied.

The decision to perform this round of BBA benchmarking was taken in February 2006. At that time, there was no standard main linac lattice for the ILC. Some groups were using the TESLA TDR lattice [13] others were using the USColdLC lattice [14] and neither utilized precisely the current ILC layout. It was decided that the TESLA TDR lattice would be the benchmarking lattice if for no other reason than most of the codes had already gotten a version of this lattice to work. The purpose of this study was not to determine the absolute alignment requirements or absolute DFS performance but rather to compare the simulation codes and DFS implementations so the choice of the lattice was rather arbitrary, provided it reflected the general layout of the machine. The wakefields used were the TESLA TDR wakefields and not the newer version [15]. Table 1 gives the initial beam parameters used in the study. These values are consistent with the TESLA TDR specification. Some codes track macroparticles (second moments) whereas others track a distribution of single particles (first moments). The number of particles tracked also varies between the codes.

# 3 Study #1: Betatron Oscillation

The first study was to simply track a betatron oscillation due to a 5 micron vertically offset beam entering the linac. The linac is perfectly aligned. The absolute orbit of the betatron oscillation is not interesting and will not be plotted here but for comparison with the plotted data, the amplitude was about 10 microns at the beginning of the linac and damped down adiabatically to about 3 microns at the end. Figure 1 give the difference in orbit between five of the codes with respect to the LIAR results. The difference in orbit is no more than half a micron and is small compared to the absolute orbit amplitude. Figure 2 gives the difference in emittance for the five codes with respect to the LIAR results. The absolute emittance growth curve is again uninteresting but for LIAR the total emittance growth is 1.2 nm. Again, the difference is small compared to the absolute emittance growth. Also, since the desired accuracy in emittance measurements need not be greater than 5% the variance in the results of no more than 0.1 nm is completely negligible.

This study lead to the discovery of some differences in the codes. A wakefield lookup table was supplied with the lattice file to ensure every code used the same function. However, different codes use different methods to calculate the reference energy. Since the quadrupole strengths are relative to the reference energy we found this to be an issue. Specifically, due to beam loading, the cavities will have lower gradient than the design value of 23.4 MeV/m. Different codes calculated the beam loss separately and we settled on a specific beam loading value to ensure similarity between the results. In the end, the difference in beam reference energy was no more than 2.5 Mev at the end of the linac for three of the codes (BMAD, Merlin and SLEPT). This small difference was found to give good conformance between the codes. Figure 3 shows the difference in reference energy along the linac. All curves but one lie along the horizontal axis. The one that doesn't (PLACET) compensates for the higher reference energy by increasing the quadrupole strengths by the same relative amount. Figure 4 shows the difference in quadrupole strength along the linac. The ratio of the reference energy to the quadrupole strengths is therefore kept constant and this effectively cancels out any difference in the betatron orbit.

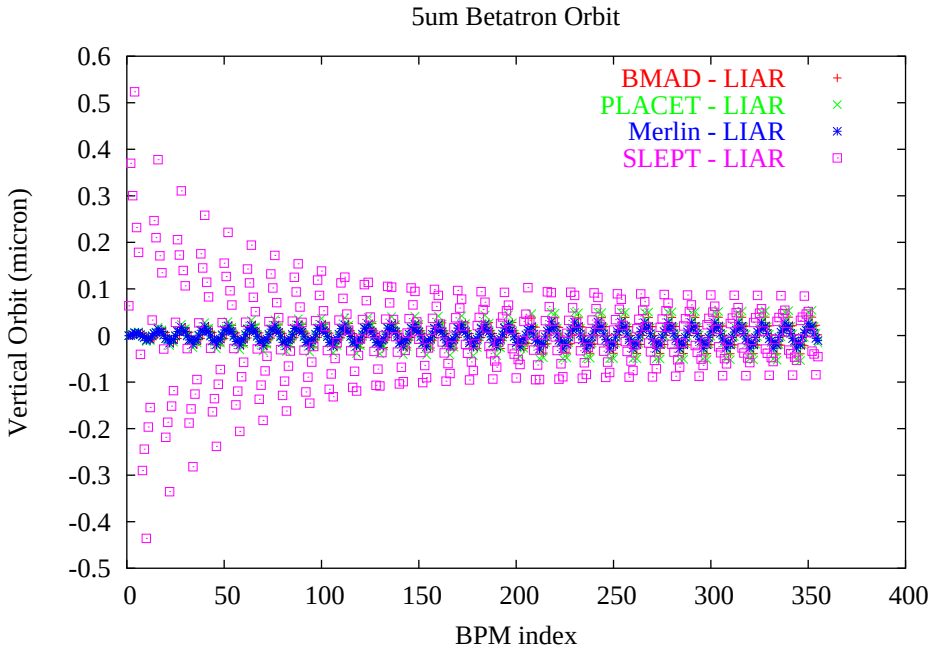


Figure 1: A betatron oscillation through the main linac due to a 5 micron vertical offset. Plotted here is the orbit difference between five codes.

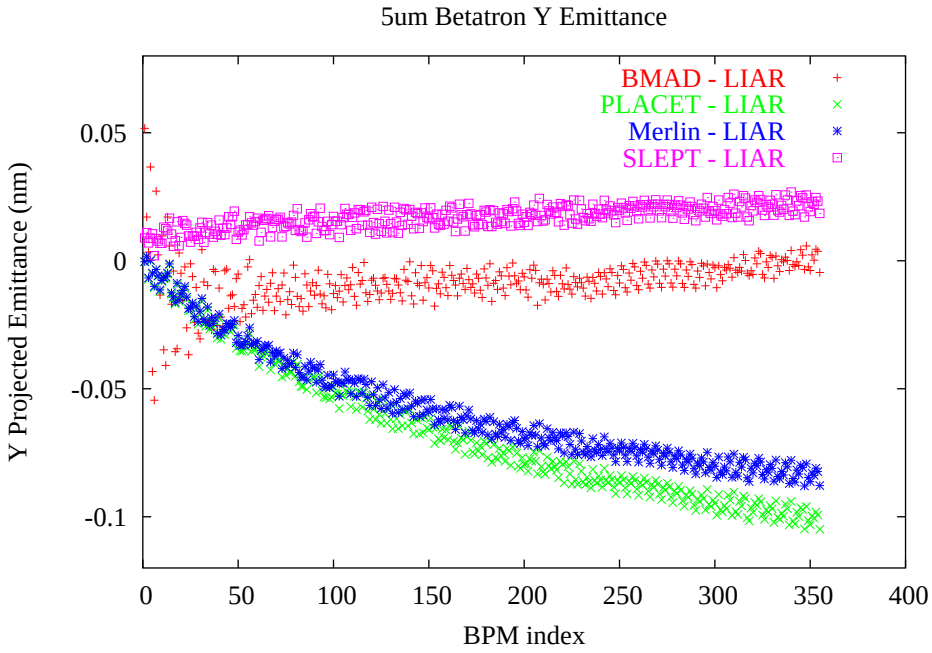


Figure 2: Betatron oscillation emittance growth through the main linac due to a 5 micron vertical offset. Plotted here is the difference in emittance between five codes.

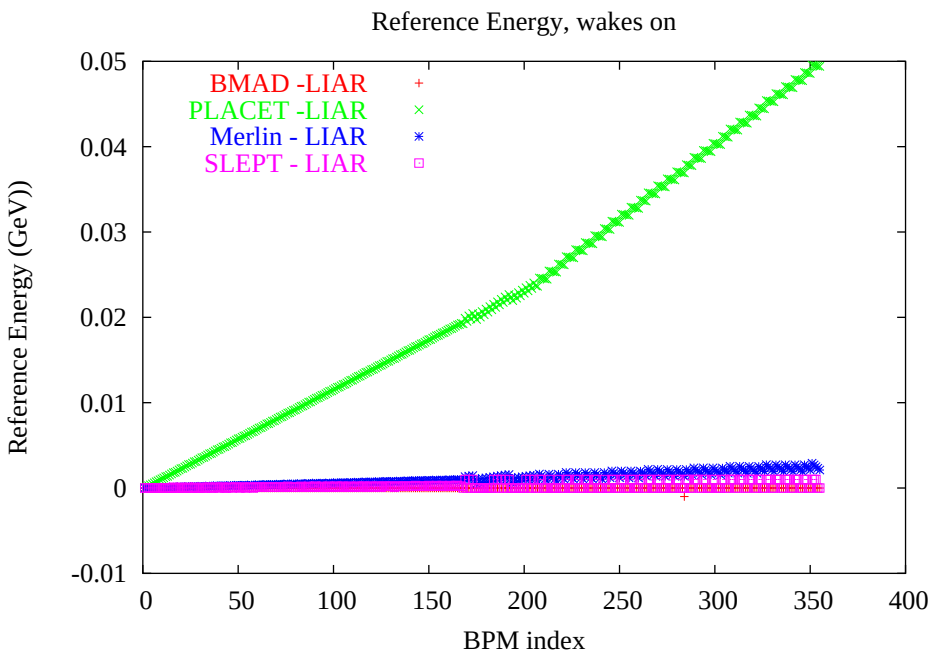


Figure 3: Lattice reference energy along the Linac.

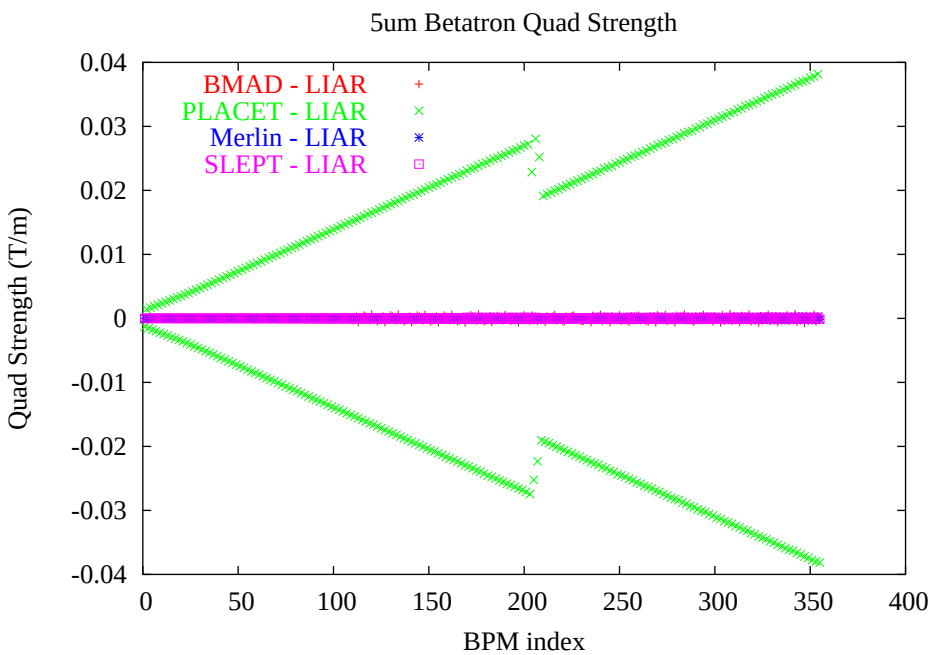


Figure 4: Quadrupole strength along linac.

| Error | RMS | With respect to... |
|---|---|---|
| Quad Offset | 300 $\mu$m | Cryostat |
| Quad Tilt | 300 $\mu$rad | Cryostat |
| BPM Offset | 300 $\mu$m | Cryostat |
| RF Cavity Offset | 300 $\mu$m | Cryostat |
| RF Cavity Pitch | 200 $\mu$rad | Cryostat |
| Cryostat Offset | 200 $\mu$m | Survey Line |

Table 2: Initial Main Linac Beam Parameters

Another issue was the ponderomotive force [19]. One code package, BMAD, includes this force in the accelerating cavities. It was found to affect the orbit on the order of 0.1 microns in this study and is measurable on the scale of Figure 1. For the sake of the comparison, the ponderomotive force was turned off for the remainder of the studies in this paper. The effects of the ponderomotive force are discussed in more detail in reference [20].

# 4 Study #2: A Standard Set of Misalignments and Corrector Settings

The second study consisted of generating a set of misalignments and then running DFS in only one of the codes. This set of misalignments and corrector settings was then loaded into the other codes to compare the emittance dilution in each. Table 2 gives the RMS values used to generate the misalignment file. These values are not necessarily to be treated as the alignment tolerances for the main linac but just a standard used for the comparison. The BPM resolution was set to zero (i.e. perfect BPM resolution). This was done in an effort to simplify the problem. The various codes may very well treat BPM resolution differently in the DFS algorithm and a future study should probably include this source of error. Another step taken to simplify the problem was to perfectly align the first 9 cryomodules plus all components located on them. This was done in order to ignore the varying methods used to re-steer the beginning of the linac. DFS cannot be performed in this region due to insufficient energy variance from turned off cavities so some other method must be used (or the bunch compressor could possibly be used to alter the incoming beam energy).

Figure 5 gives the emittance dilution in each of the codes after reading in LIAR's misalignments and corrector settings. The agreement is remarkable and well within acceptable levels. This agreement was not, however, without discovering and fixing a couple bugs in some of the codes. The spikes seen at the beginning are due to the DFS method used in LIAR and have since been eliminated. Nevertheless, the other codes reproduce the spike obediently.

# 5 Study #3: A Standard Set of Misalignments but Independent DFS Runs

The final study consisted of one code generating a 100 seed set of misalignment files and then the other codes reading in the misalignments and performing their own DFS on each.

## 5.1 Dispersion Free Steering Algorithm Used in this Study

There are several Dispersion Free Steering Algorithms being used. The method chosen for the study was based on LIAR's DFS algorithm described in [16] which was derived from the original DFS method described in [17]. The method is summarized in the following steps:

1. Divide the linac into regions of 20 FODO cells where each region overlaps its neighbor by 10 cells.

2. For each region, first take an orbit at the nominal energy, call it $x_{on}$

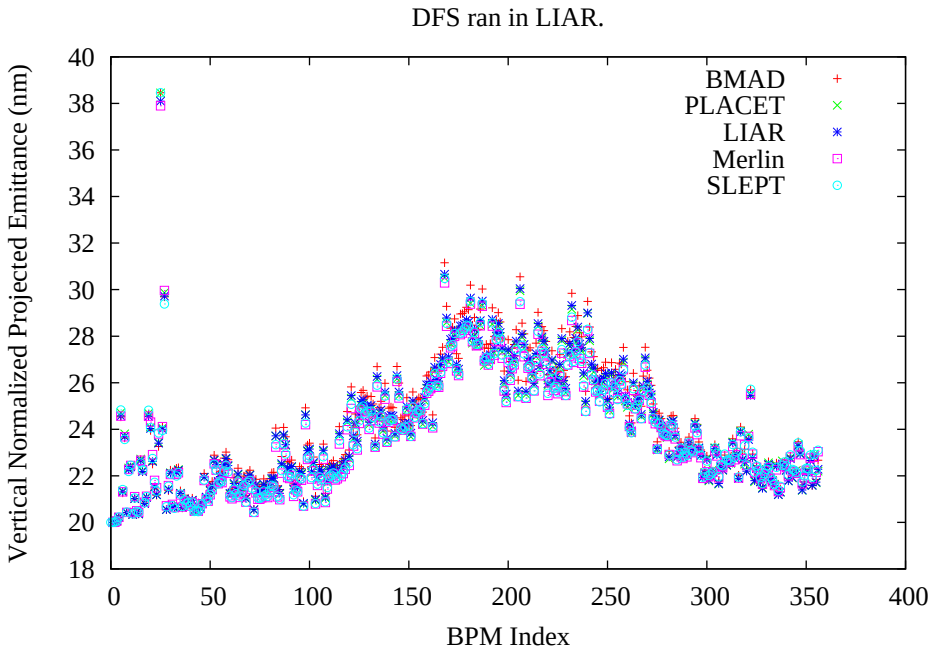


Figure 5: Emittance dilution after performing DFS in LIAR and reading misalignments and corrector settings into the other codes.

3. Now change the energy of the beam entering the region by 20% or 18 GeV, whichever is less. This is achieved by turning off an appropriate number of RF cavities upstream of the region being steered.

4. The off-energy beam will have a different orbit entering the region. Using the measured orbit before the energy change and the current orbit with the energy change, use three steering magnets and three BPMs upstream of the region to re-steer the beam to the on-energy orbit.

5. Take the off-energy orbit, call it $\mathbf{x_{off}}$. The difference between the two orbits is called $\mathbf{x_d} = \mathbf{x_{on}} - \mathbf{x_{off}}$

6. Minimize the merit function

$$\chi^2 = \sum_i w_1 \left(x_{on_i}^2\right) + \sum_i w_2 \left(x_{d_i}^2\right) + \sum_j w_3 \left(c_j^2\right) \tag{1}$$

   where $i$ runs over all BPMs and $c_j$ runs over the corrector magnet strengths in the region.

7. Goto 2 and repeat until the merit function converges.

8. Proceed to the next region and goto 2.

Before this algorithm can be applied, the response matrix for minimizing the merit function must first be determined. This response matrix is found using a theoretical model lattice without misalignments. The various codes do make slight modifications to the above method and the one described most closely resembles that found in BMAD. For this study the weighting on the corrector magnets was set to zero ($w_3 = 0.0$). The on-energy orbit weight was set to, $w_1 = 2.52 \times 10^{-5}$ and the difference orbit weight, $w_2 = 1.0$. With the corrector strength weight zeroed there is effectively only one weighting parameter, the ratio $w_1/w_2$. One important difference between this method and others is that the accelerating cavities within the DFS region are not altered from their design values. This is to ensure dispersive kicks due to pitched cavities will be correctly accounted for in the dispersion minimization.

Figure 6 gives the results of the study. The agreement is again very good. The SLEPT data is labeled "SLEPT Mode 1." SLEPT has three modes of DFS. Mode 1 is most similar to the DFS algorithm performed in the other codes, and most significantly, the accelerating cavities in the DFS regions are not

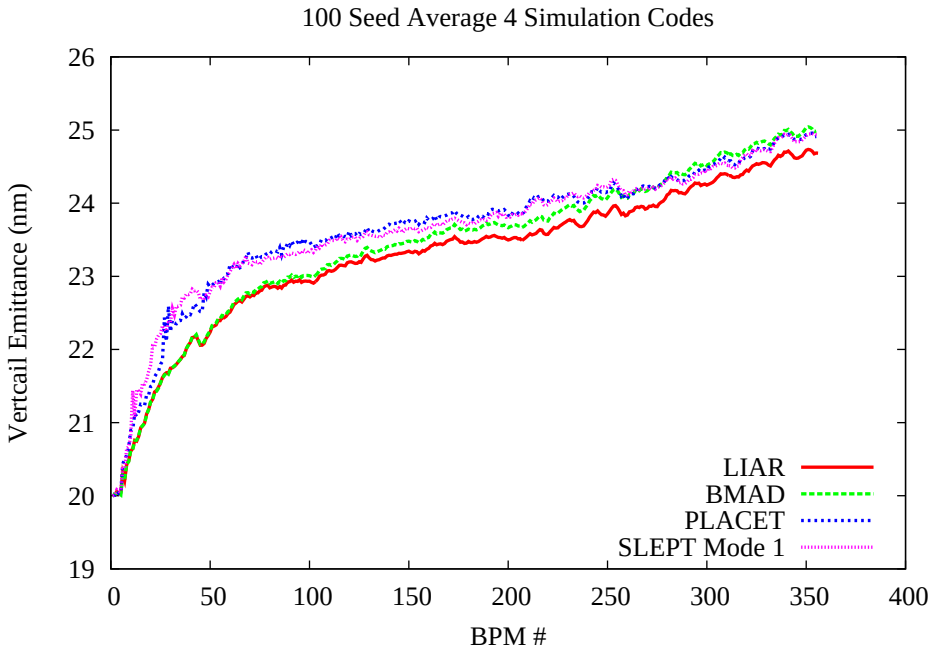


Figure 6: Each code performing DFS separately using the same 100 seeds.

altered. There are other differences between mode 1 and the BMAD method explained above but as the similarity in the curves suggests, the differences are insignificant.

A separate study has been performed comparing PLACET to MERLIN using a separate lattice and misalignment seeds [18]. Agreement was again found to be quite good between these two codes and complement the work done in this study.

## 5.2 Detailed study between BMAD and LIAR

BMAD and LIAR have the most similar agreement in Figure 6. This is not a coincidence. These two teams spent an extended period of time comparing the performance of the two codes and were able to identify the key factors contributing to any differences between the two. The results in Figure 6 are after these efforts. One notable difference was in the method used to re-steer the off-energy beam. LIAR essentially included three steering magnets before each region in the optimization process whereas BMAD did the steering separately as described in Section 5.1. Another issue was precisely which accelerating cavities were turned off. It would be too laborious to describe precisely which cavities were turned off here, but stated simply, Bmad defined a region to begin at the beginning of a cryomodule whereas LIAR defined it to begin at a BPM. The last turned off cavity in both codes was upstream of the beginning of their respective region so the section of cavities turned off is shifted along the linac between the codes. This provided the most significant difference in the performance between the two codes. Figure 7 shows the difference in performance before and after this careful analysis was performed. The difference in curves begins precisely at the beginning of the second region and mainly due to which cavities are turned on and off. Careful comparison between Figure 7 and Figure 6 suggests this may also be one of the reasons for the slight difference between BMAD and PLACET. However, the differences here are slight and may not be worth pursuing.

## 5.3 Detailed Study between BMAD and SLEPT's three modes.

As briefly mentioned above, SLEPT has three "modes" of DFS. The main difference is that SLEPT will scale all accelerating cavities by a set amount versus turning off cavities. Two other differences are that SLEPT will also change the incoming beam energy and only two upstream BPMs are used for off-energy

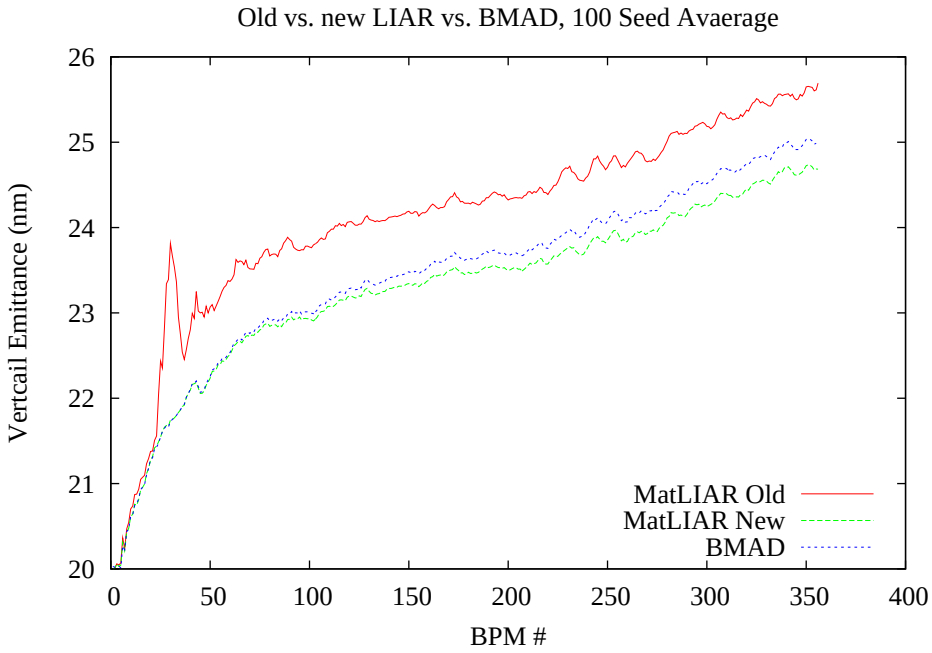


Figure 7: Comparison between BMAD and LIAR before and after modification to LIAR to perform more closely to BMAD.

re-steering, not three as in the "standard" method. The critical differences are summarized as follows:

1. Mode 0 scales the energy gradient of the whole machine including the DF region being steered. This effectively reduces the ability of DFS to correct pitched accelerating structures.

2. Modes 1 only alters the gradient from the beginning of the LINAC to the beginning of the DF region. The DF region being steered is therefore unchanged. This mode is most similar to the "standard" method described above.

3. Mode 2 is just like Mode 1 except there is no re-steering of the off-energy beam as it enters the DF region.

Figure 8 gives a comparison of BMAD's 3 modes and SLEPT's 3 modes. These were all performed with the same 100 seeds as in the previous studies. The agreement between BMAD and SLEPT is good however BMAD appears to handle the first region better than SLEPT but the difference is mostly removed by the end of the linac. Figure 9 gives the three modes plus the "standard" mode all simulated in BMAD. Mode 1 performs the best and is virtually identical to the "standard" mode. Mode 2 begins to diverge at the beginning of the second DFS region suggesting that the re-steering is important though not critical. It should be noted that if the "standard" mode is performed with no re-steering the curve is completely off-scale and fails to perform at even remotely acceptable levels. Scaling all cavities (versus turning off some of them) reduces the orbit change for the off-energy beam.

# 6 Conclusions

Studies #1 and #2 have shown that emittance dilution behaves very similarly between five of the ILC simulation codes. Each uses a different beam representation and this was not found to affect the results. Study #3 shows that each code can reproduce the others' results when performing DFS. However, there were several simplifications with this study that may be ignoring potential differences between the codes. One is that the BPM resolution was set to zero. Considering the expected high sensitivity of DFS to BPM resolution, any future studies should include a non-zero BPM resolution. Furthermore, the beginning of

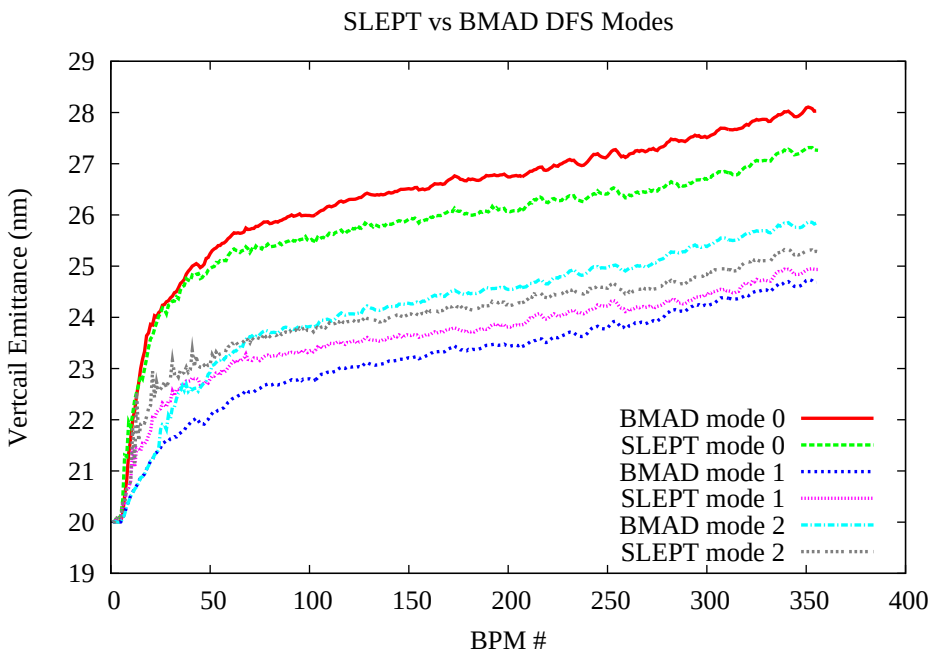


Figure 8: Comparison between BMAD's and SLEPT's 3 modes.

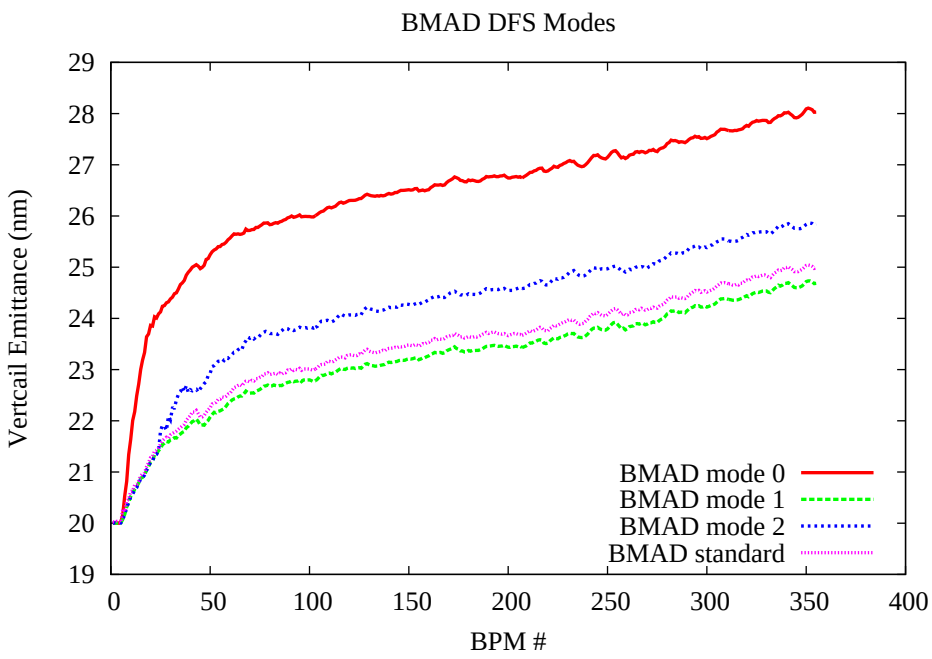


Figure 9: BMAD's 3 modes plus the "standard" mode.

the linac was perfectly aligned since each code had a different method to re-steer this region. Further studies should make a comparison between these methods.

The lattice used is not the current baseline configuration. Once this baseline is in a more final state another set of comparisons would be beneficial. Nevertheless, the studies performed so far still show that each code can reproduce the others' results for an ILC-like lattice. There is therefore now a "benchmark" for Dispersion Free Steering in the context of the ILC main linac that newer codes can be compared to when beginning ILC emittance preservation work. The importance of these comparisons cannot be overstated. Beam-Based Alignment cannot be directly tested experimentally before the construction of the ILC. We must rely on simulations. Comparisons such as in this paper should be conducted at regular intervals and include all areas of the ILC to insure overall agreement. Only through this process will we have the required confidence in our results.

# 7 Acknowledgments

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