Comparison of Beam Based Alignment Algorithms in the Presence of Beam Jitter

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For optimal usage, the alignment of the International Linear Collider (ILC) should maintain the vertical normalized projected emittance growth to at or below one hundred percent of the initial normalized projected emittance (The initial design emittance is 20 nm in the vertical direction). There are three common alignment algorithms (Ballistic Alignment, the Kubo method, and Dispersion Free Steering)[3] that may be employed on the main linear accelerator (linac) of the ILC in order to minimize emittance growth. After preliminary studies of the effectiveness of each of these methods on the basis of only beam jitter (utilizing the standard misalignments), it is found that Ballistic Alignment proves itself to be the most successful algorithm at keeping the vertical normalized projected emittance to at or below the allowed forty nm.

I. INTRODUCTION

The International Linear Collider (ILC) is an electron-positron collider currently in the design stage. Research on the machinery and diagnostics of the ILC is currently being done, through beam simulations, in nations around the world including (but not limited to) The United States, Japan and Germany. Much of the study involving low emittance transport is being done at Cornell University in Ithaca, New York (USA) using a home based program, Tao [1].

Schematically, the ILC is planned to use the TESLA RF cavity design highlighted in [2]. The TESLA design includes two linear accelerators (one accelerating an electron beam and the other accelerating a positron beam) pointed directly at each other, toward an IP (Interaction Point). The length of the machine is planned to be 33 km long in total with the two main linacs taking up the majority of the length. This massive length causes an increased need for precise alignment.

While the alignment of all the instrument parts is essential to a well running machine, the alignment of the two main linacs is of particular importance to maintaining high luminosity and low emittance where the vertical emittance is defined as:
$\epsilon = (< y^2 >< y'^2 > - < yy' >)^{(1/2)}$ [8].

In particular, precise alignment of the quadrupole and dipole magnets (which may improperly kick the beam if misaligned), beam position monitors (which will read incorrect beam position if improperly aligned, giving erroneous information to the magnets), and radio frequency cavities (which can accelerate the beam in the incorrect direction if misaligned) is required for optimal efficiency of the machine. A misaligned linac may raise the emittance of the beam (effectively increase the cross sectional beam size) and reduce number of electron-positron collision, reducing the luminosity. It is for this reason that the linacs must be well aligned and the emittance must be kept as low as possible.

A perfectly aligned machine of this length is quite impossible to accomplish utilized surveying techniques alone. As described in [3], surveying techniques across the length of the collider can produce misalignments of hundreds of microns, so other forms of alignment are required. Three Beam Based Alignment algorithms are studied to reduce the emittance growth due to a misaligned linac in conjunction with surveying tolerances as the preferred alignment algorithm is still uncertain.

The three internationally proposed algorithms are ballistic alignment (BA), Dispersion Free Steering (DFS), and the Kubo method (kubo). Each algorithm is implemented as in [3] and studied in the Cornell University simulations, utilized TAO. Vertical normalized projected emittance growths are tracked and compared [1].

The alignment algorithms themselves assume that the beam is going in a predictable betatron trajectory, however, due to terrestrial and machine motion, the incoming beam may jitter about it's designed path. The jitter itself injects the beam into a linac element off of the design axis which may cause a dispersive kick on some particles in the beam, particularly when the beam travels through a quadrupole or dipole. As in [8], this displaced beam's emittance will then raise as it moves through these dispersive regions. Beam jitter can occur in any dimension of the beam, including x,y, and z (where z is the direction of motion) raising the emittance. The algorithms do not directly address jitter itself, as their purpose is to minimize emittance, so the impact of jitter on each algorithm is studied.

II. ALIGNMENT ALGORITHMS

Ballistic Alignment

Ballistic Alignment (BA) is an algorithm described in [4]. In this method all fields that influence the particle beam are turned off in a particular section of the linac and shielding is used to minimize the effect of outside fields, such as the earth's magnetic field. The natural ballistic, or "golden", orbit is then found for the region through Beam Position Monitor (BPM) readings. As highlighted in [3], with no stray fields the golden orbit of the beam will create a straight line trajectory. After the golden orbit is found the fields are restored and the beam is steered to the golden orbit.

As explained in [3] the linac is divided into sections of 7 FODO cells each. The BPMs at each region end are pivot positions which are zeroed before the ballistic orbit is taken.

Dispersion Free Steering

Dispersion Free Steering (DFS) is an algorithm that steers the beam to minimize the dispersion. As implemented in [3], the linac is divided into regions of twenty FODO cells. Each region overlaps it's surrounding regions by 10 cells. Unlike BA, where only one orbit is taken before steering, DFS utilizes two orbits in order to obtain sufficient data before steering. The first orbit is taken with the beam energy at 100 percent (or full desired beam energy). The second orbit is then taken with the beam energy reduced by 20 percent or 18 GEV (whichever is less). This lowered energy creates a new path for the beam and the difference effectively gives the dispersion. An optimizer (Levenberg-Marquardt [3]) is then employed in order to find the corrector settings that minimize the dispersion. A well aligned linac will create the least amount of dispersion (as dispersive particles will be properly kicked back into the beam from the quadrupoles and steering magnets) and therefore the optimized orbit will also be the orbit at which the machine is properly aligned.

It is important to note that when using DFS the first region can only begin after the first three BPMs, because of the need for sufficient energy change. This indicated that another form of alignment may have to be employed in the ILC to align the first three BPM in order to optimize the performance of DFS.

The Kubo Method

The Kubo method (kubo) is an algorithm in which the steering magnets are set to exactly cancel the kick given to the beam by a misaligned quadrupole by a one-to-one BPM-to-magnet relationship. According to [3] this kick can be mathematically determined by the relationship:

$\theta = k_1 L_q Y_q$.

Where θ is the kick from the quadrupole, k_1 is the quadrupole strength, L_q is the length of the quadrupole, and Y_q is the vertical BPM reading due to the kick from the quadrupole.

Since Y_q gives the beam position through the quadrupole, if a quadrupole and BPM are not aligned a false Y_q term may be read. Quadrupole shunting is employed to properly zero the BPM with the quadrupole (find a zero position that takes displacement into account). In quadrupole shunting the quadrupole strength is diminished by about 20 percent. The resulting change in the orbit is measured on the BPMs downstream and the BPM-to-quad offset is then determined by the shift in the read values of Y_q. This shunting gives an accurate value for the position of the beam through the quadrupole.

The offset is then taken into account, as in [3], and the true kick from the quadrupole is found to be:

$\theta = .01\theta_b + k_1 L_q Y_q$.

Where θ_b is the kick that would be placed on the steering magnet in order to zero the orbit and 0.1 is a weighting factor [3]. This is then implemented in order to properly steer the beam.

III. EQUATIONS AND FIGURES

Given that the beam size in any given direction is: $\sigma_t = (\epsilon * \beta_t)^{(1/2)}$, where t is a horizontal, vertical or longitudinal parameter, and β_t is the twist parameter found in the Tao [1] program. ϵ is found through: $\epsilon = \epsilon_{norm,t}/\gamma$. γ is found by the ratio of the total energy of the linac (5GeV) to the rest energy of an electron (.511 MeV) [1] and $\epsilon_{norm,t}$ is the normalized projected emittance in any direction. The normalized projected emittance can be found in Tao [1]. (σ_z is set by the bunch compressor used.)

Therefore the size of the beam (σ_t) in any given direction is found to be

σ_x (horizontal) = 274.0 microns

σ_y (vertical) = 9.9 microns

σ_z (transversal)= 150-300 microns [6]

It is of interest to study jitter up to about a tenth of a sigma in the X and Z direction, however, in the Y direction it is necessary to study jitter up to ten microns (a full σ_y) because of the small beam size in the direction and the direct correlation between vertical jitter and vertical emittance [7].

Results of Jitter in X direction, 100 seeds

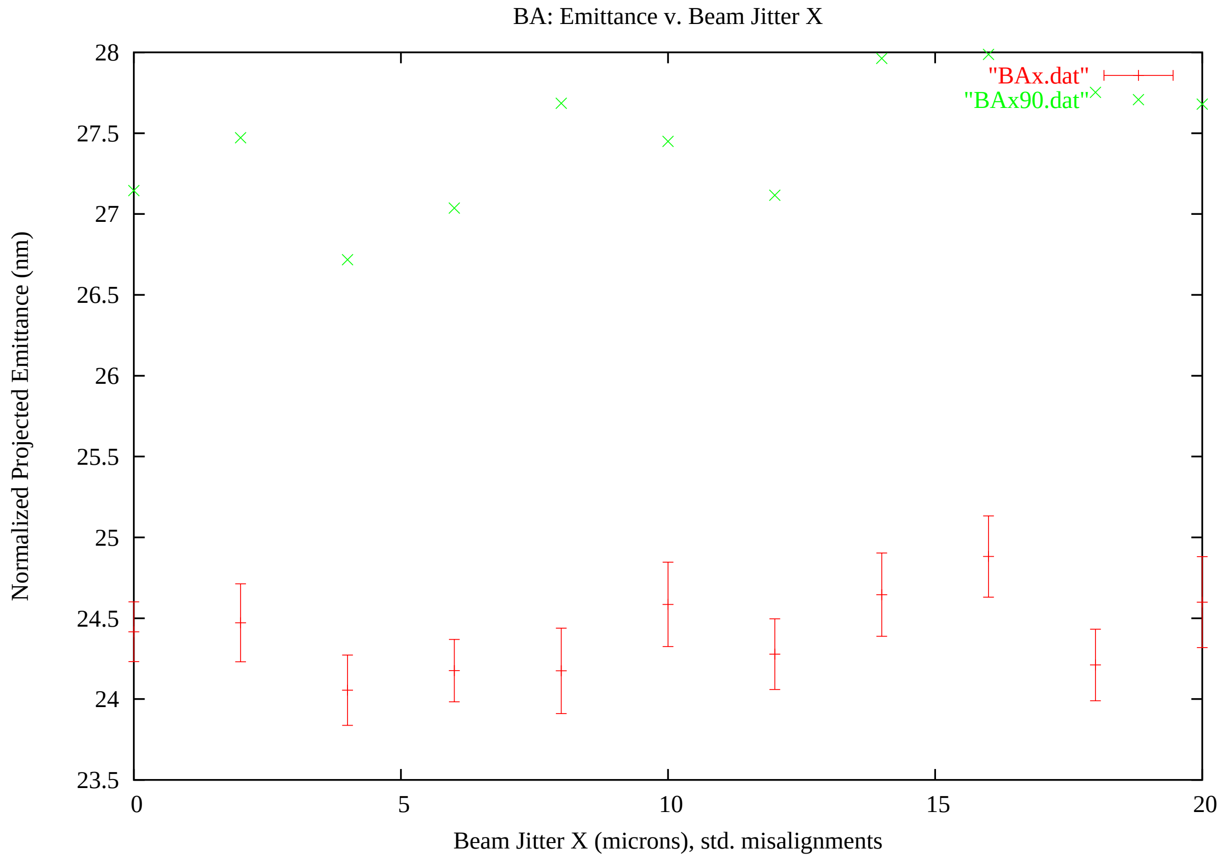

FIG. 1: Ballistic Alignment with x-Beam Jitter and Standard Misalignments - "bax.dat" represents the mean emittance of 100 seeds with the error bars (where y error is the ratio of standard deviation to the square root of the number of seeds). "bax90.dat" represents the 90 percent confidence level. Note that even at twenty micron jitter even the ninety percent confidence value of emittance is still below 40 nm allowance.

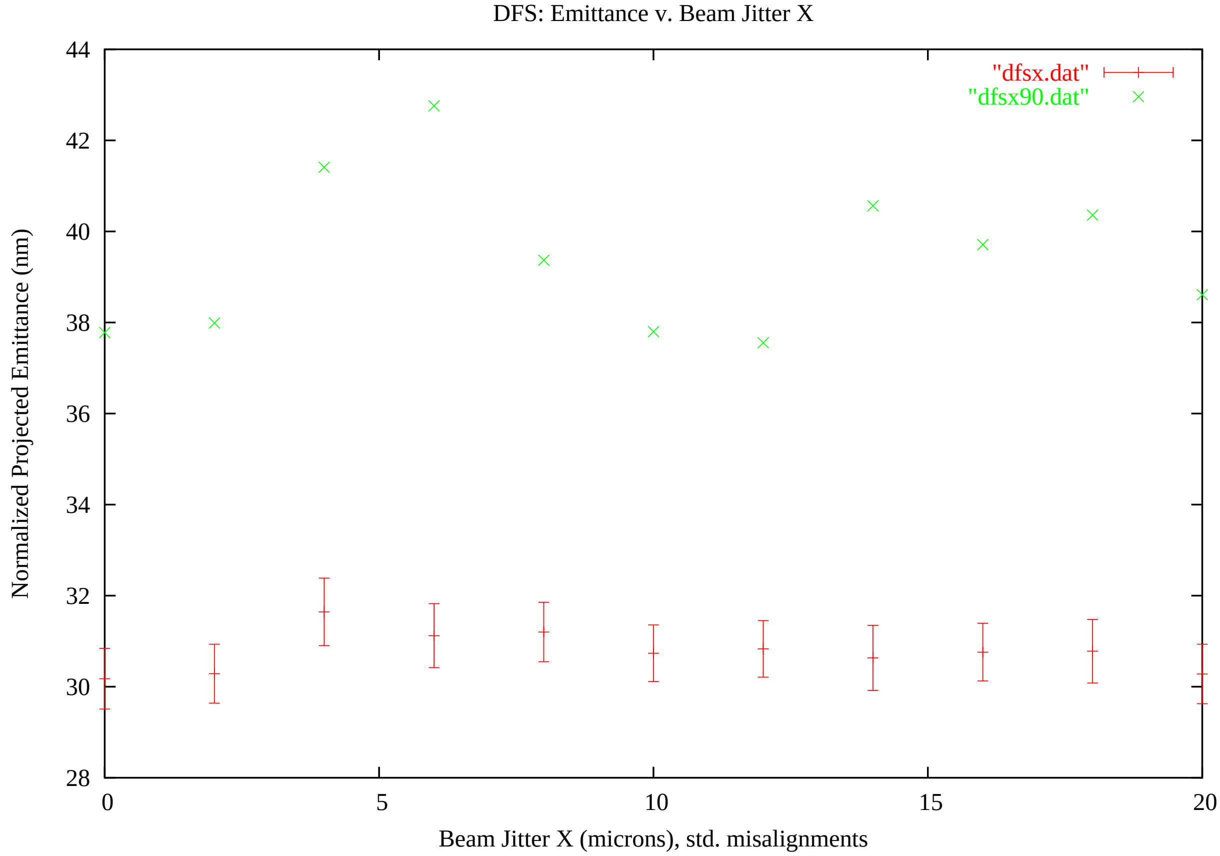

FIG. 2: DFS with x-Beam Jitter and Standard Misalignments - “dfsx.dat” represents the mean emittance of 100 seeds with the error bars (where error is the ratio of standard deviation to the square root of the number of seeds). “dfsx90.dat” represents the 90 percent confidence level

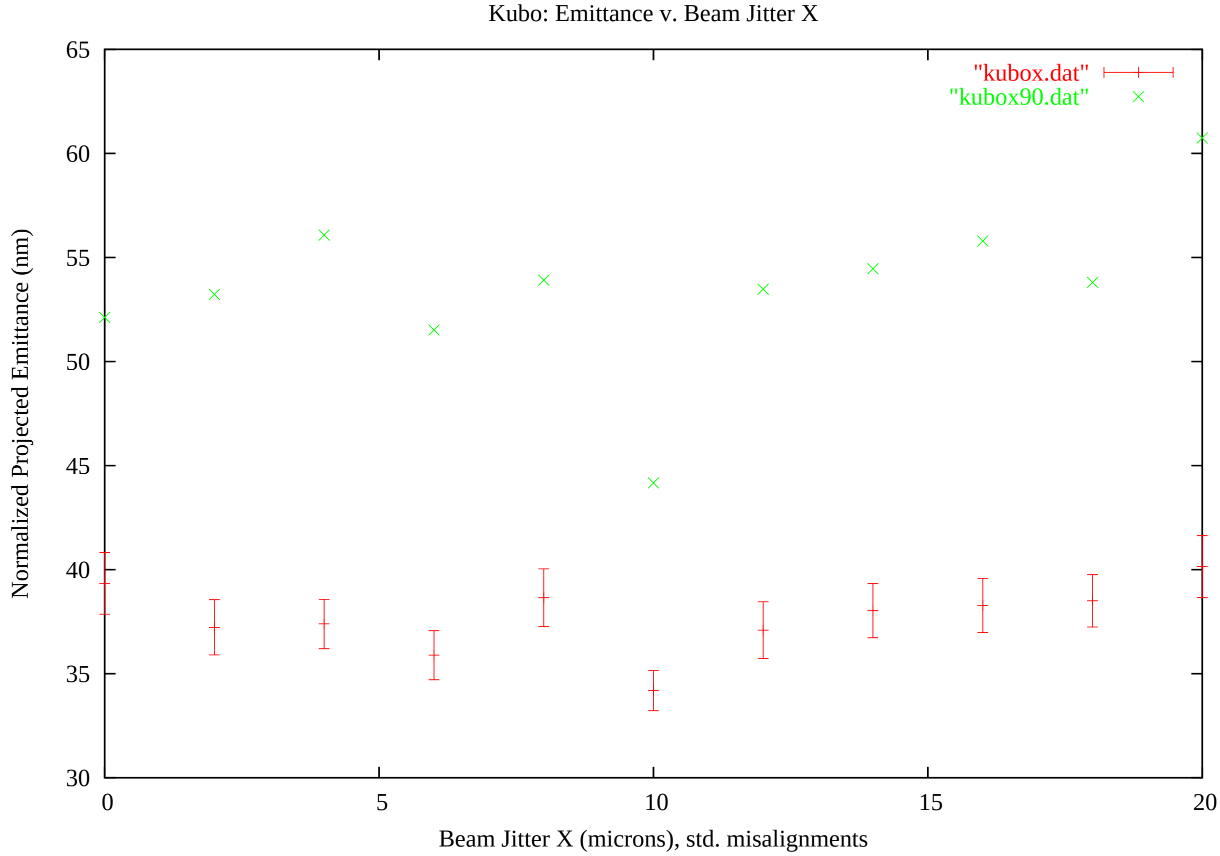

FIG. 3: Kubo with x-Beam Jitter and Standard Misalignments - "kubox.dat" represents the mean emittance of 100 seeds with the error bars (where error is the ratio of standard deviation to the square root of the number of seeds). "kubox90.dat" represents the 90 percent confidence level

Comparing Fig. 1,2, and 3:

It was accepted that as a twenty micron jitter in x is quite large (although it is not quite ten percent of the x-beam size), therefore, continuing simulations to thirty microns was extraneous.[7] In comparing the given spectra of Fig. 1, 2, and 3 it is clear that BA is the more efficient method at minimizing the emittance when there is a jitter in the x direction of the beam, as both other methods quickly gain an emittance over the allotted 40nm, (particularly in the ninety percent values). In fact, the 90 percent confidence values of emittance after BA is preformed stay well within the allowed 40 nm even up to 20 nm of jitter. It can be seen in Figure 2 the 90 percent values hover around the 40 nm mark with some statistical fluctuation. However, in Fig. 3 it becomes clear that kubo is most affected by beam jitter as the 90 percent confidence values for emittance quickly rise above 40nm.

As a whole it can be seen in Fig. 1, 2, and 3 that even at large jitter, the algorithms are not largely impacted by beam jitter in the x direction. This is shown by the linearity of the points on the graph and small statistical fluctuation between subsequent emittance points.

Results of Jitter in Y direction, 100 seeds

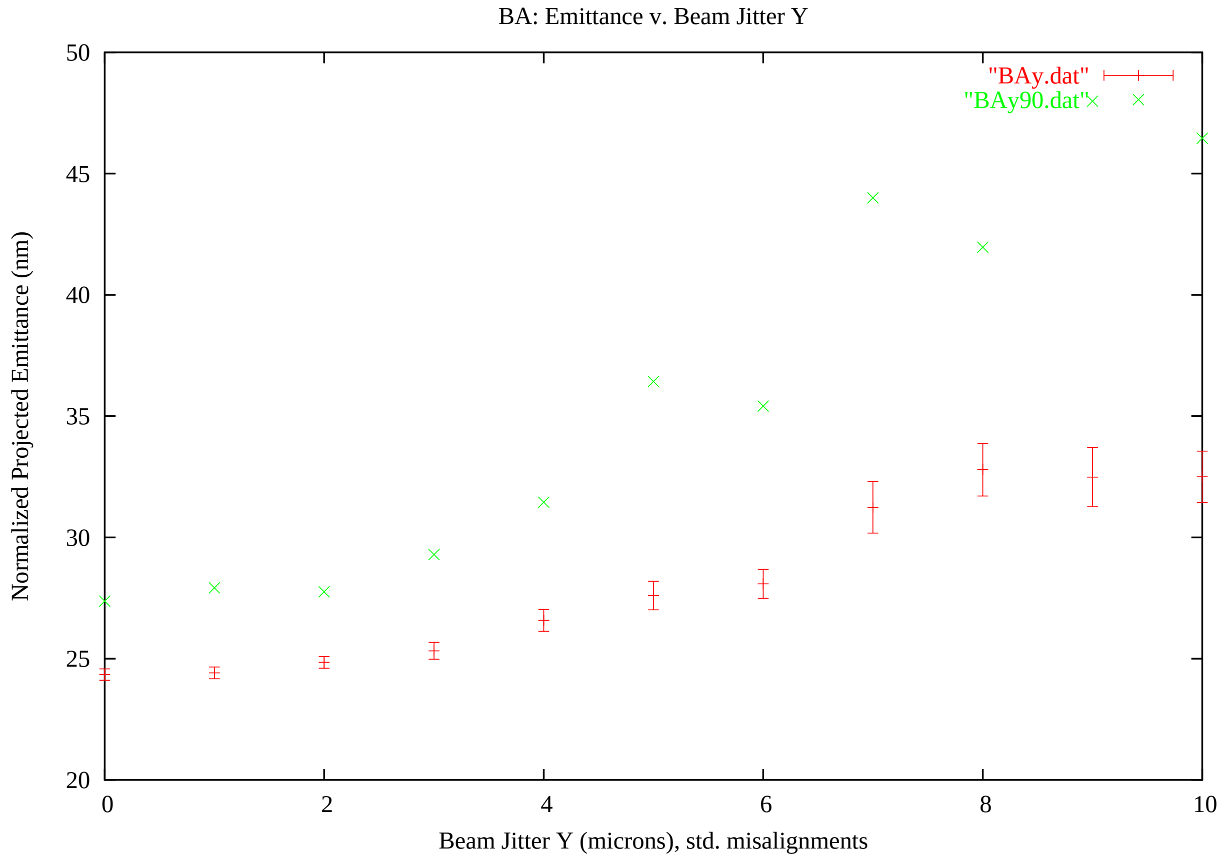

FIG. 4: Ballistic Alignment with y-Beam Jitter and Standard Misalignments - "bay.dat" represents the mean emittance of 100 seeds with the error bars (where y error is the ratio of standard deviation to the square root of the number of seeds). "bay90.dat" represents the 90 percent confidence level

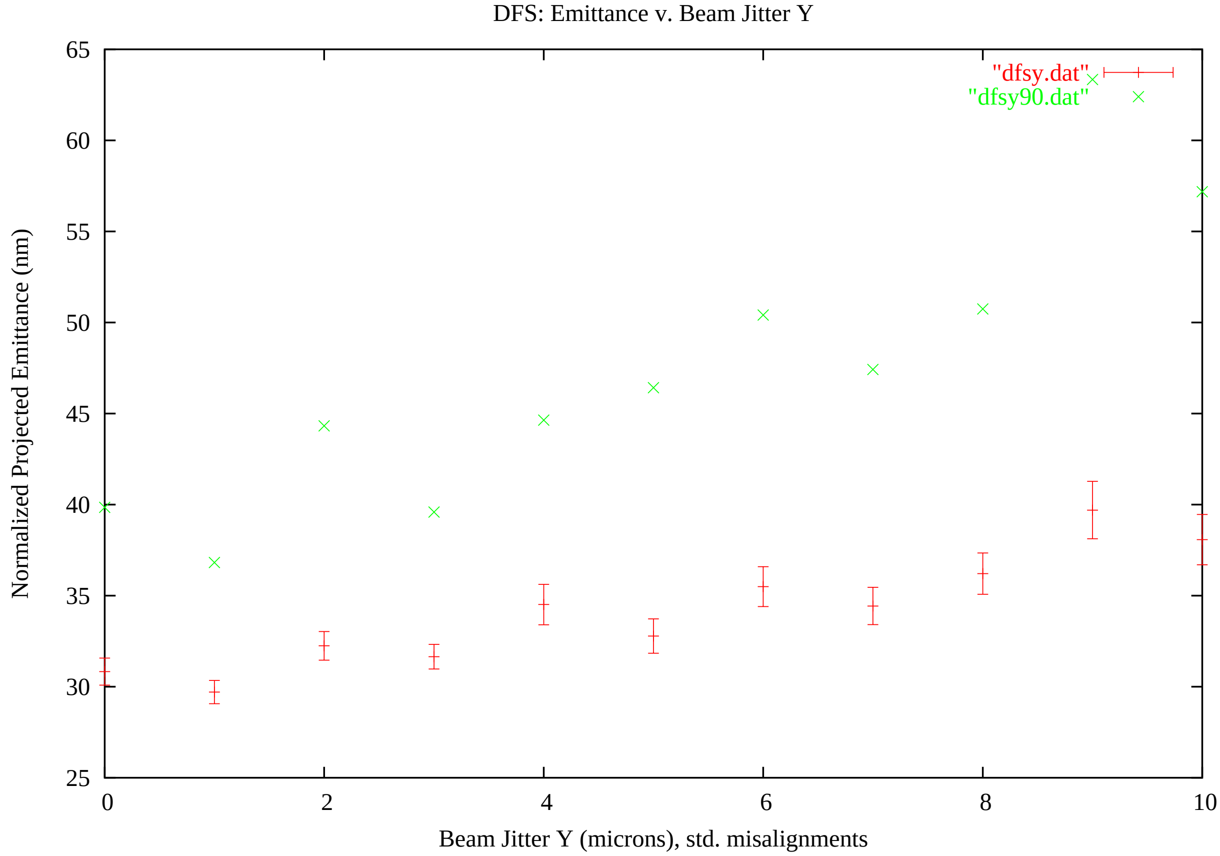

FIG. 5: DFS with y-Beam Jitter and Standard Misalignments - "dfsy.dat" represents the mean emittance of 100 seeds with the error bars (where error is the ratio of standard deviation to the square root of the number of seeds). "dfsy90.dat" represents the 90 percent confidence level

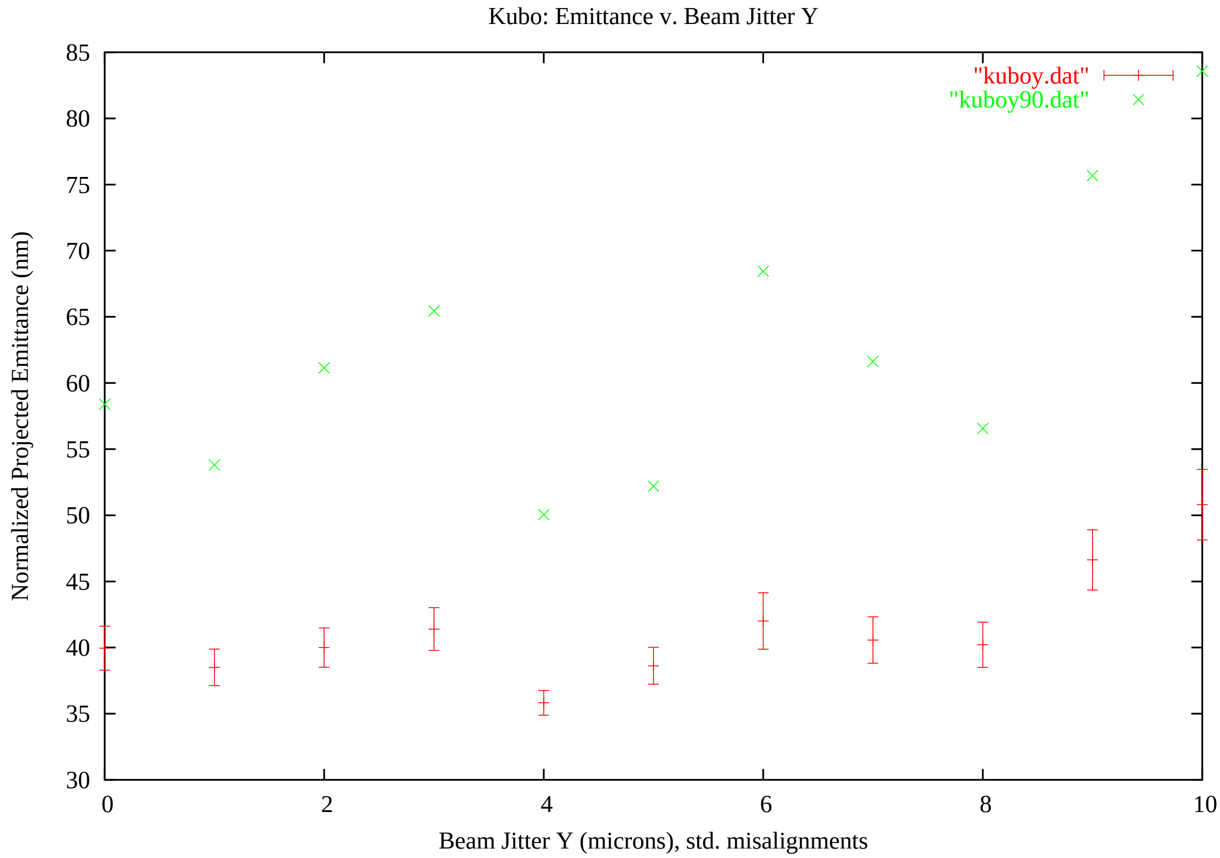

FIG. 6: Kubo with y-Beam Jitter and Standard Misalignments - “kuboy.dat” represents the mean emittance of 100 seeds with the y error bars (where error is the ratio of standard deviation to the square root of the number of seeds). “kuboy90.dat” represents the 90 percent confidence level

Comparing Fig. 4, 5, and 6:

In comparing Fig. 4, 5, and 6 it is noted that for Ballistic Alignment there can be as much as 6 microns of jitter in the y direction and the ninety percent value of emittance is within the 40 nm allowance. At six microns, however, both kubo and DFS are well beyond the accepted emittance value (although DFS's six micron emittance value may be due to a statistical fluctuations, it still produces a higher overall emittance than BA). When taking into account the mean, and error on the mean, it is shown in Fig. 4 that a full σ_y can be implemented without the vertical emittance reaching above the allowed 40nm. fig. 2 shows that DFS also keeps the emittance down to an acceptable level, however it is quite close to the maximum value. The kubo method is proven to be inefficient at 10 microns of jitter as the vertical emittance reaches well above 40nm.

Results of Jitter in Z direction, 100 seeds

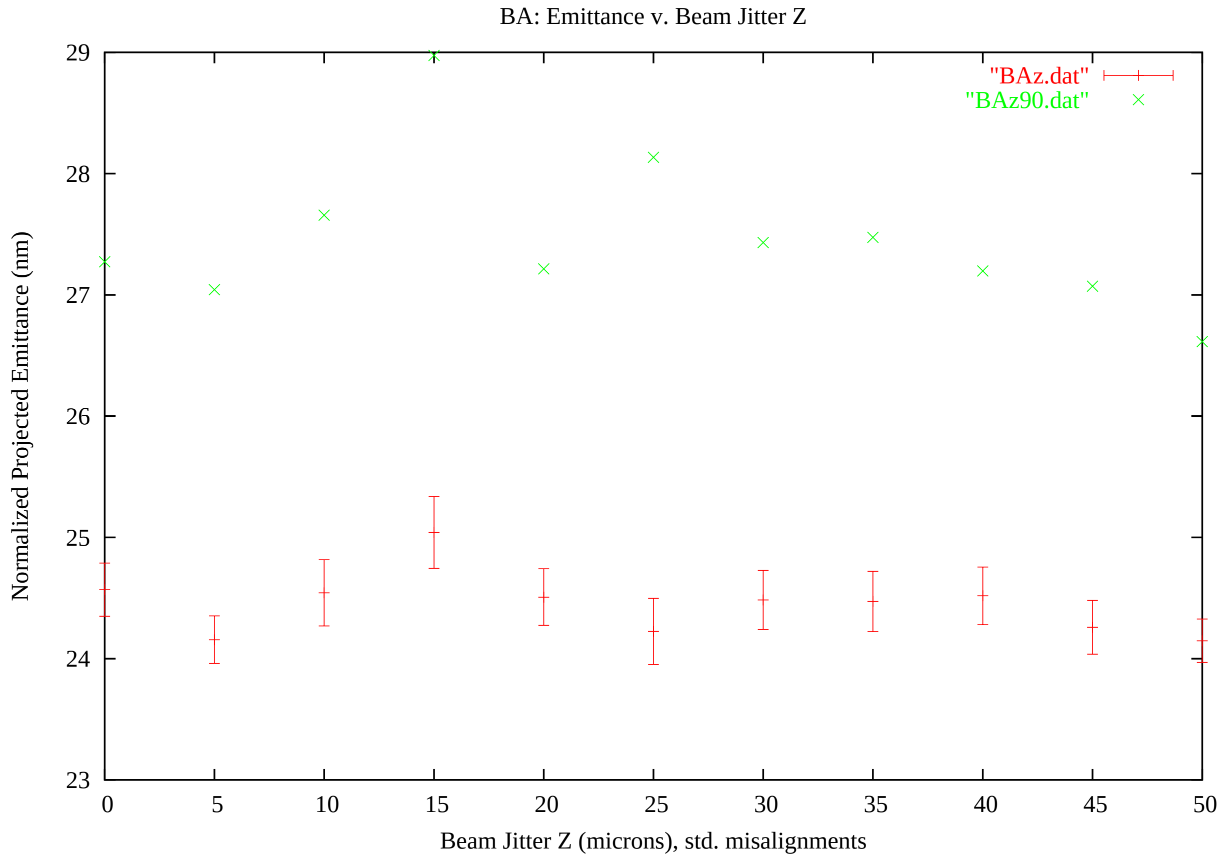

FIG. 7: Ballistic Alignment with z-Beam Jitter and Standard Misalignments - “BAy.dat” represents the mean emittance of 100 seeds with the y error bars (where error is the ratio of standard deviation to the square root of the number of seeds). “BAy90.dat” represents the 90 percent confidence level

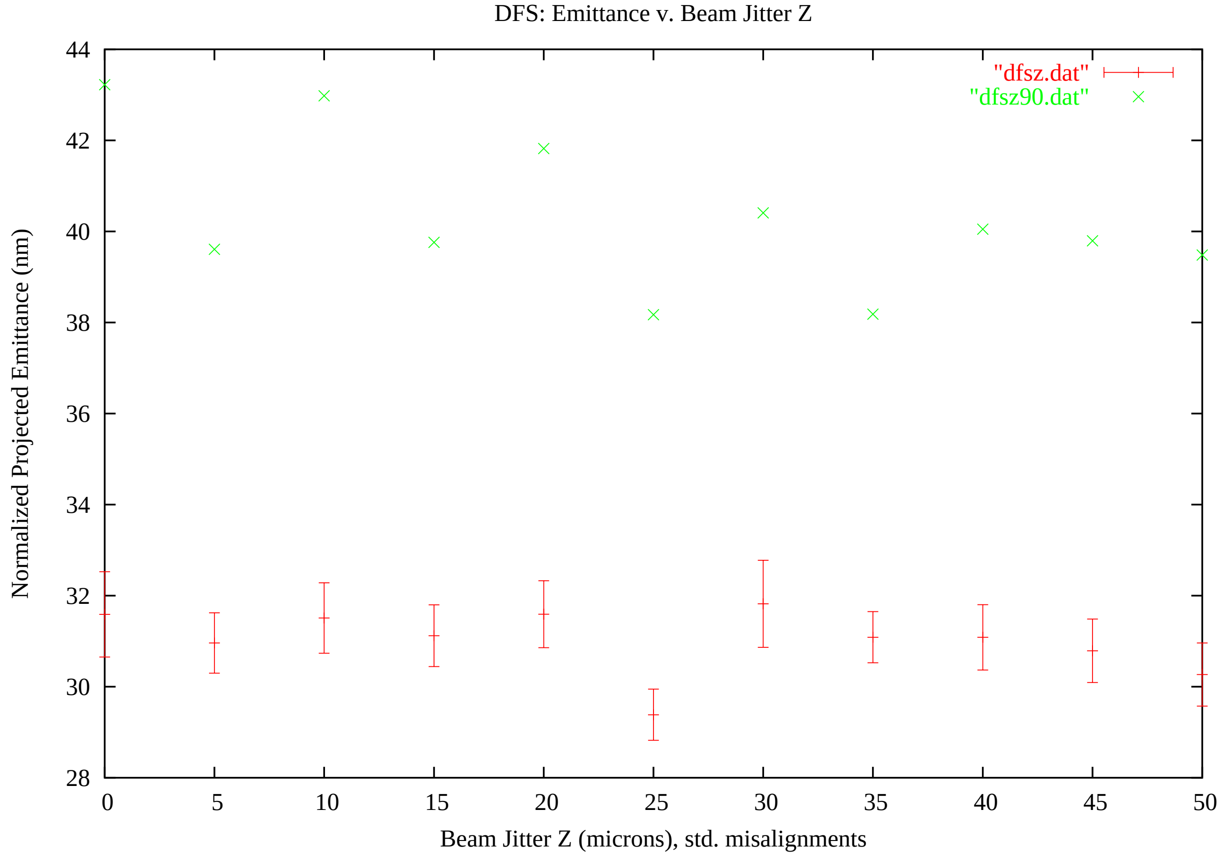

FIG. 8: DFS with z-Beam Jitter and Standard Misalignments - “dfsz.dat” represents the mean emittance of 100 seeds with the y error bars (where error is the ratio of standard deviation to the square root of the number of seeds). “dfsz90.dat” represents the 90 percent confidence level

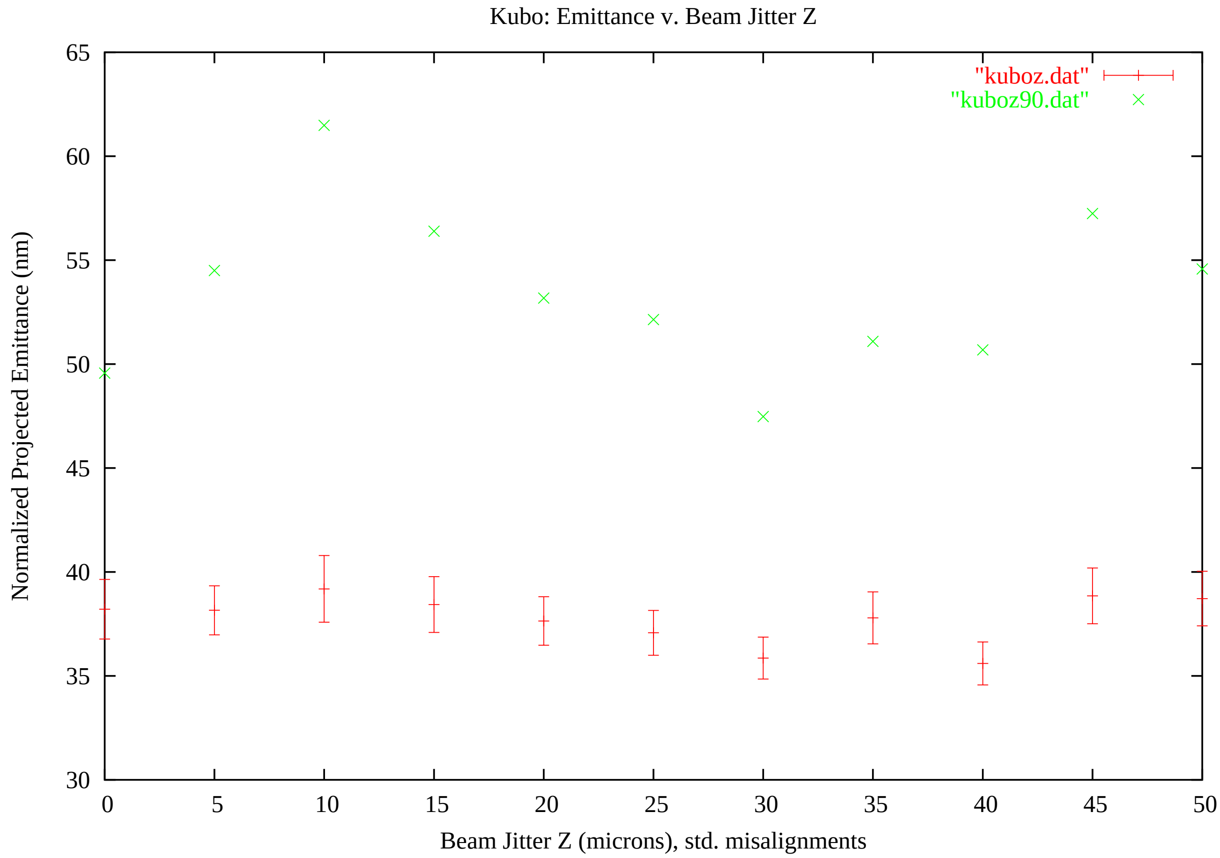

FIG. 9: Kubo with z-Beam Jitter and Standard Misalignments - "kuboz.dat" represents the mean emittance of 100 seeds with the y error bars (where error is the ratio of standard deviation to the square root of the number of seeds). "kuboz90.dat" represents the 90 percent confidence level

Comparing Fig. 7, 8, and 9: In comparing Figures 7, 8 and 9 it is clear that for BA, even with jitter well above ten percent of the beam size in the longitudinal direction, the emittance stays well within the 40nm range. In DFS the mean values (with error) all seem to stay to within an acceptable emittance value, however, the ninety percent confidence level oscillates around the maximum allowed emittance. Kubo not only begins with an average emittance value almost at 40 nm, but the average values continue to hover around an unacceptable level. The ninety percent confidence level values of emittance from kubo are always above the allowed emittance.

Results in Energy Jitter, 100 seeds

Jitter can also occur in the energy spread of the beam in the ILC. z' is defined in [1] to be a particle's energy with respect to the design energy, z'= $\delta E/E_0$, where δE is the difference in energy of the particle to the design energy (E_0). Implementing a beam jitter in this parameter causes the energy spread (given to be three percent) to jitter about the design value (Therefore a z' jitter is a percent jitter of the three percent energy spread [1]). Each algorithm was simulated using z' energy jitter of up to fifty percent, however particles were lost in the BA algorithm after thirty-five percent z' jitter, in DFS after thirty percent z' jitter, and in kubo after only twenty-five percent z' jitter.

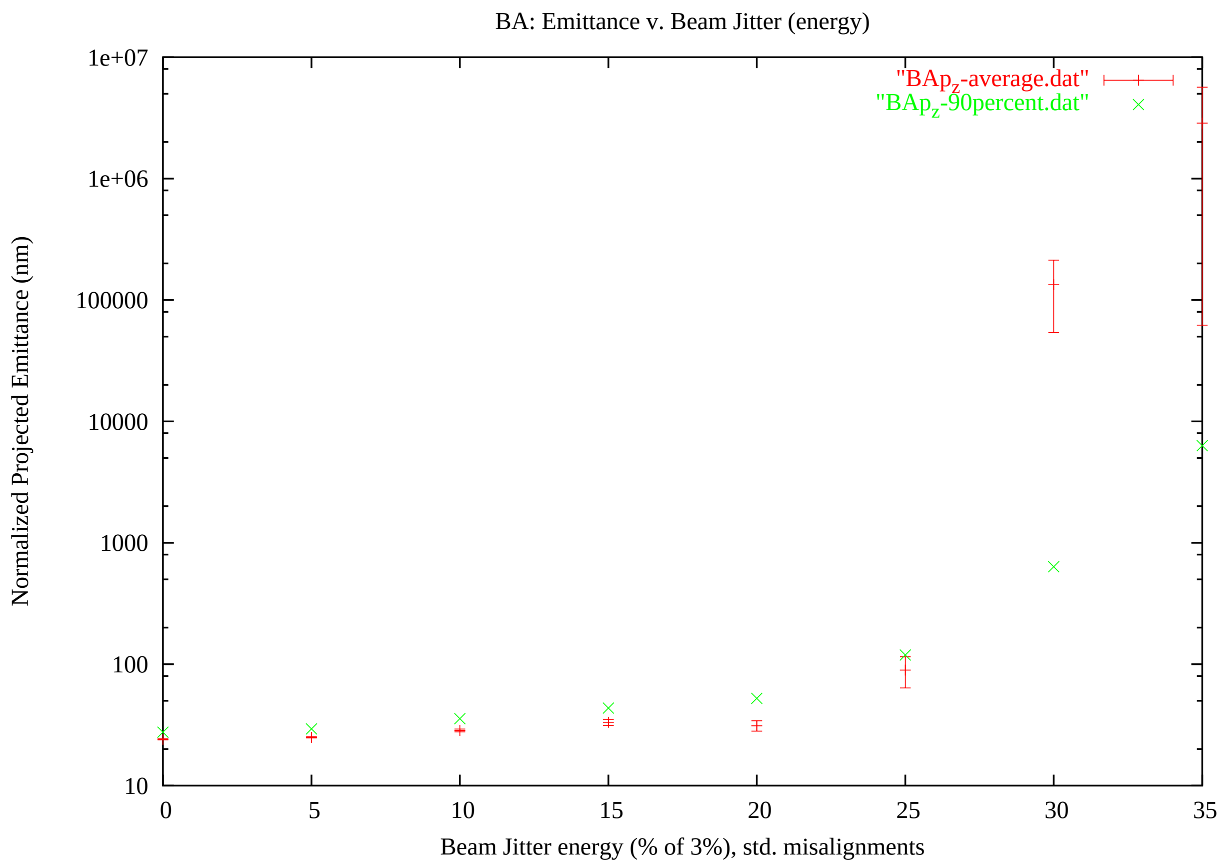

FIG. 10: Ballistic Alignment with z' Beam Jitter and Standard Misalignments-"$BAp_z-average.dat''$ represents the mean emittance of 100 seeds with the error bars (where error is the ratio of standard deviation to the square root of the number of seeds). "$BAp_z-90percent.dat''$ represents the ninety percent confidence level.

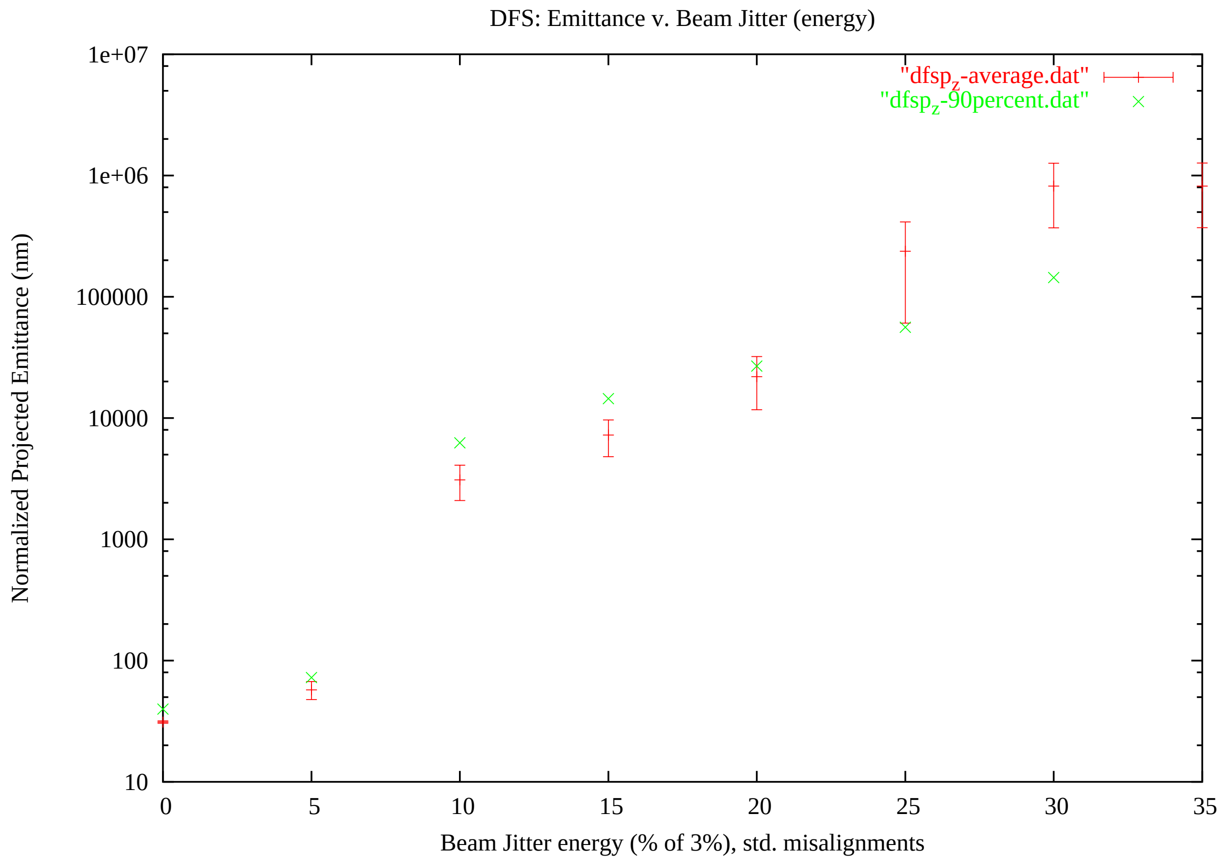

FIG. 11: DFS with z' Beam Jitter and Standard Misalignments-"$dfsp_z - average.dat''$ represents the mean emittance of 100 seeds with the error bars (where error is the ratio of standard deviation to the square root of the number of seeds). "$dfsp_z - 90percent.dat''$ represents the ninety percent confidence level.

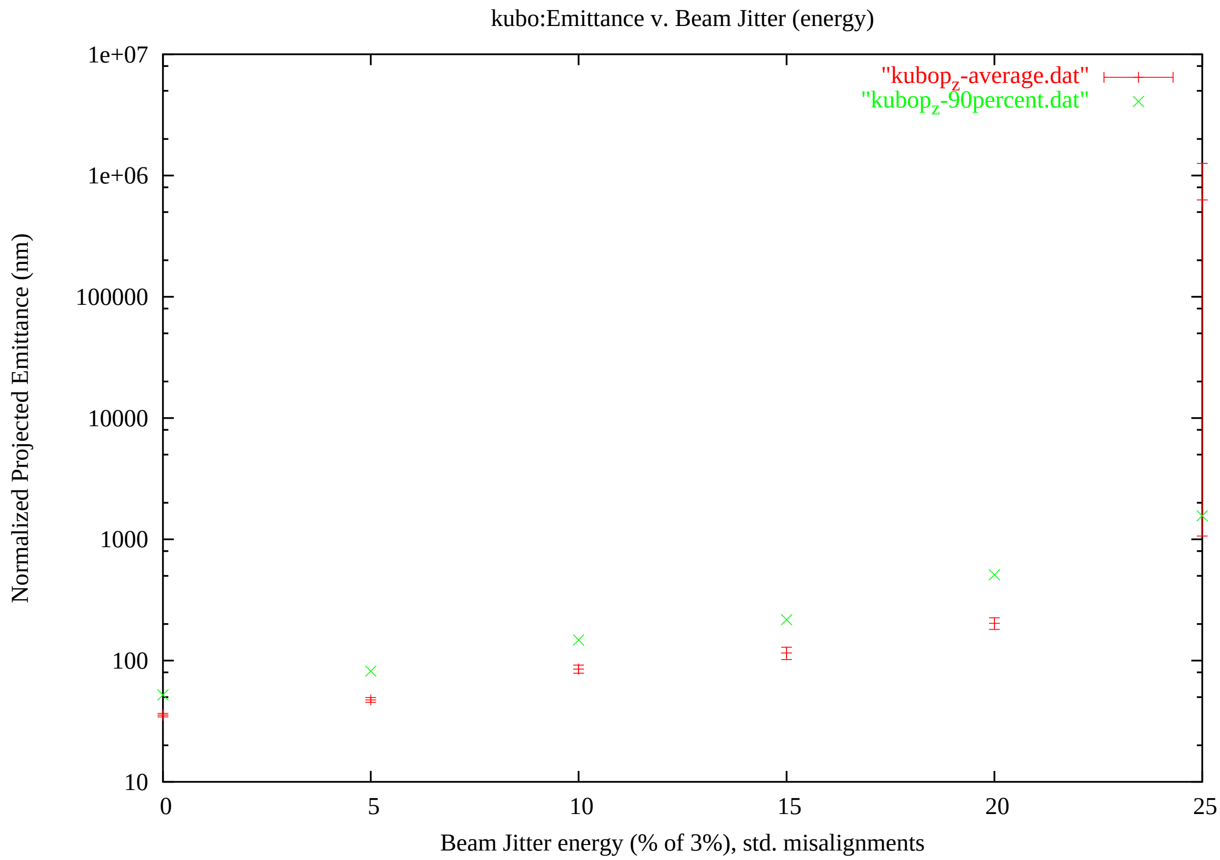

FIG. 12: Kubo with z' Beam Jitter and Standard Misalignments-"$kubop_z - average.dat''$ represents the mean emittance of 100 seeds with the error bars (where error is the ratio of standard deviation to the square root of the number of seeds). "$kubop_z - 90percent.dat''$ represents the ninety percent confidence level.

Comparing fig. 10, 11, and 12:

In comparing fig. 10, 11, and 12 it is noted that for BA there can be as much as 10 percent z' energy spread jitter, when comparing the ninety percent confidence levels, before the vertical emittance becomes too high. When comparing the average values, with error, it is seen that BA keeps a satisfactory beam emittance with z' energy jitter reaching up to twenty percent. For kubo, it is clear that even with no z' jitter the emittance value is quite high and with very little jitter, the emittance quickly rises above 40nm. In the case of DFS even without jitter the emittance at the ninety percent confidence level come quite close to 40nm. Even at five percent z' jitter, the emittance for both the ninety percent confidence level and the average emittance (with error) becomes far higher than the allowed emittance.

It should be noted that this large and quick emittance growth is surprising! This may be an implication that there is some other effect occurring, or that there is a problem with this part of the program used. This will be looked into and resolved in the subsequent weeks to the REU program.

IV. CONCLUSION

The Kubo method is the least effective method for aligning the ILC on the basis of jitter alone. This method has the potential to raise the emittance beyond the allowed 40 nm even without the presence of beam jitter (as show in Fig. 3, 6, 9, and 12). This fact leads us to the conclusion that a non-kubo method of alignment may be the best option for aligning the main linac of the ILC.

While DFS does an adequate job of lowering emittance, Ballistic Alignment seems to yield the most robust results in minimizing vertical emittance in the presence of beam jitter. This is expected because BA is the algorithm least effected by a beam injected off axis (as the magnets and RF cavities are shut off while BA measurements are taken). Also, because BA required the least number of orbit measurements (iterations between measurements) it is expected to be less sensitive to jitter. Therefore on the basis of jitter alone BA seems to be the best algorithm to align the ILC, however, it should be noted that a final decision on which algorithm to choice requires more studies.

It is quite important to note that due to a bug in TAO wakefields were not taken into account. Wakefields may increase the effects of beam jitter as they tend to increase the energy spread as a beam travels through an RF cavity. When wakefields are implemented the values obtained from Beam Based Alignment algorithms under various beam jitters may differ from these results slightly.

Some future studies, should include implementing each algorithm only after many passes of a beam with jitter are recorded and the positions are averaged. In the simulations we had done, each algorithm was implemented after only one pass of the beam yielding the most damaging effects due to jitter. Our theory is that given enough passes of jitter the random offset at each BPM will average out to a true non-jitter trajectory and proper alignment may be obtained.

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