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# Alignment tolerance of accelerating structures and corrections for future linear colliders,*

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*Abstract:* The alignment tolerance of accelerating structures is estimated by tracking simulations. Both single-bunch and multi-bunch effects are taken into account. Correction schemes for controlling the single and multi-bunch emittance growth in the case of large misalignment are also tested by simulations.

## I. ALIGNMENT TOLERANCE

Emittance growth caused by random misalignments of accelerating structures for NLC (Next Linear Collider, being designed at SLAC) main linacs are considered. Both single-bunch effects and multi-bunch effects are taken into account. The effect of other errors, for example misalignment of quadrupoles and injection jitter, are not discussed in this paper.

### *A. Tracking*

A tracking program has been developed to simulate phase space beam dynamics in main linacs of future linear colliders[1]. Parameters for a 250 GeV NLC linac, which are used in our simulations, are listed in Table 1.

To simulate single-bunch effects, each bunch is divided into five slices and each slice has five macro particles with different initial energies. For multi-bunch simulations without single bunch effects, each bunch is treated as being rigid.

The accelerating structures are misaligned randomly and the average of the emittance growth of 100 randomly misaligned machines is used to estimate the alignment tolerance. The tolerance depends on the length of an "alignment unit" which is aligned independently. Each alignment unit is assumed to consist of either (a) M structures or (b) 1/M structure (M=1,2,3, ....). Long scale misalignment is simulated in Case (a). Alignment of girders can also be simulated in the case where M structures are on a girder and each girder is aligned independently, with random errors, while the structures are perfectly aligned on each girder. Fabrication errors of each structure are simulated in Case (b). Each structure is divided into M pieces and each piece is "aligned" independently. The situation corresponds to, for example, each structure consisting of M pieces brazed together with random errors, with each piece fabricated error-free. Each slice of the beam is kicked by wakefields at the center of each structure in Case (a) and at the center of each piece of structure in Case (b).

The transverse short range wakefunction was assumed to be a linear function. Though the shape of the cells changes along a structure, only averages over a structure were used for both longitudinal and transverse short range wakefunctions.

Frequencies, kick factors and $Q$'s of the modes of the first pass band of the "damped detuned structure"[2] for the NLC were used to obtain the long range transverse wakefield, which was used to calculate the inter-bunch effect. In the case of simulations for fabrication errors (a structure is divided into pieces), each mode is assumed to be localized in that piece in which the centroid of the field amplitude is located. Because fields of some modes are distributed widely, this approximation will not be appropriate for very short pieces of structures. Though we do not discuss it here, it is possible to use a more precise method to calculate a wakefield with fabrication errors[3].

The lattice is a FODO lattice with a phase advance of about 90$^{o}$/cell and with a beta function that varies approximately as the square root of the beam energy.

| | |
|---|---|
| Accelerating frequency | 11.424 GHz |
| Beam energy | from 10 to 250 GeV |
| Loaded gradient | 37 MV/m |
| Phase advance/cell | 90$^{o}$ |
| Length of a FODO cell | from 8 to 40 m |
| Charge per bunch | $0.7\times10^{10}\,e$ |
| Bunch length | 100 μm |
| Number of bunches | 90 |
| Bunch spacing | 1.4 ns |
| Normalized emittance | $3\times10^{-8}$ m-rad |
| Length of acc. structure | 1.8 m |
| Number of cell /structure | 206 |
| Structure type | Damped detuned |
| Average aperture radius | 4.9 mm |
| Slope of transverse wake | $8.4\times10^{19}$ V/C/m$^3$ |

Table 1. Parameters used for the simulation.

One-to-one trajectory steering is assumed to be always performed so that the beam centroid goes through the center of every focusing quadrupole magnet. Because all quadrupole magnets are assumed to be perfectly aligned, alignment tolerances obtained here should be regarded as tolerances with respect to the beam or required accuracy of beam based alignment of the accelerating structures.

Figure 1 shows the alignment tolerances for averaged emittance growth of less than 25% as function of alignment unit length. The solid line shows tolerances considering both single- and multi-bunch effects. Tolerances for the single-bunch effect alone, and multi-bunch effect alone are also shown here. Comparing the three curves, it is noticed that the

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single-bunch effect is dominant for longer alignment lengths and the multi-bunch effect is important only for pieces in each structure. The curves have a minimum at an alignment length of 16 structures or 32 m, which is about the betatron function at the end of the linac. This is expected since, when the alignment unit becomes longer than the beta function, the effects of the wakefield begin to cancel. And the end of the linac is the most sensitive region because of the weakly focusing lattice. The single-bunch curve for short alignment lengths varies according to the -1/2 power up to the length of about 16 structures. This is because the effect of the kick by wakefield depends only on the average offset of the beam with respect to the structure center over the length comparable to beta function. However, the multi-bunch curve drops for alignment length less than one structure. This is because, with the misalignment (fabrication error) of pieces in a structure, the designed cancellation of the 206 dipole modes of each structure is disturbed.

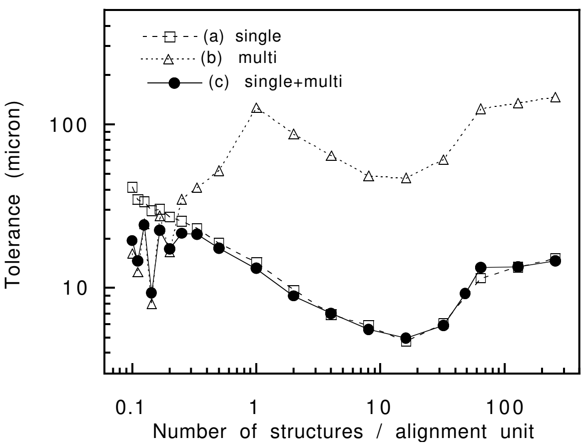


Figure 1. Tolerance of misalignment of damped-detuned structures for 25% emittance growth as function of alignment unit length, (a) considering only the single-bunch effects, (b) only the multi-bunch effects, and (c) considering both effects together. Each symbol represents the average of tracking with 100 random seeds.

The minimum alignment tolerance is 5 μm for an alignment unit length of about 32 m. The tolerance for each structure is 13 μm. The minimum tolerance for short pieces (fabrication) is 9 μm in the case of 7 pieces per structure.

### *B. Numerical Method*

In order to save calculation time, a numerical method to estimate the alignment tolerance has been developed. The essential approximation of this method is that the amplitude of betatron oscillation is negligibly small compared to the misalignment of structures. This assumption is the same as in the analytical method presented elsewhere[4].

We consider the tolerance for alignment units each of which consists of several short pieces. The expected emittance growth from kicks by wakefields due to the misalignment of accelerating structures are given as follows.

$$\langle\Delta\varepsilon\rangle \approx e^2 \sum_i a_i^2 \sum_{\lambda\in i}\sum_{\lambda'\in i} B_{f,\lambda\lambda'} L_\lambda L_{\lambda'} T_{\lambda\lambda'} \,/\, E(\lambda)E(\lambda')$$

where $i$ is index for alignment unit, $\lambda$ index for short piece and $a_i$ r.m.s. misalignment of structures.

$$B_{f,\lambda\lambda'} \equiv \frac{1+\alpha_f^2}{2\beta_f} R_{\lambda,12}R_{\lambda,12} + \alpha_f R_{\lambda,12}R_{\lambda,22} + \frac{\beta_f}{2} R_{\lambda,22}R_{\lambda,22}$$

where $\alpha_f$ and $\beta_f$ are twiss parameters at the end of linac and $R_{\lambda,12}$ and $R_{\lambda,22}$ are 12 and 22 elements of transfer matrix from $\lambda$ to the end of linac.

$$T_{\lambda\lambda'} \equiv \sum_m q_m S_{a,m}(\lambda) S_{a,m}(\lambda') \Big/ \sum_m q_m$$

$$S_{a,m}(\lambda) \equiv S_m(\lambda) - \sum_m q_m S_m(\lambda) \Big/ \sum_m q_m\,,$$

$$S_m(\lambda) \equiv \sum_k q_k W(\lambda, z_m - z_k)$$

where $q_m$ is the charge of $m$-th slice of the beam, $W(\lambda,z)$ the transverse wake function of $\lambda$ at distance $z$. $L_\lambda$ the length of the piece and $E(\lambda)$ the beam energy at $\lambda$. Assuming continuous focusing and that the alignment units are short compared with beta function, we obtain an analytical expression in Ref. [4].

This method was compared with tracking for the NLC design in the cases of considering only single-bunch effects, only multi-bunch effects, and both effects together. The estimated tolerances agree well for any alignment unit length.

Fabrication errors were studied more carefully using numerical methods. Two curves in figure 2 show the tolerances as functions of alignment length for two different approximations. In both cases the wakefield of each mode is assumed to be localized in one piece, but (a) assumes that that piece is where the centroid of amplitude is, and (b) assumes that it is where the phase velocity of the mode is closest to the velocity of light[5]. The two curves are different in detail but, generally, both have similar behavior with a minimum tolerance of about 10 μm.

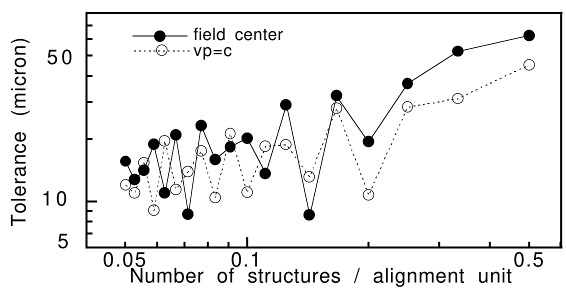


Figure 2. Tolerance of fabrication of damped-detuned structures for 25% emittance growth as function of alignment length, considering only multi-bunch effects from the numerical method, (a) assumed the field is at the center of the amplitude and (b) assumed the field is where $v_p$=c.

## II. CORRECTIONS

It is expected that one can achieve the required alignment[6]. But if this is not the case, some additional correction can be done. One technique of beam based alignment has been suggested[7], in which bunch current and/or the bunch length are changed, and the trajectories are measured. However this technique may be difficult to implement. Another possible approach is a combination of : (1) for single bunch correction, trajectory bumps or moving structures, tuned by emittance measurements and (2) for multi-bunch correction, fast kickers tuned by a bunch-by-bunch position measurement[8]. The emittance and bunch-by-bunch positions are measured at several locations in the linac. In technique (1), a beam offset with respect to structures is intentionally produced at some parts of the linac to compensate the effects of wakefield due to misalignment of other parts. In (2), the beam is kicked bunch-by-bunch so that all bunches have the same trajectory.

Tracking simulations were performed to test these techniques for the 250 GeV NLC linac. Again, note that we concentrate only on corrections for the misalignment of accelerating structures.

*A. Single-bunch*

In this tracking, some accelerating structures were moved instead of trajectory bumps, because of ease of simulation. Though, in reality, it may be more flexible and reliable to introduce trajectory bumps, both methods have almost the same effects.

We assumed emittance measurement at five locations, at beam energy of 30, 60, 100, 150 and 250 GeV. Two sets of accelerating structures were moved just before each location to minimize the emittance. Each set consisted of all structures between two quadrupole magnets and the two sets were separated by one FODO cell or about $90^{\circ}$ betatron phase. The r.m.s. of misalignment of each structure was set to be 30 µm, where the expected emittance growth without corrections is 130%. The movement of each set of structures was performed in 20 µm steps and limited to +-300 µm.

Figure 3 shows emittance growth as a function of resolution of beam size where the resolution of emittance measurement was calculated from $\varepsilon = \sigma^2 / \beta$, assuming $\beta$ at focusing magnets near each station. It is shown that precise measurement of the emittance is essential for this correction.

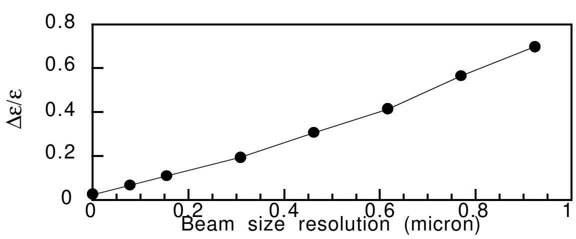


Figure 3. Emittance growth as function of resolution of beam size measurement. Each symbol represents the average of tracking with 100 random seeds.

*B. Multi-bunch*

Bunch-by-bunch trajectories were assumed to be measured by two fast BPMs located at consecutive focusing quadrupole magnets ($90^{\circ}$ phase difference) at each of the same five locations as the single-bunch correction. Two fast kickers were also located at consecutive focusing quadrupoles just before the BPMs and the beam was kicked bunch-by-bunch (except the first bunch) so that all bunches have the same trajectories. One-to-one trajectory correction was also performed to make the beam centroid go through the center of every focusing quadrupole magnet. Tracking was performed with 90 bunches including both single- and multi-bunch effects. Each structure was divided into 7 pieces and the pieces were aligned independently with an r.m.s. error of 25 µm. This misalignment was chosen so that the multi-bunch effects are much stronger than single-bunch effects because we are concentrating here on multi-bunch correction. But, because it is possible that single-bunch effects become significant due to a large bunch offset caused by the multi-bunch effects, the single-bunch effects were also considered in this simulation. The expected emittance growth without corrections was estimated as Δε/ε = 1.33.

Figure 4 (a) and (b) show emittance growth as function of BPM resolution and kicker speed, respectively, where the limit of kicker strength is 56 kV. A kicker speed 250 MHz and strength limit of 56 kV are our tentative design values and the bunch-by-bunch BPM resolution is expected to be better than 0.2 µm. The results show our design will be effective.

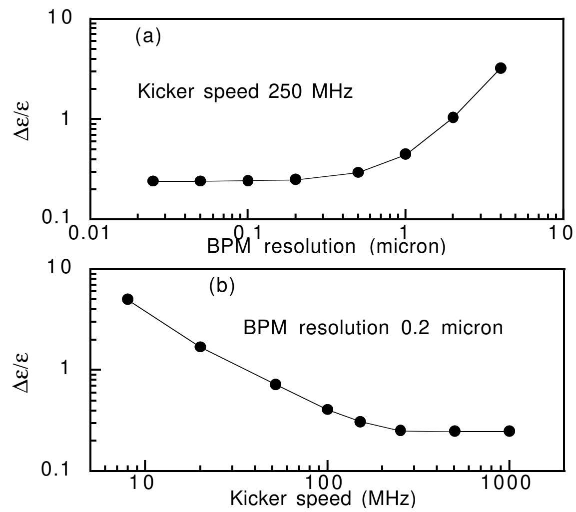


Figure 4. Emittance growth vs. (a) BPM resolution and (b) Kicker speed, with the strength limit 56 kV. Each structure was divided into 7 pieces and misalignment of pieces is 25 µm. Each symbol represents the average of tracking with 25 random seeds.

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