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NEXT-GENERATION LINEAR COLLIDER FINAL FOCUS SYSTEM STABILITY TOLERANCES*

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1. The Lattices

1.1 Introduction

The design of final focus systems for the next generation of linear colliders has evolved largely from the experience gained with the design and operation of the Stanford Linear Collider (SLC) and with the design of the Final Focus Test Beam (FFTB). We will compare the tolerances for two typical designs for a next-generation linear collider final focus system.

The chromaticity generated by strong focusing systems, like the final quadrupole doublet before the interaction point of a linear collider, can be cancelled by the introduction of sextupoles in a dispersive region. These sextupoles must be inserted in pairs separated by a $-I$ transformation (Chromatic Correction Section) in order to cancel the strong geometric aberrations generated by sextupoles. Designs proposed for both the JLC or NLC final focus systems have two separate chromatic correction sections, one for each transverse plane separated by a "β-exchanger" to manipulate the β-function between the two CCS. The introduction of sextupoles and bending magnets gives rise to higher order aberrations (long sextupole and chromo-geometrics) and radiation induced aberrations (chromaticity unbalance and "Oide effect") and one must optimize the lattice accordingly.

1.2 General Comparison of the Two Lines.

The JLC Final Focus System we present here (JLC200) was designed by K. Oide for a beam energy of 200 GeV and an L^*, the distance between the exit face of the last quadrupole and the focal point, of 1 m. It is fairly compact (250 meters) and makes use of a modified FODO cell lattice. On the other hand the NLC design (FFN15) by R. Helm and K. Brown uses a triplet based lattice and is longer† (360 meters) for a 250-GeV beam energy and an L^* of 0.4 m.

It is difficult to compare two lines so different in spirit and designed for different sets of parameters. However the tolerances for these lines give an idea of the typical range of tolerances encountered in next generation linear collider final focus designs. We will compare them where we can and point out the strengths and weaknesses of each line as we see them.

The most important difference is in the choice of L^*. This determines, through the determination of the final quadrupole, the amount of chromaticity to correct. The chromaticity in the JLC is three times that of the NLC. Both designs share comparable characteristics for the final lens: a pole tip field of 1.4 T, a full aperture of 1.6 mm and a length of 37 cm for the JLC; 1.4 T, 0.8 mm and 28 cm respectively for the NLC. The difference in aperture is directly related to the difference in L^*.

The total bend angle allowed in the line is determined by radiation induced effects (chromatic correction alteration) and amounts to 4 mrad for the NLC and 6.4 mrad for the JLC. All the dipoles bend the beam to the same direction in the NLC lattice while the JLC alternates the bending to form an elongated "S" shape.

The calculation of some vertical aberrations of the systems shows that a shorter line and higher chromaticity for the JLC leads to a higher level of aberrations than for the NLC. The long sextupoles aberration is negligible in both designs while the radiation induced vertical aberrations are dominant. As the particles lose energy in the bends between the CCS and the final quadrupoles there is some chromaticity unbalance contributing $\frac{\Delta\sigma_y^{*2}}{\sigma_y^{*2}} = 0.1$ for JLC and only 0.02 for NLC.

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† Note that the length of the system is not the only issue and a longer line may be desirable to help with tight tolerances.

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Table I[‡]

Time Scale	Generator	Cause of loss of luminosity	# of knobs	Knob Name (Corrector)
τ_0	x', y'	horiz. and vert. steering	2	dipoles at FQ
τ_1	$x'\delta, y'\delta$	dispersion	2	dipoles in FT
τ_2	x'^2, y'^2	waist motion	2	trims on final doublet
	$x'y'$	coupling	1	skew quad. in FT
τ_3	$x'^2\delta, y'^2\delta$	chromaticity	2	main sextupoles
	$x'^3, x'y'^2$	sextupole	2	sextupoles in FT
	y'^3, x'^2y'	skew sext.	2	skew sext. in FT
∞	$\delta x'y'$	chromatic skew quad.		no correction
	$\delta^2 x', \delta^2 y'$	second order disp.		no correction
variable (linac)	xx', x'^2, yy', y'^2 $x'\delta, y'\delta$	β and α mismatch incoming dispersion	6	quads in BM
	$xy', x'y'$	incoming coupling	2	skew quads in BM

These are not the only aberrations in the lines. The comparison between tracking (including radiation simulation) and first-order results shows that the total aberration content of the lines amounts to about 8% of the linear spot size for the NLC and about 18% for the JLC.

2. Low-Order Aberrations and Global Correctors

Maintaining collisions and spot sizes at the interaction point of a next-generation linear collider will require the use of global correction techniques. A global corrector cancels one aberration at the interaction point leaving other aberrations unchanged. It may be implemented by controlling one variable of one element in the line (simple knob), or it may require changing several variables simultaneously (multiknob). The information for setting the global corrector comes from the position, size and orientation of the beam at the interaction point as given by beam-beam deflection, beamstrahlung or other monitors. It does not attempt to fix the cause of the problem at its source. One assumes that the optics has been adjusted initially with other techniques such as mechanical alignment, beam-based alignment and orbit bump tuning. We will now itemize the important remaining low order aberrations and their corresponding global correctors according to four distinct time scales.

The first time scale (τ_0) originates from position jitter in the quadrupole elements of the line which can displace the final spots so that the beams miss each other. The correctors (2) used here are steering dipoles (horizontal and vertical) at the final quadrupole. The time scale is determined by the feedback system frequency (for a collision frequency of 120 Hz the correction frequency might be 10 Hz). The tolerances for jitter specify the maximum allowed quadrupole motion at frequencies above $1/\tau_0$. The signal for feedback can be a kink in the beam trajectory at the IP from beam-beam deflection. The nature of this signal at future linear colliders requires more study[1].

The setting of the remaining correctors requires minimizing the beam size with respect to the strength of the correctors. This involves a loss of luminosity during scans using beamstrahlung,

‡ FT refers to the final transformer and BM to the beta matching section.

pair production or luminosity monitors as an indication of beam size. The time required for the correction will be many beam pulses per aberration.

The second set of global correctors (2) in Table I controls beam size effects caused by dispersion originating from change of quadrupole positions. Two steering correctors are used to control the dispersion by offsetting the beam trajectory in the final quadrupoles. Although these aberrations can not be corrected without reference to the beam size, the stability of the beam within the final focus system can be monitored to ensure the aberration has not changed. The time τ_1 is determined by the time one can monitor and maintain this stability which will depend on the stability of BPMs at tenth-micron readings. τ_1 of several minutes would be desirable.

The third set of global correctors (3) controls beam size effects caused by waist motion (normal quadrupole component) in both planes and coupling (skew quadrupole component) originating from change of quadrupole strengths, change of quadrupole positions within sextupole pairs or quadrupole rotation as well as sextupole displacements. To control the waist location in both horizontal and vertical planes, one may use trim coils on the last quadrupoles. A skew quadrupole located at the final quadrupole can correct the main coupling term. Orbit bumps can be used to confirm alignment of the CCS, and with them it may be possible to extend the time scale (τ_2) for normal and skew quadrupole effects beyond the BPM stability time (τ_1).

The fourth time scale (τ_3) covers remaining correctors (6) such as the sextupole settings for chromaticity correction, and two sextupoles and two skew sextupoles in the final transformer to cancel possible sextupolar terms coming from various sources including imperfections of the final doublet. Also included here are the effects of quadrupole strength stability causing the breakdown of the $-I$ transformations. These corrections are expected to be small and have a yet longer time scale ($\tau_3 \gg \tau_2$) determined by the stability of magnet power supplies.

Finally we note that out of the 19 total third-order generators (aberrations) in x', y' and δ that can cause a loss of luminosity there are only three for which we have not assigned global correctors. The first one is an effect of chromatic skew quadrupole that may arise from vertical dispersion generated between a sextupole pair. The other two are the horizontal and vertical second order dispersion. We believe that after initial system alignment these effects will be small and correctors need not be explicitly installed.

There are also a few multiknobs (8) at the end of Table I to which we have not assigned a time scale. They are used for the matching of the incoming beam from the linac into the final focus system. Four of them will perform the matching of the beta and alpha functions, two will control the dispersion function, and two will control the two principal coupling terms. It is difficult to assign a time scale to these knobs as the effects depend essentially on the stability of the linac. A loss of luminosity correlated with some variation in the linac (acceleration pattern, trajectory,...) will be a signal to check the matching. These knobs can be viewed as matching knobs more than global correctors as defined above and are set by diagnostics within the final focus system.

Note that there is a duplication between some of these matching knobs and the global correction knobs associated with time scale τ_1 and τ_2. The two knobs for alpha matching are duplicates of the waist motion knobs, the dispersion matching knobs duplicate the dispersion correction knobs (dipoles in final transformer), and one of the two incoming coupling suppression knobs is duplicated by a skew quadrupole in the final transformer. The beta-matching knobs control the design beta function at the interaction point and are not duplicated.

3. Stability Tolerances

3.1 Tolerance Budget

The experience with measuring small spots at the interaction point of the SLC shows that it is possible to measure a relative change of 10% in the size of the beam which translates into an ability to correct aberrations to the order of 2%. We have therefore chosen this 2% figure as the maximum allowed increase of the spot size per aberration. The total beam size growth above design is then expected to be 8% in the horizontal plane (4 contributing terms) and 14% in the vertical plane (7 contributing terms). In the following discussion we will quote tolerances according to this 2% criterion for individual elements. However as different elements can contribute to the same aberration and if one assumes that their departures from design are not correlated, one must combine their tolerances in quadrature to find the tolerance for this group which gives a 2% increase in spot size. We usually separate the elements into two or more sets from most sensitive to least sensitive, and allocate a fraction of the 2% budget to each group, the largest fraction to the most sensitive group. Within each group, g, we then calculate an RMS tolerance for the group, t_g according to

$$\frac{1}{t_g^2} = (\sum_{i \in g} \frac{1}{t_i^2}) \frac{1}{f_g}$$

where f_g is the fraction of the 2% allocated to this group and t_i is the 2% tolerance for each individual element.

3.2 Steering

Our tolerances on the steering permit beam centroid motion at the interaction point to be one standard deviation of the vertical distribution *i.e.* we allow the spot to move by $\Delta y^* \approx \sigma_y^*$, and only one fifth of a standard deviation in the horizontal plane, $\Delta x^* \approx \frac{1}{5}\sigma_x^*$, as the beam-beam disruption captures the beams in the vertical plane[1]. The final quadrupole doublet (treated as one element) position tolerance is then $\Delta y_{fq} \approx \sigma_y^*$ and $\Delta x_{fq} \approx \frac{1}{5}\sigma_x^*$. Since most quadrupoles are $\pi/2 + n\pi$ from the interaction point, tolerances scale according to their strengths and the value of the β-function at their location:

$$\Delta y_q \leq \frac{1}{k_q}\sqrt{\frac{\epsilon_y}{\beta_{y_q}}}$$

and

$$\Delta x_q \leq \frac{1}{5k_q}\sqrt{\frac{\epsilon_x}{\beta_{x_q}}} \, .$$

The final vertical spot sizes are respectively 1.9 nm for JLC and 3.2 nm for NLC. The final quadrupole position stability tolerances at $t < \tau_0$ are therefore of the order of a few nanometers for both the JLC and NLC. For the other quadrupoles the β-functions and strengths put these tolerances in the range 50 to 800 nm in the vertical plane (and 0.3 to 10 microns in the horizontal plane) in the NLC case, from 24 to 400 nm in the vertical plane (and from 0.12 to 2 microns in the horizontal plane) for the JLC. Note that in both lines a small number of quadrupoles having a phase advance of about $n\pi$ to the interaction point have very loose tolerances; these same quadrupoles will have very strict tolerances as sources of dispersion.

The RMS vertical displacement tolerances are 18 nm for the NLC and 10 nm for the JLC. These values scale with the final spot size as was expected from the approximate scaling laws above.

3.3 Dispersion

Dispersion is primarily generated at the interaction point by a trajectory offset in the final quadrupole doublet $(\Delta y)_{fq}$. The 2% growth in spot size condition is written

$$\frac{\Delta y_{fq}}{\sigma_y^{fq}} \leq \frac{1}{5\ \delta_{rms}\ \xi_y}$$

where ξ is the chromaticity of the doublet. With some rough approximations one finds

$$\Delta y_{fq} \lesssim \frac{1}{5\ \delta_{rms}}\ \sigma_y^* \, .$$

This offset is of the order of 0.2 to 0.3 microns for both lines and can be monitored by a tenth micron BPM. Note that this formula shows a scaling with the final spot size and does not involve the L^* of the system. The offset at the final quadrupole can be created by a direct movement of the final quadrupole or by a displacement of another quadrupole upstream steering the beam off-axis in the final lens. To study this second effect, we introduce the notion of lattice multipliers defined as the amplification factor between the offset of a given quadrupole and the centroid offset in the final quadrupole

$$\Delta y_{fq} = (k_q R^{34}_{q \to fq})\ \Delta y_q \, .$$

Lattice multipliers depend only on the lattice structure, not on the interaction point parameters or the beam properties. The greater this multiplier the tighter the dispersion tolerances on the element. A few critical magnets are located at the beginning of the final transformer close to the last waist point before the interaction point since the phase advance between these points and the final lens is close to $\pi/2$. The multipliers for these elements in the NLC case range from 0.8 to 3.1

which leads to tolerances between 300 and 70 nm. In the case of the JLC the multipliers are respectively 7.4 and 9.3, leading to tolerances of the order of 15 nm for the stability of these magnets. Note that in the JLC the two offending magnets are very close to each other, are strong and have opposite signs. This situation could possibly be improved by having one weaker magnet and another one somewhere else.

To get the required 0.2 μ BPM precision to monitor the beam position at the final doublet, we will probably need to average over several trains. Assuming a 25-train average and a 120-Hz repetition rate of the bunch trains, a feedback system to stabilize the beam at the final quadrupoles could conceivably operate at about 0.5 Hz. This determines the time scale for which the 15 nm (JLC) or 70 nm (NLC) is required.

There is also a waist inside the chromatic correction section and both designs have magnets close to it. The multipliers are 1.2 for the NLC and 5.3 for the JLC leading to respective tolerances of 560 and 50 nm respectively. Note that these tolerances benefit from the presence of the second sextupole which compensates one half of the dispersion created by the final quadrupole.

3.4 Normal Quadrupole

A change in the final quadrupole strength will result in a movement of the waist away from the interaction point and cause an increase of the spot size at the interaction point. For a 2% increase in either the horizontal or vertical spot size, the strength tolerance is

$$\frac{\Delta k}{k} \leq \frac{1}{5\ k\ \mathrm{Max}(\beta_x, \beta_y)} \ .$$

For the final quadrupole doublet, where both the strengths and the beta functions are large, the tolerances are very tight. For other quadrupoles the tightest tolerances occur around the sextupoles where the beta functions are also very large.

In the case of the NLC the tolerances on the strengths of the final doublet are $\frac{\Delta k}{k} \leq 1.9 \times 10^{-5}$ and 1.1×10^{-4} for QC1 and QC2 respectively. The JLC tolerances for the same elements are 4.6×10^{-6} and 1.6×10^{-5}.

Taking into account all the quadrupoles in the line except the final doublet, the RMS tolerances are $\frac{\Delta k}{k} \leq 1.3 \times 10^{-4}$ for the NLC and $.8 \times 10^{-4}$ for JLC.

3.5 Horizontal Sextupole Alignment

The same quadrupole effect (waist motion) appears when the beam is horizontally offset in a sextupole, which can occur from an actual displacement of the sextupole or from one of the chromatic correction section quadrupoles steering the beam off axis in the second sextupole. It is possible to introduce here the same notion of multipliers as for the dispersion tolerance with the exception that we now take the reference to be the second sextupole:

$$\Delta x_s \ = \ k_q\ R^{12}_{q \to s}\ \Delta x_q \ .$$

Note that if the beam is off-axis in the first sextupole the effect will be cancelled by the equal and opposite displacement in the second sextupole of the pair due to the $-I$ transformation. Note that the dispersion generated by the sextupoles does not benefit from this cancellation which is only valid for normal and skew quadrupole effects.

The tolerances on sextupole horizontal offsets are

$$\Delta x_s \leq \frac{1}{5\ k_s\ \mathrm{Max}(\beta_{x_s}, \beta_{y_s})} \ .$$

The tolerances for horizontal sextupole displacement in the horizontal chromatic correction section (CCX) are 6.6 μ for NLC and 4.6 μ for JLC, while they are much tighter for the CCY: 0.3 μ for NLC and 0.1 μ for JLC.

The multipliers from the quadrupoles inside the CCY and CCX to the second sextupoles are also worse in the JLC and give quadrupole horizontal alignment tolerances of 3.1 μ and 0.5 μ for NLC in the CCX and CCY respectively, while they are 1.0 μ and 0.1 μ for JLC. Table II summarizes these results.

Table II

	NLC		JLC	
	H	V	H	V
CCX	3.1 μ	0.9 μ	1.0 μ	0.3 μ
CCY	0.5 μ	0.3 μ	0.1 μ	0.04 μ

3.6 Dipoles

The dipoles located inside the chromatic correction section can also steer the beam off-axis in the second sextupole through power supply jitter. The tolerances for the stability of the power supplies is given by

$$\frac{\Delta B}{B} \leq \frac{1}{5\ k_s\ \overline{R_{12}}\ \theta\ \mathrm{Max}(\beta_{x_s}, \beta_{y_s})} .$$

The $\overline{R_{12}}$ is the average value of the R_{12} between the entrance and the exit of the bend. Several bending magnets connected in series to one power supply are treated as one large bend. The results are $\frac{\Delta B}{B} \leq 4.5\ 10^{-4}$ for the horizontal CCS and $1.6\ 10^{-5}$ for the vertical CCS in the case of NLC. For JLC these tolerances are $1.2\ 10^{-4}$ and $5.5\ 10^{-6}$ for the horizontal and vertical CCS respectively.

3.7 Skew Quadrupole

The tolerances for the rotation of a quadrupole for the 2% increase in final spot size constraint is given by:

$$\theta \leq \frac{1}{10\ k\ \sqrt{\beta_x \beta_y}} \sqrt{\frac{\epsilon_y}{\epsilon_x}} .$$

Coupling in the optics leads to a growth of the spot size at the interaction point. Because of the step function pattern of the phase advance of final focus systems (most elements are $\pi/2 + n\pi$ away from the interaction point), there is only one important aberration caused by quadrupole rotation and the term representing the actual rotation of the beam in the physical $x - y$ space does not appear at a measurable level.

The rotation tolerances for quadrupoles of the final doublet are of the order of 3 μrad in the case of JLC and 11 μrad for NLC. It is a property of doublets that each quadrupole has the same rotation tolerances. The RMS value for other quadrupoles in the JLC line is 28 μrad, and 80 μrad for NLC.

3.8 Vertical Sextupole Alignment

The same coupling effect arises when the beam is vertically off-axis in a sextupole. Similarly to the normal quadrupole case this can be caused by a sextupole displacement or vertical steering from quadrupole offsets inside the CCS and the tolerances are

$$\Delta y_s \leq \frac{1}{5\ k_s\ \sqrt{\beta_{x_s} \beta_{y_s}}} \sqrt{\frac{\epsilon_y}{\epsilon_x}}$$

and

$$\Delta y_s \ = \ k_q\ R^{34}_{q \to s}\ \Delta y_q\ .$$

The sextupole vertical position tolerances are 180 nm and 520 nm for the vertical and horizontal chromatic correction respectively in the case of JLC. For NLC the tolerances are 680 nm and 1.2 μ. The tolerances on the vertical position of quadrupoles inside the chromatic correction sections are very tight due to high lattice multipliers. In the JLC the central quadrupole in CCX has a position tolerance of 100 nm while the one in CCY has to be stabilized to 40 nm. The worst values for the quadrupoles in these sections are 300 nm for CCX and 40 nm for CCY. For NLC they are respectively 0.9 μ and 0.3 μ.

Note that because of the flat beam configuration the tolerance on the growth of the horizontal spot size due to vertical beam offset in a sextupole is looser by the ratio of the horizontal to vertical emittance, 100 in both designs. Table II summarizes the central quadrupole alignment tolerances for both JLC and NLC.

3.9 Dipole Rotation

The same skew quadrupole effect can come from a dipole rotation steering the beam vertically off axis at the second sextupole. The tolerances on the dipole rotation is written in the case $\epsilon_y < \epsilon_x$

$$\Delta\phi \leq \frac{1}{5\ k_s\ \overline{R_{34}}\ \theta} \sqrt{\frac{\epsilon_y}{\epsilon_x}} \frac{1}{\sqrt{\beta_x \beta_y}}$$

where $\overline{R_{34}}$ is the average value of the R_{34} across the bends taken separately. The tolerances are 450 μrad for the CCX and 37 μrad for CCY in the NLC case. They are only 67 μrad for CCX and as low as 10 μrad for CCY in the case of JLC.

3.10 Sextupole and Skew Sextupole

The tolerances on the sextupole and skew sextupole content of the normal quadrupoles are expressed as a ratio of the allowed sextupole or skew sextupole component to the nominal quadrupole field taken at some reference point (usually 70% of the aperture of the magnet) $(B_{ns}/B_q)_{a=a_r}$. One can also express this in terms of some equivalent sextupole strength k_{ns} given by

$$\left(\frac{B_{ns}}{B_q}\right)_{a=a_r} = \frac{k_{ns}a_r}{2k_q} \; .$$

For a beam size increase of 2%, the normal and skew sextupole tolerances are written:

$$k_{ns} \leq \mathrm{Min}\left[\frac{\sqrt{2}}{5\sigma_x\beta_x\sqrt{1+\sigma_y^4/\sigma_x^4}} \; ; \; \frac{1}{5\sigma_x\beta_y} \right]$$

and

$$k_{ss} \leq \mathrm{Min}\left[\frac{\sqrt{2}}{5\sigma_y\beta_y\sqrt{1+\sigma_x^4/\sigma_y^4}} \; ; \; \frac{1}{5\sigma_y\beta_x} \right] .$$

For the JLC both the sextupole and the skew sextupole tolerances are $k_{ns,ss} \leq .16\ \mathrm{m}^{-2}$. They are looser for the NLC at $k_{ns} \leq 1.4\ \mathrm{m}^{-2}$ and $k_{ss} \leq .40\ \mathrm{m}^{-2}$.

4. Conclusion

Although it is difficult to compare two lines designed for different sets of parameters, it appears that the JLC lattice we have chosen for this

Table III
NLC Tolerances

Time Scale	Generator (IP coord.)	Final Quadrupoles	Other Quadrupoles Worst	Other Quadrupoles RMS	Sextupoles	Dipoles
τ_0		Δx	or	Δy	n/a	n/a
	x'	0.08 μ	0.32 μ	0.24 μ		
	y'	3 nm	53 nm	20 nm		
τ_1		Δx	or	Δy	n/a	n/a
	$x'\delta$	34 μ	1.7 μ	1.0 μ		
	$y'\delta$	268 nm	71 nm	47 nm		
τ_2		$\Delta k/k$	or	$\Delta\theta$	Δx or Δy	$\Delta B/B$ or $\Delta\phi$
	x'^2	4.7 10^{-4}	4.5 10^{-3}	6.2 10^{-3}	0.30 μ	1.6 10^{-5}
	y'^2	1.9 10^{-5}	2.9 10^{-4}	1.3 10^{-4}		37 μrad
	$x'y'$	11.3 μrad	129 μrad	80 μrad	0.68 μ	
τ_3			k_s		$\Delta k/k$ or $\Delta\theta$	n/a
	$x'^2\delta, y'^2\delta$		0.69 m^{-2}	0.33 m^{-2}	1.4 10^{-2}	
	$x'y'\delta$		1.27 m^{-2}	0.38 m^{-2}	15 mrad	
	$x'^3, x'y'^2$	1.4 m^{-2}	0.75 m^{-2}	0.37 m^{-2}	1.6 10^{-2}	
	y'^3, x'^2y'	0.40 m^{-2}	0.50 m^{-2}	0.23 m^{-2}	3.4 mrad	

Table IV
JLC Tolerances

Time Scale	Generator (IP coord.)	Final Quadrupoles	Other Quadrupoles Worst	Other Quadrupoles RMS	Sextupoles	Dipoles
τ_0		Δx	or	Δy	n/a	n/a
	x'	40 nm	120 nm	50 nm		
	y'	1.8 nm	24 nm	10 nm		
τ_1		Δx	or	Δy	n/a	n/a
	$x'\delta$	18 μ	0.4 μ	0.6 μ		
	$y'\delta$	156 nm	13 nm	28 nm		
τ_2		$\Delta k/k$	or	$\Delta\theta$	Δx or Δy	$\Delta B/B$ or $\Delta\phi$
	x'^2	1.6 10^{-5}	2.2 10^{-3}	1.1 10^{-3}	0.12 μ	5.5 10^{-6}
	y'^2	4.5 10^{-6}	1.2 10^{-4}	7.9 10^{-5}		10 μrad
	$x'y'$	2.7 μrad	78 μrad	28 μrad	0.18 μ	
τ_3			k_s		$\Delta k/k$ or $\Delta\theta$	n/a
	$x'^2\delta, y'^2\delta$		0.30 m^{-2}	0.22 m^{-2}	4.8 10^{-3}	
	$x'y'\delta$		0.34 m^{-2}	0.19 m^{-2}	4.6 mrad	
	$x'^3, x'y'^2$	0.16 m^{-2}	0.13 m^{-2}	0.13 m^{-2}	4.1 10^{-3}	
	y'^3, x'^2y'	0.16 m^{-2}	0.13 m^{-2}	0.11 m^{-2}	1.2 mrad	

study has consistently tighter tolerances than the one chosen to represent the NLC, often by factors of two to five. The basic machine parameters alone are not enough to explain these differences and it is obvious that the lattices themselves have a strong influence on the tolerances. One should not judge a final focus system for a next-generation linear collider based only on its performance (spot size, remaining aberration content, etc.) but also on its tolerances. Many tolerances are very small and the stabilization, correction and tuning of these lines will be difficult, even with the help of global correction techniques. A better understanding of the inherent sensitivities of different lattices (e.g. FODO vs. triplet or multiplet) is needed in order to optimize the design of a final focus system for a next-generation linear collider, optimizing for ease of correction and tuning as well as performance. Tables III and IV summarize the tolerances for the particular NLC and JLC designs we have analyzed. We have separated here the final quadrupoles from the rest of the elements for which we quote the worst individual tolerances as well as the rms values as defined in the text taking all remaining elements together. The final quadrupole displacement tolerances are those of the final doublet considered as a single object. For the dipoles and sextupoles the tightest tolerance, whether from the CCX or the CCY, is quoted.

References

[1] P. Chen, *Snowmass '88, High Energy Physics in the 1990s*, Snowmass CO, p. 673.