SLAC–PUB–5485
May 1991

Review of tolerances at the Final Focus Test Beam.* (A)

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Abstract

We review the tolerances associated with the Final Focus Test Beam (FFTB). We have computed the acceptability window of the input beam for orbit jitter, emittance beta functions mismatch, incoming dispersion and coupling; tolerances on magnet alignment, strength and multipole content; and the initial tuneability capture of the line.

I. The Acceptability Window.

A. Bandwith and Energy.

The bandwidth is defined as the energy spread range over which the spot size at the focal point (FP) does not increase by more than 2%; it is of the order of $\pm 0.4\%$. It is expected that the beam actually delivered will have a an energy spread of the order of $\pm 0.2\%$. The tolerance on beam energy stability is then of the order of $\pm 0.2\%$ for a beam energy of $50GeV$.

B. Emittance and Beta functions.

The final horizontal spot size at the FFTB scales *linearly* with the emittance since we have to maintain the design 10σ clearance along the line and change the beta-functions accordingly. In the vertical plane, the scaling goes with the square root of the emittance up to a factor of two increase in emittance. The range of beta matching covers at least two orders of magnitude around the nominal beta functions in both horizontal and vertical planes.

C. Dispersion.

Incoming dispersion from the linac is estimated at the level of .2 to $.5\sigma$ and is linearly transformed to the focal point. The FFTB has the ability to correct as much as 7σ of dispersion at the focal point.

D. Coupling.

There are only two important coupling terms for the FFTB and it is expected that the magnitude of the incoming coupling is about 10%. We can correct at least a magnitude of 20% for both terms.

E. Position Jitter.

The position jitter at the end of the linac is estimated at the level of $.2\sigma$ and the acceptability tolerances are of the order of $.3\sigma_x$ and $.3\sigma_y$ ($150\mu m$ and $55\mu m$) for the position and $1\sigma_{x'}$ and $.3\sigma_{y'}$ ($5\mu rad$ and $.5\mu rad$) for the angles at the input. However the beam jitter should not exceed $.2\sigma$ at wire scanners in order to keep the measurement error below a 2% level.

II. Stability Tolerances.

A. Tolerance Budget.

The experience with measuring small spots at the interaction point of the SLC is 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). We will also quote tolerances according to this 2% criterion for *individual elements*. We refer to the RMS tolerance as the combination in quadrature of individual tolerances to establish the design tolerance related to a given aberration.

B. Steering.

We permit beam centroid motion at the focal point to be one standard deviation ($\Delta y^* \approx \sigma_y^*$). The final quadrupole doublet (QC2 and QX1-QC1, all treated as one element) position tolerance is then $\Delta y_{fq} \approx \sigma_y^*$. Since most quadrupoles are $\pi/2+n\pi$ from the focal point, tolerances scale according to their strengths and β-functions:

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

The final quadrupole position stability tolerance is therefore of the order of the final vertical spot size, 60 nm. For the other quadrupoles the β-functions and strengths put these tolerances in the range 0.4 to a few microns in the vertical plane and 1.6 to 10. μm in the horizontal plane. The RMS vertical displacement tolerance is $.2\mu m$.

C. Dispersion.

Dispersion is primarily generated at the focal point by a trajectory offset in the final quadrupole triplet. 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. This translates into a vertical position tolerance of $5\mu m$. The offset

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Presented at the IEEE Particle Accelerator Conference, San Francisco, CA, May 6–9, 1991

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 focal point parameters or the beam properties. The greater this multiplier the tighter the dispersion tolerances on the element. Critical magnets are located at the beginning of the FT with vertical alignment tolerances between 10. and 1.5μm. The quadrupole at the midpoint of the CCY has a tolerance of 2μm as it benefits from the presence of the second sextupole which compensates close to one half of the dispersion created by the final quadrupole.

D. Normal Quadrupole.

A change in the final quadrupole strength moves the waist away from the focal point, increasing the spot size at the focal 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 strengths and beta functions are large, the tolerances are very tight: $\frac{\Delta k}{k} \leq 2.3 \times 10^{-5}$ and 2.0×10^{-4} for QC1 and QC2 respectively. For other quadrupoles the tightest tolerances occur around the sextupoles (large beta functions also): $\frac{\Delta k}{k} \leq 1.7 \times 10^{-4}$ around SD1. Taking into account all the quadrupoles in the line except the final doublet, the RMS tolerance is $\frac{\Delta k}{k} \leq 7.3 \times 10^{-5}$.

E. Skew Quadrupole.

Coupling in the optics leads to a growth of the spot size at the focal point. Because of the step function pattern of the phase advance in final focus systems, 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 significant level. The tolerances for quadrupole rotation for the 2% increase in final spot size constraint is given by:

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

They are of the order of 7 μrad for the final quadrupoles and 33 μrad for the rotation of all three magnets as a whole. It is a property of doublets that each quadrupole has the same rotation tolerances. The RMS value for other quadrupoles is 40 μrad.

F. Sextupole Alignment.

Waist motion and coupling also appear when the beam is horizontally or vertically offset in a sextupole, which may come from an actual displacement of the magnet or from one of the chromatic correction section (CCS) quadrupoles steering the beam off axis in the second sextupole. The same notion of multipliers applies here taking the second sextupole as the reference: $\Delta x_s = k_q\ R^{12}_{q \to s}\ \Delta x_q$. If the beam is off-axis in the first sextupole the effect is cancelled by the equal and opposite displacement in the second sextupole ($-I$ transformation). The tolerances for sextupole horizontal and vertical offsets are

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

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

resulting in 3.5μm for the CCX sextupoles, and only 0.9μm for the CCY. The vertical tolerances are 3.5μm and 1.4μm for the CCX and CCY respectively. The multipliers for the quadrupoles inside the CCY and CCX to the second sextupoles give quadrupole horizontal alignment tolerances of .7μm and 1μm in CCX and CCY respectively and the central quadrupole in CCX has a vertical position tolerance of 4μm while the one in CCY has to be stabilized to 0.3μm.

G. Dipoles.

Dipoles located inside the CCS can steer the beam off-axis in the second sextupole: horizontally through power supply jitter and vertically through dipole rotation, giving rise to norma and skew quadrupole effects respectively. The tolerances for the stability of the power supplies and the rotation of the magnets are given by

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

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

The $\overline{R_{ij}}$ is the average value of the R_{ij} matrix element between the entrance and the exit of the bend. For powers supply jitter tolerances, several bending magnets connected in series are treated as one large bend. The results are $\frac{\Delta B}{B} \leq 3.3\ 10^{-5}$ for the CCX and $1.0\ 10^{-5}$ for the CCY. Rotation tolerances are of the order of 37 μrad for CCX and 14 μrad for CCY.

H. Sextupole and Skew Sextupole.

The tolerances on the normal and skew sextupole content of the quadrupoles are expressed in terms of equivalent sextupole strength and under the condition of a 2% beam size increase:

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

and the expression for k_{ss} is obtained by exchanging σ_x for σ_y in the expression above. For FFTB the normal and skew sextupole tolerances are $k_{ns,ss} \leq .08\ m^{-2}$ for QC1 and $k_{ns,ss} \leq .004\ m^{-2}$ for QC2. The RMS values for the other quadrupoles are $k_{ns} \leq .009\ m^{-2}$ and $k_{ss} \leq .006\ m^{-2}$.

FFTB TOLERANCES

Time Scale Generator	Final Quads	Other Quads Worst	Other Quads RMS	Sextu-poles
τ_0	Δx or Δy [μm]			n/a
x'	1.	1.6	0.75	
y'	.06	.46	.18	
τ_1	Δx or Δy [μm]			n/a
$x'\delta$	50.	1.6	0.8	
$y'\delta$	4.7	1.2	.7	
τ_2	$\Delta k/k$ [10^{-5}] or $\Delta\theta$ [μrad]			Δx, Δy
x'^2, y'^2	2.	17.	7.3	0.9 μm
$x'y'$	33.	110.	40.	1.4 μm
τ_3	k_s [$10^{-3} m^{-2}$]			$\Delta k/k$, $\Delta\theta$
$x'^3, x'y'^2$,	5.	12.	9.	5.2 10^{-3}
y'^3, x'^2y',	4.	6.	6.	0.7 $mrad$

III. The Capture and Tuning of the FFTB

We will now outline the different steps necessary to carry out the initial capture and the tuning of the FFTB in order to reach the design spot size. [1]

A. Mechanical Alignment

Early results of alignment tolerances and tuning simulations showed that it is possible to correct misalignments in the line within the alignment tolerances of 100μ horizontally and 30μ vertically. [2] The tuning involved orbit bumps to cancel the dispersion at the IP and sextupole alignment to cancel the normal and skew quadrupole effects. These figures have therefore been chosen as the goals for the initial mechanical alignment of the line.

B. Input Beam Matching

Using a different configuration of the Beta Matching section, one can analyze the incoming beam (beta functions, emittance) and match it at the entrance of the CCX. This tuning can be verified and refined at a later stage (including dispersion and coupling) using other beta minimum points in the Beta eXchanger and Final Transformer sections (BXx,BXy,FTy).

C. Beam-Based Alignment

One can determine the offset of a given quadrupole with respect to the beam by varying its strength and observing the trajectory downstream. Each quadrupole being mounted on a magnet mover it is possible to move the elements along a straight line defined by the beam. The straight section can then be hinged into alignement with other sections. With a BPM precision of $1\mu m$ all the quadrupoles can be aligned nearly to tolerances.

D. Quadrupole Tuning

Quadrupole strengths can be probed by orbit bumps launched across different sections (CCX, BX, CCY, and FT) by dipole correctors. As the sections all have π phase advance and there are always less than four effective quadrupoles per section, the sensitivity of this process is enhanced and the system is fully determined. The sensitivity in the setting of the quadrupole strengths using this method is better than the required tolerance.

E. Stability Monitoring

Dispersion appears when the beam is off-axis in an element which is a source of chromaticity. By monitoring and maintaining a constant beam position at a few locations (final doublet, sextupoles) the dispersion can be stabilized for as long as one can rely on the stability of the BPM readings. Normal and skew quadrupole aberrations arise with beam position changes at the sextupoles. After aligning the sextupoles the sum of their BPM readings can be monitored and should remain constant.

F. Global Correction

Maintaining a small spot size at the focal point will require the use of global correction techniques. A global corrector is a knob used to cancel one aberration at the focal point. One can itemize the global correctors for the FFTB according to four time scales: The first one (τ_0) corrects for position jitter in the quadrupoles displacing the final spot and is determined by the feedback system correction frequency. The second controls the dispersion originating from change of quadrupole positions and is determined by the time one can maintain the stability of the line and depends on the BPM stability at micron readings. The third set of global correctors cancels normal and skew quadrupole effects. With orbit bumps to confirm CCS alignment it may be possible to extend this time scale (τ_2) beyond the BPM stability time (τ_1). The fourth time scale (τ_3) covers remaining higher order aberrations (*e.g.* sextupole setting) and is determined by the stability of magnet power supplies. A few multi-knobs (8) finally depend on the linac running conditions and are used for the matching of the incoming beam.

IV. References

[1] F. Bulos *et al.* Beam-Based Alignment and Tuning Procedures for e^+e^- Collider Final Focus Systems, YPH5 these proceedings

[2] K. Oide, SLAC-PUB 4953