

THE FINAL FOCUS TEST BEAM PROJECT*

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Abstract

An overview is given of the Final Focus Test Beam (FFTB) that is being constructed as a prototype final focus system for a future electron-positron linear collider. This beam line will use as input the 50 GeV electron beam from the SLC linac, and is designed to reduce the transverse dimensions of the beam spot at the focal point to $1 \mu\text{m} \times 0.06 \mu\text{m}$.

1. INTRODUCTION

One of the greatest challenges to the development of future e^+e^- linear colliders is to make particle beams with extremely small sizes. Whereas the particle bunches in the SLC are millimeter-long needles, 4–5 μm across, those in future machines will have to be ten times shorter and up to a thousand times narrower. The part of a linear e^+e^- collider that reduces the beam sizes and maintains the beams in collision is called the final focus. Producing and colliding tightly focused beams requires careful control and stabilization of the magnetic elements of the final focus, placing considerable emphasis on accurate measurement of the properties of the beam itself. We have learned a great deal from operation of the SLC, but successful implementation of future machines at higher energies will demand that even tighter mechanical and electrical tolerances be respected, and greater measurement precision, as well as more powerful tuning mechanisms and techniques, be achieved.

We [1] have recently begun to build and instrument a prototype final focus system for a future linear collider. This Final Focus Test Beam (FFTB) [2]—which will occupy some 185 meters in the straight-ahead channel at the end of the SLAC linac (Fig. 1)—is designed to accept the SLC electron beam as input and to produce a focal point at which the beam height will be demagnified, by a factor of 300, to a size smaller than 100 nanometers. Just such a compression factor will be required for the final focus of a TeV-scale linear collider.

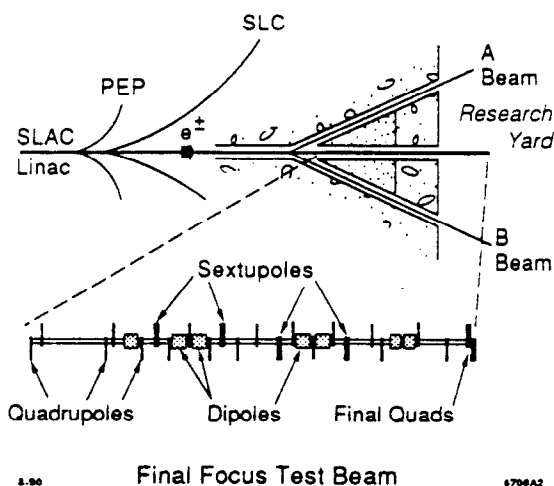


Figure 1. Location of the FFTB at the end of the SLAC 50 GeV linac.

Table I. Parameters of the Final Focus Test Beam

Parameter	NLC	SLC	FFTB
Beam energy (TeV)	0.25 to 0.75	0.05	0.05
Emittance $\gamma\epsilon_y$ (rad-m)	3×10^{-8}	3×10^{-5}	3×10^{-6}
Focusing β_y^* (μm)	100	7000	100
Demagnification	300	30	380
Beam height σ_y (nm)	3 to 5	2000	60
Aspect ratio	100 to 200	1	15
Bunch length σ_z (μm)	50 to 100	500	500
Bandwidth $\delta p/p$ (%)	± 0.3	± 0.3	± 0.3
Bunch population (10^{10})	1 to 2	3 to 5	1 to 2

II. Optical Design

The parameters of the FFTB have been chosen to match as closely as possible those of a future collider (Table I). The SLC damping ring can produce an invariant emittance of $\gamma\epsilon_y = 7 \times 10^{-7}$ rad-m at quantum mechanical equilibrium when operated with the horizontal and vertical phase space components decoupled from each other. The optics of the FFTB [3] are corrected to third order for geometric and chromatic aberrations, and would theoretically be able to reduce such a beam to a spot with vertical height 27 nm. We anticipate, however, that the invariant emittance of the beam will be enlarged during acceleration in the linac. It is expected that, for beam intensities up to 10^{10} particles per pulse, this growth can be controlled well enough to deliver $\gamma\epsilon_y = 3 \times 10^{-6}$ rad-m to the entrance of the FFTB. This is sufficiently small that the FFTB will be able to achieve a vertical spot dimension of 60 nm while maintaining a horizontal size of 1 μm .

The FFTB contains five optical sections. The beam that appears at the end of the linac is first matched to the lattice of the FFTB beam line. The matching section controls the launch of the beam orbit into the FFTB, and contains lenses to match the betatron space of the beam to the FFTB lattice at the entrance to the chromatic correction section. The FFTB design has two chromatic correction sections to allow the chromaticities of each plane to be separately tuned. This guarantees that the sextupoles can always be placed at their optimal locations ($N\pi$ phase advance to the focal point, with N integer). The lattice includes a “ β -exchanger” to match the β -function from one chromatic correction section to the other. The overall demagnification of the system is controlled by the focal lengths of the initial betatron match and of the final telescopic section. The basic principles of this scheme have been successfully demonstrated at the SLC, but the chromaticity that is being corrected in the FFTB lattice is an order of magnitude greater.

There are two major third-order aberrations that remain in the spot produced by the above chromatic correction procedure. The first is created by the finite thickness of the sextupole magnets. Third-order geometric aberrations (octupole-like), introduced as the beam envelope changes within the length of the sextupoles, lead to an increase in the final spot size of approximately 4%. The second effect is more subtle, but just as significant. As particles pass through the bend magnets that create the dispersion necessary for the chromatic correction to occur, they lose some energy through synchrotron radiation. The cancellation between the chromaticity introduced by the sextupoles and that introduced by the final quadrupole lenses can no longer be rigorous. This causes a 7% increase of the spot.

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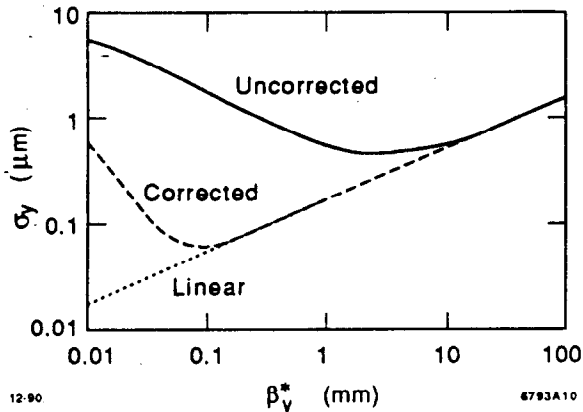


Figure 2. Vertical beam height at the FFTB focal point as the focusing strength of the lattice is varied. The curves show the result for optics uncorrected for chromaticity (solid), corrected (dashed), and the monochromatic linear behaviour (dotted).

The optimal design that minimizes the spot dilution from the two effects discussed above has been determined [4] and will be used for the FFTB. The performance of this design is shown in Fig. 2. A similar optimization that includes the emittance growth due to synchrotron radiation in the bend magnets is done for the horizontal plane.

III. Magnets

The FFTB beam line consists of discrete dipole, quadrupole, and sextupole magnetic elements. Aperture sizes for these magnets have been determined to assure at least 10σ clearance between the pole-tips of the elements and the nominally β -matched beam with design emittance. Tolerances on the harmonic content of the fields have been calculated by placing a limit of 2% on the dilution (per magnet) of the final spot size due to imperfections in the fields.

The optical design of the FFTB has been tailored so that 28 of the 39 quadrupoles required for the system can be constructed from a single mechanical design—the “Standard Quadrupole.” This is a solid iron-core magnet with an effective length of 46.1 cm and bore diameter of 2.3 cm that will be operated with pole-tip fields below 10 kG in all cases. The pole-tip contour has been designed (with the program POISSON) to limit the non-quadrupole field to less than 0.1% of the primary quadrupole field at 70% of the full aperture.

The lenses of the final doublet are more difficult to design and fabricate than the remainder of the quadrupole elements. The restrictions on their harmonic content are reduced to 0.03%, and in some cases these magnets must operate with pole-tip fields that are as large as 14 kG. The alignment tolerances for these elements are such that they are best designed and fabricated as a complete set, and that they be supported by a common mounting structure. A prototype magnet with pole-tips made from the composite material Permendur is presently being fabricated, and is expected to lead to a successful design of a full scale set of lenses.

The dipole bending magnets for the FFTB are all of a single design—the “Standard Dipole.” This is a solid iron-core “H”-type magnet with relatively modest field strengths and tolerances. Each magnet is 2.8 meters long with the same 2.3 cm gap spacing used for the Standard Quadrupoles. These magnets are used in pairs spaced slightly apart to provide access to the center of each bend, or hinge, point in the lattice.

All sextupole magnets in the FFTB are of a single design. The harmonic content of the sextupole field in these magnets

need only be pure to one part in 100, but to avoid severe saturation of the magnetic field in the pole-tip, it has been necessary to reduce the aperture of these magnets to 2.1 cm and set their overall length to 25 cm. The magnet steel will remain slightly saturated ($\approx 5\%$) at 50 GeV beam energy, and there is some dilution of the performance of the system due to the length of the magnets. The effect on the spot size of the thick-lens sextupole has been discussed above.

IV. Mechanical Alignment and Stabilization

Errors in the positioning or orientation of the magnetic elements of the FFTB (with respect to the ideal beam line coordinates) degrade the performance of the system by introducing anomalous dispersion and/or coupling into the beam phase space.

The relative alignment of the beam line will suffer from finite motions that occur with a range of frequencies from ≈ 100 Hz down to the static alignment limit. Alignment errors that are within certain tolerances (typically, a few tens of microns for the FFTB) can, in principle, be compensated by tuning the parameters of the lattice. This method will be successful if the errors are static, or at least develop slowly compared to the time required to accomplish the tuning. Completely tuning the lattice may require several hours. Motions of beam line elements that produce microns of displacement in shorter times must be monitored and eliminated by additional hardware. With a few exceptions, “vibrations” that occur at frequencies above the bandpass of the alignment hardware cannot be corrected in any fashion. Fortunately, propagation of acoustical waves with frequencies above a few tens of Hz is significantly damped in materials such as concrete and earth.

Initial Alignment Tolerances

If the positions of the magnets of the FFTB are assumed to be stable, then simulations of the optical tuning have shown that the spot size at the focal point can be reduced to differ from its design value by only several percent, as long as the magnetic centers (nodal points) of the quadrupole and sextupole magnets are initially displaced from the local straight line along which they lie by amounts

$$\delta r_{rms} < 100 \mu\text{m} \quad \text{and} \quad \delta y_{rms} < 30 \mu\text{m}$$

Each local line segment must intersect the adjoining segments with a distance of closest approach no greater than $30 \mu\text{m}$, but the bend points of the beam line need only be within

$$\Delta x < 2 \text{ mm} \quad \text{and} \quad \Delta y < 0.2 \text{ mm}$$

of the design trajectory. Bending magnet power supplies can be adjusted to compensate for errors in geometric angles.

Stability During Tuning

If sufficiently well-aligned, it will be possible to adjustment the optics of the test beam to produce the desired spot at the focal point, but to do so, the position of the beam line elements must not change during the tuning procedure. If we demand that the magnet positions be sufficiently stable that no individual motion change the spot size by more than 2% (either larger or smaller), then straightforward calculations show that we must maintain the position of each magnet to within $\pm 2 \mu\text{m}$ of a location set with respect to the remainder of the magnets in the beam line. Similar calculations show that the roll angles of several elements about their magnetic centers need to be maintained to within 0.2 mrad.

A stretched-wire alignment system has been designed [5] to monitor changes in the positions and orientations of the elements of the beam line, with the required accuracies. Data from this system will be acquired continuously on a minute-to-minute basis.

Long Term Stability

We anticipate that during periods of use, the optical tuning procedure will yield configurations of magnet positions that produce small spots. We would like to be able to return the magnets to positions that are close to one of these configurations, after periods of extended interruption of the operation of the beam line. Our philosophy is that, on these occasions, the calibration of the stretched-wire system may drift substantially or be compromised by work on the beam line. We are also concerned about the stability of the foundation of the structures that house the beam line.

We have chosen to provide an "absolute" reference for the FFTB by extending the 3-km long Fresnel-lens system used to monitor alignment of the SLAC Linac/BSY. The positions of the stretched wires will be monitored with respect to this reference line. Changes in the wire positions need to be determined with accuracies that are substantially smaller than the tolerances on their initial absolute positions. Our goal is to be able to stabilize the wire system to remain within 10 μm of its initial horizontal position and within 5 μm of its initial vertical position.

Magnet Movers

Each of the quadrupole and sextupole magnets will be placed on remotely-controllable supports capable of translating their lateral (horizontal and vertical) positions over a range of ± 1 mm, in steps of 0.5 μm . Trim coils on the backleg flux return of each quadrupole may also be used to move the magnet centers of the focusing elements by small amounts (up to 10 μm).

Vibration Tolerances

The alignment system for the FFTB is not intended to be able to correct movements of beam line components that occur faster than can be followed with mechanical magnet movers controlled by a microprocessor—i.e., vibration at frequencies above ≈ 0.01 Hz. To avoid dilution of the final spot size, the critical beam line components will have to be isolated from high-frequency mechanical vibrations with amplitudes larger than a micron.

V. Power Supplies

The total DC power requirements for the FFTB magnets, less than 500 kW, is not large, but the need to control the strength of individual magnetic elements along the beam line dictates that there be a relatively large number of power supplies. A total of 32 large supplies and 64 bipolar corrector supplies will be required to provide sufficient control to operate and tune the lattice optics. Tolerances on the stability of these supplies range between 0.01% and 0.001% of full scale. None of the supplies required for the FFTB are beyond presently available technology, and we plan to use commercially available devices.

VI. Beam Position Monitors

The beam position monitors *BPMs* used in the FFTB will be similar to monitors developed [6] for use in the SLC Final Focus. A monitor will be inserted into the aperture of each quadrupole magnet with the "strips" recessed into the space between the pole tips. This is done by extruding the beam pipe into a four-leaf clover cross section such that each *BPM* strip becomes the center conductor of a coaxial transmission line. Approximately 25% of the coax is exposed to the beam, so a sizable image charge flows on the center conductor.

A new philosophy is being adopted for the calibration of the beam position monitors used in the FFTB. We have developed a fixture that measures the axis of the field of the magnet, and simultaneously calibrates the response of the *BPM*. This is done

by stretching a taut wire through the *BPM* after it is mounted in the quadrupole. The wire is vibrated to induce across its ends an EMF that is determined by the net integral magnetic field along its length. The symmetry axis of the magnet can be found by moving the end of the wire in micron steps until the signal is minimized. The vibration is then stopped and a voltage pulsed down the wire to simulate the passage of the beam. This provides a measure of the response of the *BPM* to a beam that passes at that wire position. The software can use this *BPM* response as its reference for locating the beam, relative to the axis of the magnet.

Systematic errors in the measurement of the beam position are generated by electrical imbalances caused by the mechanical construction of the *BPMs*, attenuation differences between the four cables that bring the signals to the electronics, errors in the calibration of the signal-processing module, and mechanical alignment errors. We expect to be able to hold the sum of these errors to less than 30 μm on average.

Pulse-to-pulse stability of the beam-position measurement is dependent on the noise in the signal-processing electronics and the least count of the ADC. Stray beam particles that strike the electrodes of the *BPM* can also contribute to pulse-to-pulse noise. The mechanical design of the beam line includes shielding for the locations of the *BPMs*, and bench tests of the signal processing electronics indicates that we will be able to maintain uncorrelated pulse-to-pulse errors to below 2 μm .

VII. Control System

Operation of the FFTB beam line and detectors will be done from the SLC Main Control Center (MCC), where it will be possible to monitor and control the upstream portions of the machine, as well as the FFTB itself. Touch-panel consoles located in MCC provide the human interface to the machine hardware. Control of the FFTB hardware, and acquisition of data from the sensors and instrumentation in the beam line, will be done by a CAMAC-based system that is an extension of the existing SLC control structure. The FFTB hardware is designed to be compatible with the SLC database and protocols, and the full complement of on-line analysis and modelling programs that have been developed for the SLC will be available for use by physicists and operators working with the FFTB.

VIII. Schedule and Plans

Components of the Final Focus Test Beam are presently under fabrication at the laboratories of the participating institutions around the world. It is expected that construction and installation of the beam line will be completed by the end of 1992. Initial operation with beam will represent a significant step in the research and development necessary to realize the next e^+e^- linear collider.

REFERENCES

- [1] The FFTB Collaboration consists of scientists and engineers from: Deutsches Elektronen-Synchrotron, DESY, Hamburg, Germany; Institute for Nuclear Physics, Novosibirsk, USSR; Laboratoire de l'Accelérateur Lineaire, Orsay, France; Max-Planck-Institute, Munich, Germany; National Laboratory for High Energy Physics, KEK, Tsukuba, Japan; and Stanford Linear Accelerator Center, Stanford, CA, USA.
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