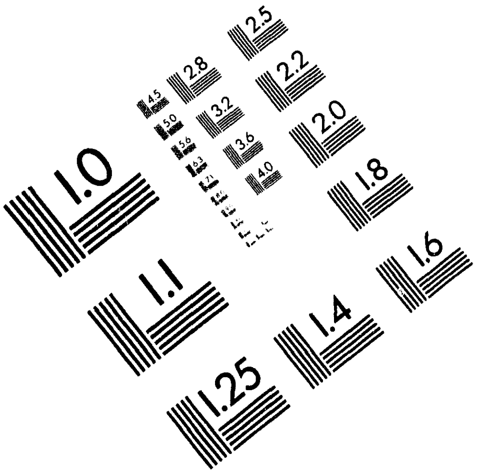
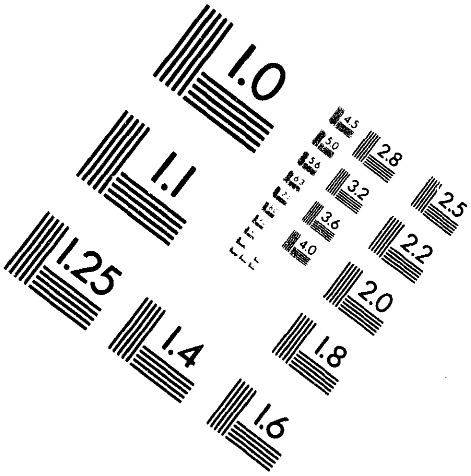
Association for Information and Image Management

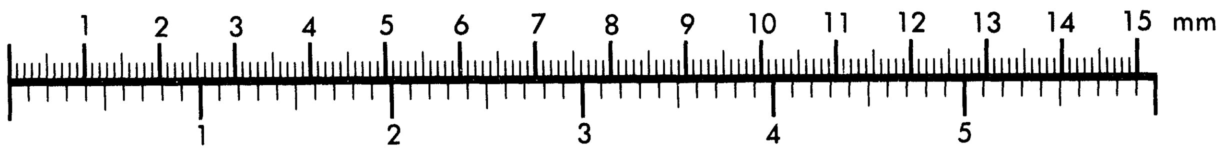
1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910

301/587-8202

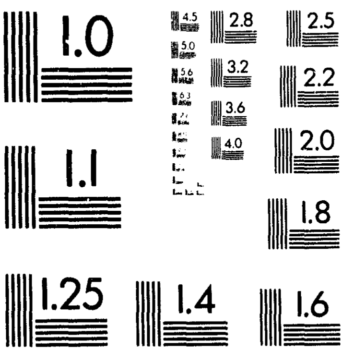


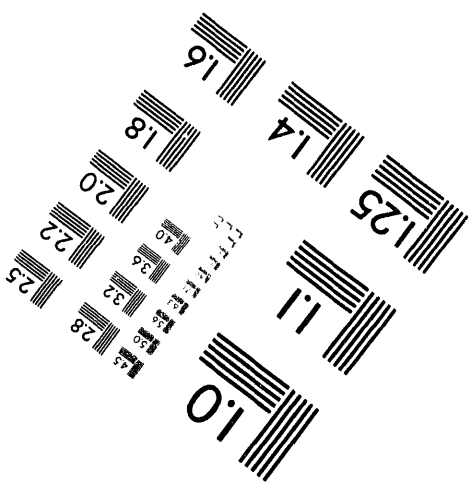


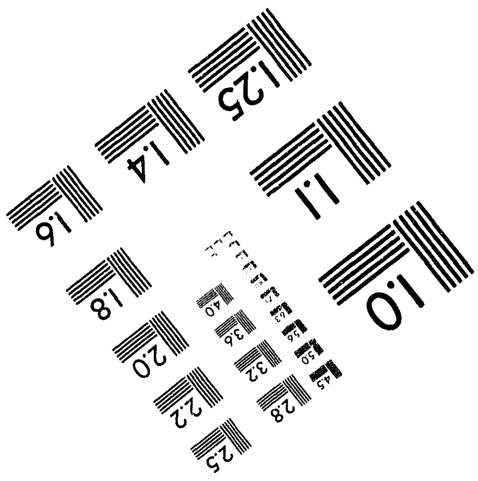
Centimeter



Inches







MANUFACTURED TO AIIM STANDARDS
BY APPLIED IMAGE, INC.

11/29-94 8 (1)

CONF-940618--48

SLAC–PUB–6609
July 1994
(E/A)

Results from the Final Focus Test Beam*

The Final Focus Test Beam Collaboration [1]

Reported by David L. Burke

Stanford Linear Accelerator Center
Stanford University, Stanford, CA 94309

ABSTRACT

First experimental results from the Final Focus Test Beam (FFTB) are given in this report. The FFTB has been constructed as a prototype for the final focus system of a future TeV-scale electron-positron linear collider. The vertical dimension of the 47 GeV electron beam from the SLAC linac has been reduced at the focal point of the FFTB by a demagnification of 320 to a beam height of approximately 70 nanometers.

One of the challenges to the development of TeV-scale e^+e^- linear colliders is to make particle beams with extremely small sizes. Whereas the bunches in the SLC are millimeter-long needles a micron across, those in future machines will need to be ten times shorter and up to a hundred times narrower. Producing and colliding tightly focused beams requires careful control and stabilization of magnetic elements, and places considerable emphasis on accurate measurement of the properties of the beam itself.

We have completed construction of a prototype focussing system for a future linear collider. This Final Focus Test Beam (FFTB) [2]---which occupies 200 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 is demagnified by a factor of 380, to a size smaller than 100 nanometers. Similar compression factors will be required for the final focus of TeV-scale linear colliders.

The SLC damping ring can produce an invariant emittance of $\gamma\varepsilon_y = 7 \times 10^{-7}$ rad•m, and the results presented here were obtained with 0.65×10^{10} electrons per pulse transported to the end of the linac with a vertical emittance of typically 2×10^{-6} rad•m. The nominal beam energy was 46.6 GeV, and the spread in particle energies was maintained at ± 0.05 - 0.1%. The optics of the FFTB [3] are corrected to third order for geometric and chromatic aberrations, and are designed to reduce this beam to a spot with vertical height of 52 nm.

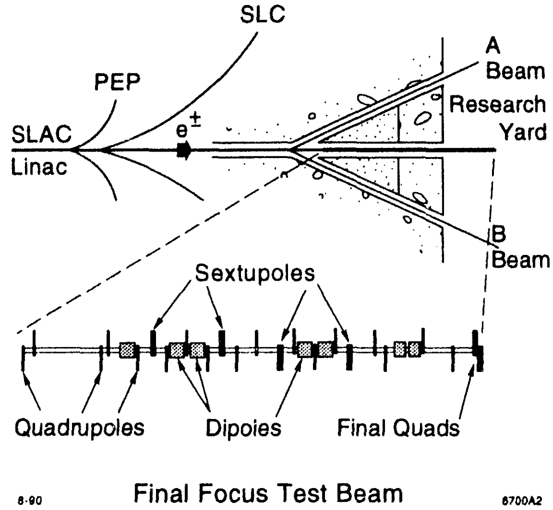


Fig. 1. Location of the FFTB at the end of the SLAC 50 GeV linac.

The FFTB contains five optical sections. The beam at the end of the linac is

* Work supported by Department of Energy contract DE–AC03–76SF00515.

Invited talk presented at the Fourth European Particle Accelerator Conference, London, England June 27–July 1, 1994

MASTER

first matched to the lattice of the FFTB in a section that controls the launch of the beam into the FFTB, and contains quadrupole lenses, both normal and rolled, that are able to fully adjust the betatron space of the beam. Two sections that contain sextupole magnets at points of high dispersion allow the chromaticity of the lattice to be tuned separately in the horizontal and vertical planes. The chromaticity introduced by the focussing quadrupoles must be cancelled with approximately 1% accuracy by that generated in the sextupoles. Geometric aberrations are controlled with pairs of sextupoles placed at points of equal dispersion but spaced exactly π radians apart in betatron space. These aberrations must also be cancelled to $\approx 1\%$, so it is important to maintain the proper phase advance between the sextupole magnets. The lattice includes a "β-exchanger" to match the optics from one chromatic correction section to the other. This section contains an intermediate focal point at which the vertical beam height is reduced to 1 micron. The overall demagnification of the beam is determined by the focal lengths of the initial matching section and the final telescopic section. The basic principles of this scheme have been successfully demonstrated at the SLC [4], but the demagnification of the beam in the FFTB is an order of magnitude greater.

Two major third-order aberrations remain in the spot produced by the FFTB. Geometric aberrations are introduced as the beam envelope changes within the finite length of the sextupoles. Also, synchrotron radiation in the bend magnets destroys the exact cancellation between the chromaticity introduced by the sextupoles and that by the quadrupole lenses. An optimal design that minimizes the spot dilution from these two effects is used. Its performance 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.

The FFTB beam line contains discrete dipole, quadrupole, and sextupole magnetic

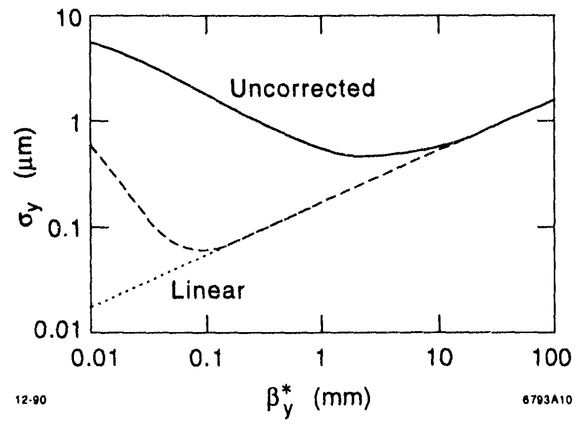


Fig. 2. Vertical beam height at the FFTB focal point. The curves are uncorrected for chromaticity (solid), corrected for chromaticity (dashed), and the ideal monochromatic behaviour (dotted).

elements. Aperture sizes for these magnets were determined to assure at least 10σ clearance between their pole-tips and the nominal design beam. Tolerances on the harmonic content of the fields were 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 is tailored so that 28 of the 31 quadrupoles required to focus the beam are constructed as identical solid iron-core magnets each with an effective length of 46 cm and bore diameter of 2.3 cm operated with pole-tip fields below 10 kG. The design of the pole-tip contour limits the non-quadrupole field to less than 0.1% of the primary field at 70% of the full aperture. Tolerances on the lenses of the final doublet are more stringent with restriction on their harmonic content of 0.03%, and in some cases these magnets must operate with pole-tip fields as large as 14 kG. Permendur is used in the fabrication of the pole-tips of these magnets. There are four sextupole magnets in the chromatic correction sections of the FFTB. The field in each need only be pure to 1%. All FFTB magnets meet or exceed the requirements for strength and harmonic content.

Errors in the position or orientation of magnetic elements in the FFTB (with respect to the ideal beam line coordinates) can introduce anomalous dispersion or coupling into the beam phase space and can change the focusing of the optics. Alignment errors also introduce linkage between the correcting elements of the beamline. Errors in alignment can occur as initial positioning errors, or can develop over time as components of the beamline move with respect to each other.

Optical effects created by errors in the alignment of the main FFTB magnets can be corrected with vernier tuning elements as long as the alignment is within certain tolerances. Simulations showed that spot sizes could be created at the focal point that differ from the design value by only several percent, as long as the magnetic centers of the quadrupole and sextupole magnets are initially placed within 100 microns of their ideal horizontal and 60 microns of their ideal vertical positions. A tracking laser interferometer and liquid-level system were used to place the FFTB beamline with the required accuracy.

The position of the beamline magnets must not change as the vernier elements are tuned. It is necessary to maintain the position of each magnet (with respect to its neighbors) to within 1-3 microns in order to avoid growth of the focussed spot by more than 2%. Similarly, the roll angles of elements about their magnetic centers need to be maintained to within 0.2 mrad. A stretched-wire alignment system was developed [5] to monitor changes in the positions and orientations of the elements of the beamline. Steel wires, stretched along straight sections of the beamline, carry a 100 MHz signal that is detected by electrodes attached to each magnet. The sensors resolve motions of individual magnets with $\sigma \approx 200$ nm; the systematic errors and long-term stability of this system are still under study.

Each quadrupole and sextupole magnet in the beamline is placed on a remotely-controllable support capable of translating laterally over a range of ±1 mm in steps of 0.3 micron [6]. The design uses a set of cam shafts driven by precision stepping

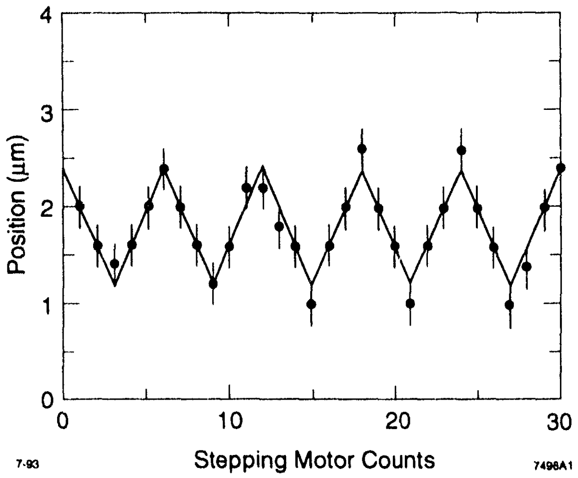


Fig. 3. Measured response of a magnet mover. The solid line traces the input command value, and the points are the measured response of the mover. The errors on the points are the estimated resolution of the position readout.

motors. Shown in Figure 3 is the response of a typical magnet mover. These devices are linear to a few parts per mil over their full range of motion, and are able to move quarter-ton magnets with submicron precision and little or no backlash. The precision of these movers makes it possible to use the beam to accurately align the FFTB magnets, and to simultaneously calibrate the response of the beam position monitors. Magnet-to-magnet alignments of 10-50 microns are estimated to be acheived with application of beam-based procedures.

Measurement of the properties of the beam in the FFTB is done with strip-line beam position monitors (BPMs), wire scanners, and beam profile monitors. A BPM is inserted into the aperture of each quadrupole magnet. Pulse-to-pulse stability of the beam-position measurement depen 's on the noise and least-count of the signal-processing electronics, and the number of stray beam particles that strike the electrodes of the BPM. The mechanical structure of the beamline includes shielding for the BPMs, and the electronics was designed [7] to resolve the signal generated by a pulse of 10^{10} electrons displaced 1 micron from the BPM center. Tests with the FFTB beam and magnet movers verify that the goal of the electronics design has been reached. Backgrounds due to beam spray limit the BPM resolution in a few instances to as much as 10 microns, but in most cases the electronics limit is reached.

Measurement of transverse profiles of the distribution of beam particles is done at several points along the FFTB beamline. Wirescanners, able to resolve beam profiles as small as 1 micron, are used to make measurements of the beam phase space and to verify the properties of the magnetic lattice in the β-matching and β-exchange sections. A pair of scanners are also located near the final focal point. These scanners are similar to those used in the SLC, but contain wires oriented at angles of a few degrees with respect to each other to measure the beam profiles with aspect ratios as large as 300 to 1 found in the FFTB.

Carbon filaments used in wirescanners are destroyed by thermo-mechanical stresses induced by sub-micron beams, so new instrumentation is required to measure beam profiles at the final focal point of the FFTB. Two devices were built for this purpose. One monitor uses [8] the coherent interaction of the electron bunch with a gas-jet. Atoms of helium or argon, injected into the path of the beam, are ionized and trapped in the potential-well created by the passing electron bunch. Plasma oscillations, excited in the plane transverse to the beam direction, effectively transfer energy to the ions. The amplitude of the oscillations in the horizontal and transverse planes are proportional to the corresponding dimension of the electron bunch, so the azimuthal distribution of ejected ions reflects the aspect ratio of the bunch. The distribution and time-of-flight of the ejected ions are detected in a ring of multichannel plates that surrounds the focal point.

A second monitor built for the FFTB focal point uses the concept of an optical cavity [9] illustrated in Figure 4. A laser beam is split, and folded onto itself to produce an interference fringe pattern in space. The electron beam is scanned across this pattern to yield a modulated rate of Compton-scattered photons in the forward direction. The ratio of peak to minimum Compton rates depends on the size of the beam and the fringe spacing.

Following a brief shake-down run in August 1993, data were taken with the FFTB during a three-week period in April and May of 1994. A wirescanner in the β-matching section was used to measure and tune the phase space of the incoming beam. An observed small coupling was corrected with rolled vernier quadrupoles by minimizing the projected vertical emittance of the beam at the entrance to the FFTB, and standard quadrupole adjustments were computed to match the betatron space of the beam to the FFTB lattice. Wirescanners in the β-exchange section were used to confirm that these corrections were accurate and that no optical errors were introduced by the quadrupoles in the horizontal chromatic correction section. The magnet movers and BPMs were used to adjust the element-to-element alignment of the beamline. The resulting dispersion in the FFTB lattice was well within the 5mm tolerance of the design values set by the range of available vernier correction.

Commissioning of the focal-point spot monitors required time to reduce backgrounds in the detectors by proper steering and collimation, and to set voltages and timing and debug data acquisition software. These monitors were then used to tune the final spot. Time-of-flight signals and azimuthal distributions from the gas-jet monitor agreed well with theoretical expectations, and were used to optimize the position of the beam waist, and to adjust skew quadrupoles to remove astigmatic coupling introduced by the final quadrupole lenses. This monitor was able to measure beam heights from a few microns down to 100-200 nm, and was an important tool to make intial adjustments of the beamline optics.

Precise tuning of the smallest spots was acheived with the laser-Compton monitor. Iterative tuning of vernier knobs to

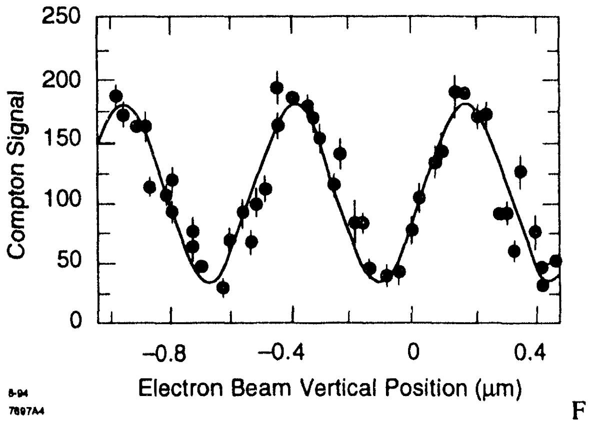


Fig. 5. Measurement of vertical height of the beam at the FFTB focal point with the laser-Compton spot monitor. The observed fringe spaceing agrees well with the 0.5 micron expected from the wavelength of the laser. The beam height is 73 nm in this case.

minimize residual dispersion and coupling of the beam phase space resulted in beam heights $\sigma_y \approx 100$ nm. Further reduction was made by adjustment of trim sextupoles just upstream and at the same betatron phase as the final quadrupoles. An example of the measurement is shown in Figure 5. The beam size measured by the laser-Compton monitor must be corrected for the mismatch between the length of the electron bunch, its divergence at the focal point, and the extent of the laser field along the beamline. This is estimated to be a 10% correction. Repeated measurements taken at the focal point over a period of several hours were distributed approximately Gaussian with corrected mean 70 nm and standard deviation 6 nm.

Estimates have been made of several sources of systematic error that might occur in the laser-Compton measurement of the beam height: (i) motion of the transverse position of the beam or laser fringe pattern, (ii) lack of complete contrast in the laser fringe pattern, and (iii) error in subtraction of background counts in the Compton detector. These lead to an uncertainty in the measured spot size estimated to be less than 7 nm.

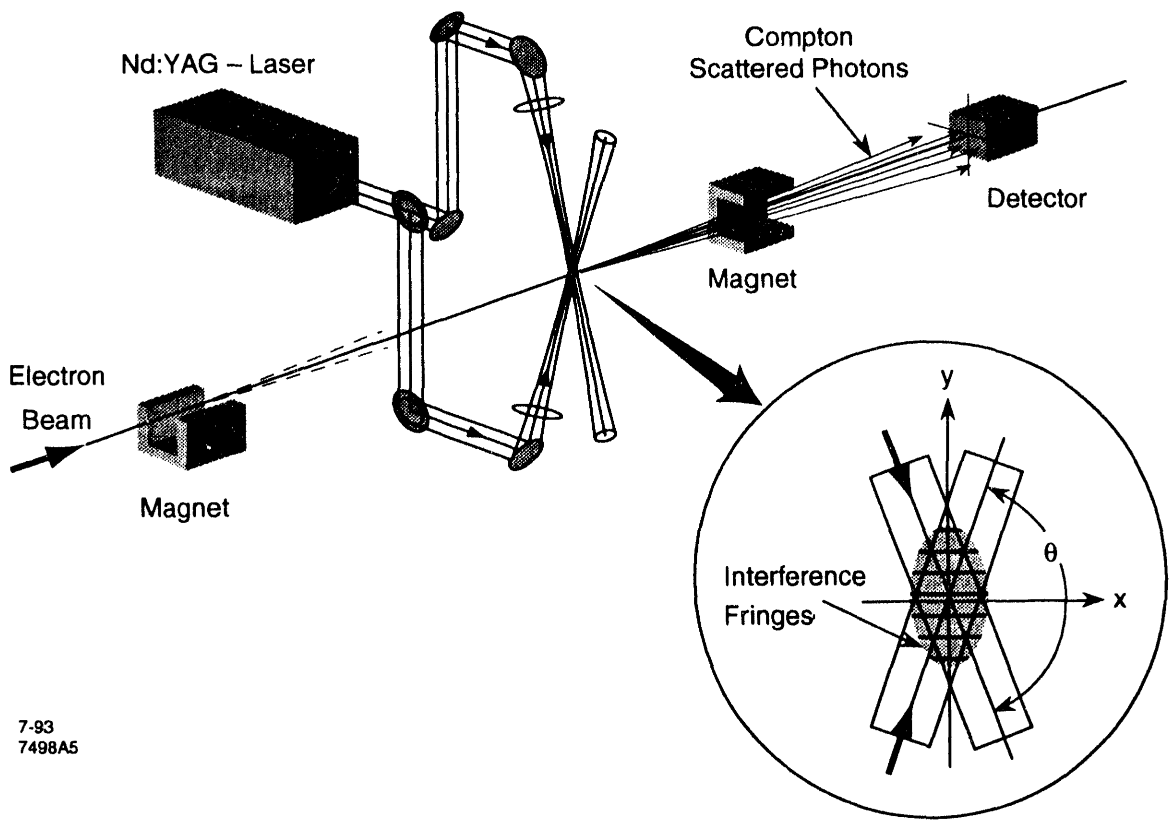


Fig. 4 Conceptual sketch of the laser-Compton spot-size monitor for the FFTB focal point.

We conclude that we have focused the SLC 47 GeV electron beam through a demagnification ≈ 320 to a vertical height of $\sigma_y \approx 70$ nanometers. This represents a significant advance of technologies and accelerator physics required for the design and implementation of a future TeV-scale electron-positron collider.

References

1. The FFTB Collaboration: Deutsches Elektronen-Synchrotron, DESY, Hamburg, Germany; Fermi National Laboratory, Batavia, IL, USA; The Budker Institute for Nuclear Physics, Russia; Laboratoire de l'Accelerateur 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.
2. Final Focus Test Beam Design Report, SLAC-REP-376, 1990.
3. K.Oide, SLAC-PUB-4953, 1989; J.Irwin et al., SLAC-PUB-5539, 1991; G.Roy, Phd Thesis, SLAC-REP-397, 1992.
4. N.Phinney, invited talk at this conference.
5. W.Schwartz et al., 2nd Int. Workshop on Accel. Alignment, Hamburg, 1990.
6. G.Heimlinger, Diplom Thesis, MPI-PhE 93-13, 1993.
7. H. Hayano, et al., Nucl.Instr.Methods, A320, 47, 1992.
8. J.Buon, et al., LAL/RT 90-14, 1990; P.Puzo, Phd Thesis, LAL 94-09, and talk contributed to this conference.
9. T. Shintake, Nucl.Instr.Methods, A311, 453, 1992.

DATE FILMED

9 /27/94

END