Focusing of Submicron Beams for TeV-Scale e^+e^- Linear Colliders

V. Balakin, V. A. Alexandrov, and A. Mikhailichenko
Budker Institute of Nuclear Physics, Novosibirsk and Protvino, Russia

K. Flöttmann, F. Peters, and G.-A. Voss
Deutsches Elektronen Synchrotron, Hamburg, Germany

V. Bharadwaj, M. Halling, and J. A. Holt
Fermi National Accelerator Laboratory, Batavia, Illinois

J. Buon, J. Jeanjean, F. LeDiberder, V. Lepeltier, and P. Puzo
Laboratoire de l'Accélérateur Linéaire, Orsay, France

G. Heimlinger, R. Settles, and U. Stierlin
Max-Planck-Institut für Physik, Werner-Heisenberg Institute, Föhringer Ring 6, D-80805 Munich, Germany

H. Hayano, N. Ishihara, H. Nakayama, K. Oide, T. Shintake, Y. Takeuchi, and N. Yamamoto
National Laboratory for High Energy Physics, KEK, Tsukuba, Japan

F. Bulos, D. Burke, R. Field, S. Hartman, R. Helm, J. Irwin, R. Iverson, S. Rokni, G. Roy, W. Spence, P. Tenenbaum, S. R. Wagner, D. Walz, and S. Williams
Stanford Linear Accelerator Center, Stanford, California 94309
(Received 17 October 1994)

First experimental results from the final focus test beam (FFTB) are reported. The vertical dimension of a 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 nm.

PACS numbers: 41.85.Lc, 29.27.Eg, 29.27.Fh, 41.85.Ew

One of the challenges to the development of TeV-scale electron-positron linear colliders is to focus particle beams to extremely small sizes. Whereas the bunches in the Stanford Linear Collider (SLC) are made of needles a micron across, those in future machines will need to be up to 300 times narrower. Producing and colliding tightly focused beams requires careful control and stabilization of magnetic elements, and places emphasis on accurate measurement of the properties of the beam. We constructed a prototype focusing system for a future linear collider. This final focus test beam (FFTB) [1], which occupies 200 m in the straight-ahead channel at the end of the SLAC linac (Fig. 1), accepts the SLC electron beam as input and is designed to produce a focal point at which the beam height is demagnified by a factor of 380, to a size smaller than 100 nm.

The magnetic optics of the FFTB include the features and controls required for the final focus of a future linear collider. Most of the demands placed on the hardware in the FFTB such as the accuracy of the fields in the magnetic elements and their mechanical alignments are also similar to those expected at higher energies. While beam spots of a few to a few tens of nanometers in height will be required at a TeV-scale linear collider, the demagnification of the SLC beam in the FFTB is in excess of that required for such a future machine; so the optical tolerances and corrections that must be met in the FFTB present a significant challenge and test in collider development.

The SLC damping ring can produce an electron beam with invariant vertical emittance $\gamma\varepsilon_y = 7 \times 10^{-7}$ m rad, and the results presented here were obtained with 0.65×10^{10} electrons per pulse transported to the end of the linac

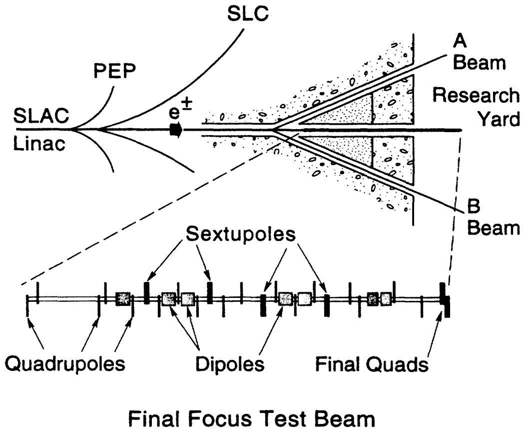

FIG. 1. Location of the FFTB at the end of the SLAC 50-GeV linac.

0031-9007/95/74(13)/2479(4)$06.00

with a vertical emittance of typically 2×10^{-6} m rad. The nominal beam energy was 46.6 GeV, and the spread in particle energies was maintained to $\pm 0.1\%$. The optics of the FFTB [2] 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.

The FFTB contains five optical sections. The beam at the end of the linac is 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 about the beam axis, 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 focusing quadrupoles must be canceled to $\approx 1\%$ accuracy by that generated in the sextupoles. Geometric aberrations are controlled with pairs of sextupoles placed at points of equal dispersion but spaced exactly 180° apart in betatron space. These aberrations must also be canceled to $\approx 1\%$. 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 μm. 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 [3], but the demagnification of the beam in the FFTB is an order of magnitude greater.

The FFTB beam line contains discrete dipole, quadrupole, and sextupole magnetic 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 nonquadrupole field to less than 0.1% of the primary field at 70% of the full aperture. Tolerances on the final doublet lenses are more stringent with restriction on their harmonic content of 0.03%, and one of these magnets must be able to operate with pole-tip fields as large as 14 kG. Permendur is used in the fabrication of the pole tips of this magnet. 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 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 beam line. 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. Spot sizes can be created at the focal point, which 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 μm of their ideal horizontal and 60 μm of their ideal vertical positions. Each quadrupole and sextupole magnet in the beam line is placed on a remotely controllable support capable of translating laterally over a range of ± 1 mm in steps of 0.3 μm [4]. The design uses a set of cam shafts driven by precision stepping motors. These magnet movers are linear to a few parts per mil over their full range of motion, and exhibit backlash less than a step size. The quadrupoles at the focal point of the beam line form an optical doublet and are mounted together on a table capable of six-dimensional motion [5]. The precision of these movers makes it possible to use the beam to accurately align the FFTB magnets. We estimate that magnet-to-magnet alignments of 10–50 μm were achieved with application of beam-based procedures.

Measurement of the properties of the beam in the FFTB is done with strip-line beam position monitors (BPM's), 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 depends 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 beam line includes shielding for the BPMs, and the electronics were designed [6] to resolve signals generated by pulses of 10^{10} electrons that differ in transverse position within the BPM by 1 μm or greater. 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 μm, 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 beam line. Wirescanners, able to resolve beam profiles as small as 1 μm, 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 is 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 thermomechanical stresses induced by submicron 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 [7] the interaction of the electron bunch with a gas target. 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. Light He^+ ions oscillate in the plane transverse to the beam direction with horizontal and vertical amplitudes proportional to the corresponding dimension of the electron bunch. Following passage of the electrons, the azimuthal distribution of ejected He^+ ions reflects the aspect ratio of the bunch. Heavy Ar^+ ions receive a kick from the passing bunch that is inversely proportional to (mainly) the largest bunch dimension. The azimuthal 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 [8]. 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 BPM's were used to adjust the element-to-element alignment of the beam line. The resulting dispersion in the FFTB lattice was well within the 5 mm 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, set voltages and timing, and debug data acquisition software. These monitors were used to tune the final spot. Time-of-flight signals and azimuthal distributions from the gas-ionization monitor agreed well with theoretical expectations. These were used to reduce beam tails [9], optimize the position of the beam waist, and adjust skew quadrupoles to remove astigmatic coupling introduced by the final quadrupole lenses. At this commissioning stage, the monitor measured beam heights in a wide range from 50 μm to 200 nm.

Precise tuning of the smallest spots was achieved with the laser-Compton monitor. Iterative tuning of vernier knobs to minimize residual dispersion and coupling of the beam phase space resulted in beam heights $\sigma_y = 100$ nm. Further corrections were 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 Fig. 2. 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 beam line. This is estimated to be a 10% correction. Repeated measurements taken at the focal point over a period of several hours were approximately normally distributed with corrected mean 70 nm and standard deviation 6 nm. This latter number is to be interpreted as a measure of the stability of the beam size and monitor system.

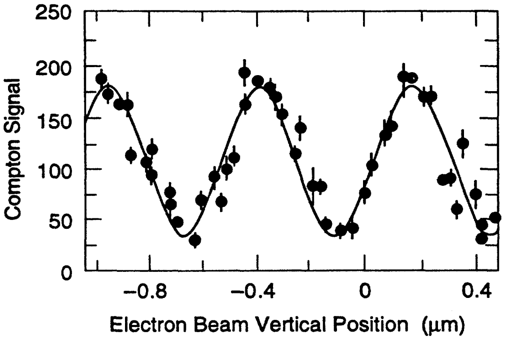

FIG. 2. Measurement of the vertical height of the beam at the FFTB focal point with the laser-Compton spot monitor. The observed fringe spacing agrees well with the 0.5 μm expected from the wavelength of the laser. The beam height is determined from the ratio of the Compton signal at the minima of the fringe pattern to the signal at the peaks of the pattern. In this case, the beam height is 73 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.

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

We take this opportunity to thank the engineering and technical staffs of the institutions in the FFTB Collaboration for their imagination and hard work in the design and construction of the FFTB. We also appreciate the importance of the skill and efforts of the operations crews of the SLAC accelerator to the successes of the FFTB experiment.

[1] M. Berndt *et al.,* Final Focus Test Beam Design Report, SLAC-REP-376, 1991 (unpublished).
[2] K. Oide, Report No. SLAC-PUB-4953, 1989 (unpublished); J. Irwin *et al.,* Report No. SLAC-PUB-5539, 1991 (unpublished); G. Roy, Ph.D. thesis [Report No. SLAC-REP-397, 1992 (unpublished)].
[3] N. Phinney, in Proceedings of the European Particle Conference EPAC94, London, 1994 (unpublished).
[4] G. Bowden *et al.,* Report No. SLAC-PUB-6132 (unpublished); G. Heimlinger, Ph.D. thesis [Report No. MPI-PhE 93-13, 1993 (unpublished)].
[5] N. Ishihara *et al.,* KEK Print Report No. 92-89, 1992 (unpublished).
[6] H. Hayano *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 47 (1992).
[7] J. Buon *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **306**, 93 (1991).
[8] T. Shintake, Nucl. Instrum. Methods Phys. Res., Sect. A **311**, 453 (1992).
[9] P. Puzo, in Proceedings of the European Particle Accelerator Conference (Ref. [3]).