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FIRST RESULTS FROM THE FINAL FOCUS TEST BEAM*

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ABSTRACT

We have used the Final Focus Test Beam beamline and associated instrumentation to reduce the 46.6 GeV SLAC electron beam to a vertical size of 70 nm. This represents a reduction from the linac beam size by a factor of 320, comparable to the demagnification required by a TeV-scale linear collider, and addresses the same aberrations predicted in such an environment. The beam dimensions were measured by two novel beam size monitors at the focal point. Details of the optical and hardware design of the beam line, necessary tuning operations, beam size monitor principles, and future plans are discussed.

1. Introduction

In order to generate interesting events at a reasonable rate, future linear colliders with E_{cm}=0.5–1.0 TeV will require luminosities in the range[1] of $10^{33}-10^{34}$ cm^{-2} sec^{-1}. Because linear colliders are limited in repetition rate and bunch charge, such high luminosities place severe requirements on the final focus sections of such machines. Specifically, the focused beams are expected to be extremely flat (100:1 aspect ratio), with vertical spot sizes down to 3 nm at the Interaction Point (IP).

The Final Focus Test Beam (FFTB) is a prototype for a future linear collider final focus. The FFTB is designed to focus the 46.6 GeV Stanford Linear Collider (SLC) electron beam to an RMS size of 1 μm in the horizontal by 60 nm in the vertical. This represents a vertical demagnification of 380 from the linac beam size, which is the same factor expected in the future linear collider. Table 1 shows the IP beam parameters of the FFTB, the expected Next Linear Collider (NLC), and the SLC.

Table 1. Interaction Point beam parameter comparison.

Parameter	Stanford Linear Collider	Next Linear Collider	Final Focus Test Beam
E_{cm} (GeV)	45.6	1000	46.6
σ_E/E_{cm} (%)	0.25	0.25	0.25
σ_y (nm)	800	3	60
Aspect ratio (x/y)	2.5	100	16

2. Design of the Final Focus Test Beam

The FFTB can be divided into five optical modules upstream of the focal point, plus an extraction line that transports the beam from the focal point to the dump. The first

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Presented at the Meeting of the American Physical Society, Division of Particles and Fields (DPF94), Albuquerque, New Mexico, August 2–6, 1994 section is a beam matching section, which contains five normal quadrupoles and two rolled ("skew") quadrupoles. This allows us to match the incoming beam to the rest of the line without retuning the other sections. The last section is the final telescope, which contains the final pair of quadrupoles that do the actual demagnification.

Achieving the required demagnification requires the use of strong quadrupoles, which in turn gives rise to large chromatic aberrations. These aberrations cause off-energy particles to be brought into focus in the wrong longitudinal location. These are corrected in the same fashion as in the SLC, using bend magnets to introduce dispersion and sextupole magnets in dispersive regions to produce an energy-dependent focusing effect.[2] The SLC sextupoles are gathered in a single optical section, and the magnets which correct primarily horizontal and vertical chromaticity are interleaved. The FFTB has two such chromatic correction sections (CCS), each of which corrects principally the aberrations in a single plane. In the first section, $\beta_x >> \beta_y$, and consequently the horizontal chromaticity is corrected. This relationship is inverted in the beta exchanger, a section of beamline between the two CCS sections, and consequently the second CCS section corrects the vertical chromaticity. Each CCS section contains two sextupoles separated by a $-I$ transform, which cancels their geometric contribution to the spot size that would otherwise be 40 times the design spot size for each sextupole. In order to keep sextupole aberrations minimal, it is therefore necessary for the CCS quadrupoles (which generate the $-I$) to be no more than a few parts per thousand from their design strengths.[3]

The magnetic elements of the FFTB beamline were machined in Russia and Japan to state-of-the-art tolerances. Each quad upstream of the IP is powered by a separate power supply capable of regulating current at ten parts per million, in order to eliminate use of backleg trim windings which excite sextupole moments. Primary beam diagnostic equipment includes 40 beam position monitors capable of a pulse-to-pulse resolution[4] of 1 μm, and wire scanners capable of measuring a 1 μm beam size. Each optical element is mounted on its own remote control mover, capable of translations of up to 1.5 mm in x and y in steps[5] of less than 1 μm. Finally, the motions of all optical elements are monitored by a unique stretched-wire system, which is itself referred to an external laser system.[6]

3. Tuning of the Beamline

3.1. *Reconstruction of Incoming Beam*

The incoming beam was reconstructed by stopping the beam downstream of the beam matching section, and matching the beam such that a dual waist (beam size approximately 15 μm in x and y) was formed on a special wire scanner installed for this purpose. By scanning quadrupoles upstream of the wire and measuring the beam size, it was possible to reconstruct the uncoupled emittances and Twiss parameters of the beam using a technique common at SLAC.[7] Once measured, any number of first-order transport programs were able to compute settings for the beam matching quadrupoles that gave the desired properties at the IP. This enabled us to start with a relatively large beam size, 2 μm × 2 μm, for which no chromatic correction was needed. This beam size was used for first order diagnostics and coarse location of the waist on a focal point wire scanner. Later it was possible to rematch the incoming beam to gradually smaller and smaller sizes, finally matching to a beam which was expected to be 2 μm × 50 nm.

It was found that the vertical emittances measured using this technique were consistently larger than those measured at the end of the linac by an array of wire scanners. This was presumed due to coupling, which tends to preferentially enlarge the vertical emittance. In order to minimize the effects of coupling, we repeated the above measurement of emittance for several settings of a skew quadrupole upstream of the first normal quadrupole in the FFTB. By doing this, we found that we were able to reduce the FFTB ε_y to a value below that measured in the linac.

Further improvement in ε_y was made by increasing the electron store time in the SLC damping ring. This was possible because the FFTB is limited to a repetition rate of 30 Hz, while SLC runs at 120 Hz. By increasing the store time from 8.3 msec to 16.7 msec, the invariant emittance was reduced to 2.5×10^{-6} m-rad, below the FFTB design emittance. Because of this we expected a beam at the IP that was smaller than the design.

3.2. Local Tuning

Because of the number of independent controls and diagnostic devices present in the FFTB, it was possible to do local, real-time beam-based correction of several aberrations. Most noteworthy was beam-based alignment of quadrupole and sextupole magnets. The tolerance of the FFTB to *a priori* alignment errors has been computed to be as large[8] as 100 μm. By changing the strengths of the FFTB quadrupoles one at a time and observing the orbital deviations downstream, it was possible to align the quads with resolutions down to 3 μm in some cases. This was achieved by using online programs to step the quads and capture synchronous BPM data which was then passed to a fitting engine, together with the first-order (R_{ij}) model of the beam line. The analysis program separated the data into three regions: (1) all data upstream of the first quad to be stepped in a given data set was used to resolve the incoming beam's geometric centroid for each shot; (2) all data downstream of the last quadrupole in the FFTB line was used to resolve the centroid energy, since this region contains strong vertical bend magnets; and (3) all other data was used to fit the misalignments. The appropriate corrections of the magnet positions were then made with the remote-controlled movers. This allowed us to align the magnets without entering the tunnel or deactivating the magnets, which would have produced systematic alignment errors as the magnets cooled.

The CCS sextupoles were aligned by scanning the sextupole horizontal and vertical movers, and observing the beam horizontal position downstream. Because the horizontal kick given an electron in a sextupole field is proportional to x^2-y^2, a plot of mover position against beam position generated a parabola whose minimum was the well-defined zero of sextupole alignment. By stepping the mover through ±1.4 mm, the sextupoles could be aligned in x and y with resolutions of 10–20 μm.

The FFTB's energy was stabilized by a fast feedback which used the dumpline BPMs, in the high vertical dispersion region, in order to measure the pulse-to-pulse energy variations. By stepping the energy feedback's setpoint and reading out all the BPMs, it was possible to measure the dispersion throughout the beamline. In the horizontal, the dispersion was qualitatively close to design, although systematics in the energy computation rendered quantitative corrections impossible. In the vertical, a point-source of dispersion was found in the CCSX region which is currently under investigation. This corresponded to an area in which there was a discontinuity found by the beam-based alignment procedure.

During this time several experiments in lattice diagnostics were performed, using both traditional corrector magnet bumps and introducing orbit bumps with quadrupole movers. It was found that the quadrupole mover bumps were able to resolve quadrupole strengths at the level of a few parts per thousand. A more complete set of diagnostics is being prepared for the next FFTB run.

3.3. *Global Tuning*

Because the beam at the IP is smaller than at any other point in the beamline, it is sensitive to errors that cannot be resolved by any technique at any other point. It is therefore necessary to complete tuning of the beamline through global corrections to the beam size itself. The primary global errors which can appear are: waist position, dispersion, chromaticity, geometric sextupole, and a single x-y coupling term ($x'y$) due to rolled quadrupoles. To perform final corrections to the beam, it is necessary to derive orthogonal corrections ("knobs") for each of these aberrations, using degrees of freedom of the beamline, and then scan these corrections and measure the spot size. For aberrations added in quadrature, the square of the beam size forms a parabola when plotted against the value of the knob, which then indicates the amount of correction to be applied.

Traditionally, the tuning knobs have been based on linear combinations of quadrupole strengths. In this case, we used the well known property that a misaligned sextupole introduces normal or skew quadrupole component into the beamline. Combinations of sextupole movements were determined which generated x and y waist motion, x and y dispersion, and $x'y$ coupling. These knobs had the advantage of greater resolution and freedom from magnet hysteresis. Once coarse tuning with global quadrupole strength knobs was complete, sextupole mover knobs were used for fine tuning. We were also able to use small geometric sextupoles in the final telescope to correct residual sextupole aberrations. Because our beam energy spread was much smaller than design, the CCS sextupole strengths were never scanned.

4. **Beam Size Monitors**

Because of the extremely high-energy density of the focused spot, conventional beam-size devices, such as wire scanners, are inadequate for beam size measurement. The FFTB has two devices, separated longitudinally by 52 cm, which use unconventional techniques to measure the beam size. The focal point of the FFTB can be tuned at will to be at either device.

4.1. *Orsay Gas-Ion Time-of-Flight Monitor*

The Orsay Beam Size Monitor (BSM) functions by injecting a burst of noble gas into the path of the electron beam. The gas ionizes when the beam passes through, and the ions are subsequently accelerated by the electric field of the beam. This results in a velocity distribution dependent on the maximum electric field, which in turn depends on the beam size. By measuring the minimum time-of-flight of the ions, the beam's larger transverse size can be computed. The time-of-flight measurement is made with helium ions for large beams, and argon ions for smaller beams.

If the electron bunch is sufficiently small, some ions will become trapped in the potential well of the beam. Elliptical beams will preferentially trap ions traveling across the shorter dimension of the bunch, causing an anisotropy in the distribution. This anisotropy can be used to compute the aspect ratio of the electron beam. This measurement is always made with helium gas.[9]

The Orsay BSM was successfully used to measure beam sizes down to 250 nm. Systematic errors due to longitudinal ion acceptance prevented smaller measurements.

4.2. KEK Laser-Compton Monitor

The laser-compton BSM splits a Nd:YAG laser (λ = 1064 nm) and crosses the two beams at an angle at the IP. This produces an interference pattern in space. When the electron beam crosses the laser collision region, the laser photons are compton-scattered (as seen in the electron rest frame) into detectors downstream of the IP. The intensity of the compton signal is a function of both the size of the electron beam relative to the interference fringe spacing and the position of the beam in the interference pattern.

The electron beam is then scanned across this pattern by horizontal and vertical correctors upstream of the final quadrupole. The observed intensity pattern is therefore sinusoidal, with a modulation depth dependent on the beam size.[10]

The KEK BSM has three crossing modes for measuring different beam sizes: a 174° mode for measuring the smallest spots; a 30° mode for measuring vertical spots up to 600 nm; and a 6° mode perpendicular to the first two for measuring micron-sized horizontal spots. During the Spring 1994 run, the KEK Beam Size Monitor measured horizontal beam sizes down to 2.5 μm, and vertical sizes down to 70 nm. Stability and systematic errors prevented precise measurements of smaller beam sizes.

5. Future Plans

The FFTB is expected to operate for two weeks in September of this year. During this time we expect to complete commissioning of the two beam size monitors and use them to tune the beam down to the design dimensions. We will then perform experiments to determine the true bandwidth of the beamline. Further tests will involve monitoring the stability of the focused spot, as constant scanning of global tuning correctors is not an acceptable luminosity strategy for a linear collider. Finally, it may be desirable to increase the horizontal size of the beam in order to attempt tuning to an aspect ratio of 100:1, which we expect to have in a future linear collider.

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