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# BEAM-BASED OPTICAL TUNING OF THE FINAL FOCUS TEST BEAM*

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In order to reduce the SLAC 46.6 GeV beam to sub-micron sizes, the Final Focus Test Beam (FFTB) must meet tight tolerances on many aberrations. These aberrations include: mismatch and coupling of the incoming beam; dispersion; chromaticity; lattice errors in the chromatic correction sections; lattice coupling; and residual sextupole content in the quadrupoles. In order to address these aberrations, we have developed a procedure which combines trajectory analysis, use of intermediate wire scanners, and a pair of novel beam size monitors at the IP. This procedure allows the FFTB IP spot to be reduced to sizes under 100 nanometers.

## I. INTRODUCTION

In order to achieve luminosity in the range of $10^{34}$ cm$^{-2}$ sec$^{-1}$, a TeV-scale linear collider will need to reduce the size of electron and positron bunches at collision to sizes on the order of several nanometers. This vertical size mandates a demagnification from the linac to the IP of a factor of 400. Such a severe demagnification places unprecedented tolerances on many optical aberrations of the final focus system, most of which cannot be met *ab initio*, but only as a result of beam-based tuning of the final focus. Any linear collider must have an algorithm and diagnostics which will allow such tuning to converge in a finite time.

The Final Focus Test Beam (FFTB) is a prototype linear collider final focus, designed to reduce the 46.6 GeV SLAC beam to a size of 2 microns by 60 nanometers. The FFTB has the horizontal and vertical demagnifications required by a future linear collider, and thus addresses all the same optical aberrations. We have developed such an algorithm for the FFTB, which allows the spot to be focused to 70 nanometers.

## II. THE FINAL FOCUS TEST BEAM

The optics of the FFTB have been discussed in detail elsewhere[1]. The optical layout consists of: a 5-quadrupole beam matching section; a horizontal chromatic correction section (CCSX) with a pair of sextupoles separated by a *-I* transform; a beta exchanger (BX), which enlarges the vertical beam size and reduces the horizontal; a vertical chromatic correction section (CCSY); a final telescope (FT), including the final doublet (FD) magnets; and an extraction line.

The primary aberrations which affect the horizontal beam size are: waist and magnification errors; dispersion; chromaticity; and a single normal sextupole aberration, for a total of 5. The vertical beam size is affected by these aberrations, plus an additional two skew sextupole aberrations, and two xy coupling effects, for a total of 9 aberrations.

## III. INCOMING BEAM MATCHING

Because of the "stair-step" phase advance properties of a linear collider final focus, the multi-wirescanner technique for measuring incoming beam emittance, Twiss parameters, and coupling[2] is not applicable in the FFTB. Instead, the incoming beam is measured by scanning a quadrupole magnet and measuring the beam size on a downstream wire scanner as a function of the magnet strength. This technique has been described elsewhere[3], and has been used for many years at SLAC. In the FFTB, the first quadrupole magnet is scanned, and a wire scanner in the beam-matching section is used[4]. For this measurement the beam matching quads are set to a special optics which focus both x and y waists on the wire, and the beam is stopped before entering the CCSX.

Because of the sensitivity of the FFTB to xy coupling, the beam measurement scanner contains 7 micron wires set to measure the beam in x, y, and v (one of the diagonals). Two algorithms have been developed to measure the fully-coupled sigma matrix using this wire scanner and quadrupole strength scans. It was determined that the incoming beam coupling is dominated by a single term, which can be eliminated using a skew quadrupole upstream of the first normal FFTB quadrupole. When this is done, the measured vertical projected emittance agrees with the emittance measured at the end of the SLAC linac by the multi-wire system there ($\gamma\epsilon_y = 2 \times 10^{-11}$ m.rad), and is below the FFTB design value.

The five normal quadrupoles of the beta matching section are then employed to match the incoming Twiss parameters onto the desired IP parameters. This allows us to adjust the IP divergence (and hence the focused size) up or down, depending on requirements of the experimental program. The beam is then allowed to travel to the dump.

The BX section contains horizontal and vertical "intermediate waists," with respective beta functions of 8.3 cm and 2.5 cm (design), separated by 2.85 meters. Special wire scanners[4] with 4 micron wires at angles optimized for

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**Current address: Eurpoean Laboratory for Particle Physics (CERN), Geneva, Switzerland measuring flat beams are used to verify and tune the beta match (both magnification and waist). The beam size on the horizontal wasit wire is 5 microns by 80 microns, and on the vertical waist wire is 200 microns by 710 nanometers.

## IV. LOCAL TUNING AND DIAGNOSTICS

Wherever an aberration can be traced to an error in a single magnet, it is preferable to correct the error in that device rather than to apply a global tuning correction. The primary localized aberrations arise from misalignments of quadrupoles and sextupoles, and errors in the strengths or roll angles of quadrupoles. To maximize tunability, all quadrupoles upstream of the IP are powered by separate power supplies, and all quadrupoles and sextupoles are mounted on remote-controlled magnet movers with positioning accuracy of under 1 micron in x and y[5]. All quadrupoles up to the first doublet magnet contain stripline beam position monitors (BPMs) with resolutions of 1 micron[6].

The procedure for quadrupole and sextupole alignment is described elsewhere[7]. The technique uses a shunt technique for the quadrupoles, and scans of the mover positions vs downstream bpms for the sextupoles. The overall tuning procedure is guaranteed to converge if the RMS misalignments of quadrupoles and sextupoles is below 100 microns in the horizontal and 30 microns in the vertical, and these tolerances are met by the alignment algorithm. The alignment is done with the IP divergence low, and this reduces the beam size in all the limiting apertures of the FFTB. Because the procedure does not rely on beam size diagnostics at any time, the specifics of the beam matrix are not important, and in fact alignment is usually performed before incoming beam reconstruction for this reason.

In order to minimize sextupole aberration, it is necessary to tune the *-I* transforms of the CCSX and CCSY as thoroughly as possible. This is done by introducing closed orbit oscillations, generated by moving quadrupole magnets on their movers in appropriate linear combinations to probe all phases of oscillation[8]. The technique allows quadrupole strength measurements of 1 part per thousand, and roll measurements of 1 milliradian. These are adequate for guaranteeing convergence of the overall algorithm.

## V. IP BEAM SIZE MONITORS

Because the IP beam size is smaller than at any other point in the beam line, it is subject to aberrations which cannot be measured elsewhere. Consequently, once incoming beam and FFTB lattice properties have been tuned to the limits of the upstream measuring devices, it is necessary to use measurements of the IP spot size itself.

Initial tuning of the beam can be accomplished using wire scanners set in the IP region. These scanners use 4 micron carbon wires, and are useful down to a beam size of about 1 micron, although wire damage becomes a likely occurrence at this point[4]. The spot can be measured down to its design size by a pair of novel beam size monitors (BSMs) set 52 cm apart in the IP region.

### *A. Gas Time of Flight Beam Size Monitor[9]*

A Gas Time-of-Flight BSM injects a small amount of Helium gas into the beam as it passes through the device. The beam produces ions, which are then accelerated transversely by the electric field of the beam. The maximum velocity of the ions is proportional to the maximum field. Additionally, the vertical beam is small enough that the ions are trapped by its intense electric field and oscillate with horizontal and vertical amplitudes proportional to the coordinates of their creation point inside the beam. In average, horizontal amplitudes are larger than vertical ones for horizontally flat beams, leading to an anisotropy in the distribution that scales as the beam flatness.

By measuring the velocity and angular distributions of escaped ions (via a ring of multi-channel plates surrounding the IP), the beam size in both planes can be measured. Figure 1 shows a typical distribution, which indicates a beam size of 1.6 microns by 80 nanometers.

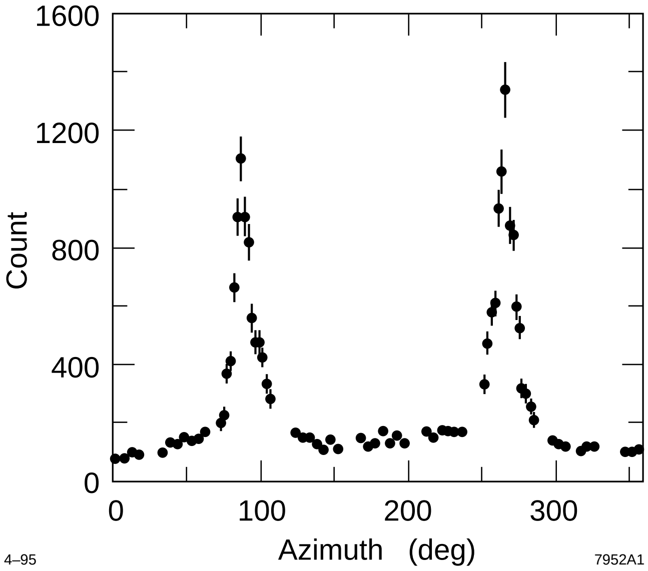

Figure 1. Angular distribution of $He^+$ ions produced by beam ionization of Helium gas. The distribution is peaked in the horizontal direction (90˚ and 270˚), indicating a flat beam.

### *B. Laser Interferometer Beam Size Monitor[10]*

A laser interferometer BSM splits a Nd:YAG laser pulse and crosses the two beams thus produced at an angle in the path of the electron beam. This produces an interference pattern with a characteristic modulation spacing. When the beam encounters the laser, the laser photons are Compton-scattered forward into a detector. The amplitude of the signal depends upon the relative transverse position of the electron beam and the laser pattern, and also upon the relative size of the electron beam and the modulation spacing. Scanning the electron beam across the interference fringes gives a sinusoidally-varying Compton signal, whose modulation depth gives the beam size. Figure 2 shows such the results of such a scan, and indicates a beam size of 73 nanometers.

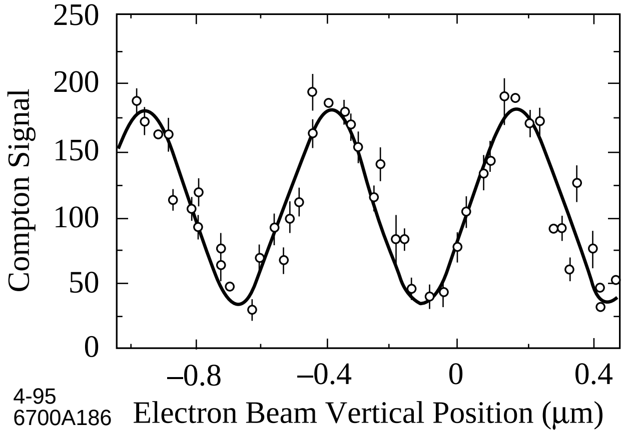

Figure 2. Laser-Compton Beam Size Monitor Compton photon signal vs. beam position, showing the sinusoidal modulation expected. The beam size indicated is 73 nm, with a statistical uncertainty of 4 nm.

## VI. GLOBAL TUNING ON IP BEAM SIZE

In order to minimize the IP beam size, it is necessary to prepare linear combinations of tuning elements ("knobs"), which are properly orthogonal. Knobs which cause more than trace alterations in secondary aberrations require additional iterations, and may prohibit tuning altogether.

The knobs of greatest concern are waist, dispersion, and the single coupling term (x'y) which arises from any rolled quadrupoles in the FFTB line, including the doublet. Because these knobs are scanned repeatedly, and need to be incremented by small amounts, magnet hysteresis and power supply granularity are significant issues. These issues are addressed by moving the CCS sextupoles, via their movers, in patterns which generate orthogonal waist shifts, dispersion shifts, and coupling at the IP. Because the mover positions are monitored by a sensor system independent of the stepper motors, the positions are not subject to hysteresis, and have the step size needed to change aberrations by the small increments required. In order to minimize the sextupole offsets from their aligned positions, only small changes in these aberrations are implemented via the mover knobs. Large changes are converted to an equivalent magnet knob. The tuning elements for each aberration are as follows:

### *A. Waist Position*

The waist positions are moved by changing the strengths of the final doublet quadrupoles.

### *B. Dispersions*

The IP dispersions are changed by steering the beam off-axis across the final doublet magnets.

### *C. Coupling (x'y)*

The "Rolled Quadrupole" coupling term is changed via a skew quadrupole close to the final doublet.

### *D. Chromaticity*

The lattice chromaticity is changed by changing the strengths of the CCSX or CCSY sextupoles. In order to keep this correction orthogonal from the linear aberrations above, the sextupoles must be near their aligned positions, thus the use of magnet knobs for coarse changes.

### *E. Geometric Sextupole*

The geometric sextupole aberrations are changed via two normal and two skew sextupoles in the dispersion free region of the FT. Of the four aberrations these magnets generate, one effects only the horizontal beam size, one effects only the vertical, and two have combined effects. These magnets are scanned in combinations which excite aberrations singly.

## VII. RESULTS

The scheme described above has been used repeatedly to tune the beam size of the FFTB, and 70 nanometers has been regularly achieved. Further improvements in the spot size are anticipated as unexpected effects are fully understood.

## VIII. ACKNOWLEDGMENTS

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