THE FINAL FOCUS TEST BEAM

Encouraging results on the path towards a future Linear Collider

by
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SINCE THE SUMMER of 1993, accelerator physicists from around the world have been performing a series of experiments on a challenging new beam line at SLAC. The Final Focus Test Beam (FFTB) is the product of an international collaboration to design and build a prototype for a future linear collider final focus system. The goal of the experiments: to focus the SLAC electron beam to a vertical size of 60 nanometers—one tenth the wavelength of visible light, and about one-tenth the smallest spot yet produced by the present SLC final focus system.

The FFTB's construction was completed in the summer of 1993. At that time, a series of shakedown tests were performed of the behavior of the hardware under running conditions. Spring of 1994 saw the FFTB commissioning begin in earnest. These runs accumulated a total of three weeks of beam time, during which the lion's share of hardware and software was fully utilized and commissioned. The beam was ultimately focused down to a vertical size of 70 nanometers and maintained for several hours through dozens of measurements. During a two-week run in September 1994, the 70 nanometer size was quickly recovered, the beam-size measuring devices were more completely optimized, and measurements with the beam energy and energy spread indicated that the chromatic (energy-dependent) aberrations of the beam line were quite small. A quick two-day run in January 1995 was used to resolve minor mysteries which had previously appeared and to perform early tests on a new super-high resolution beam-position monitor.

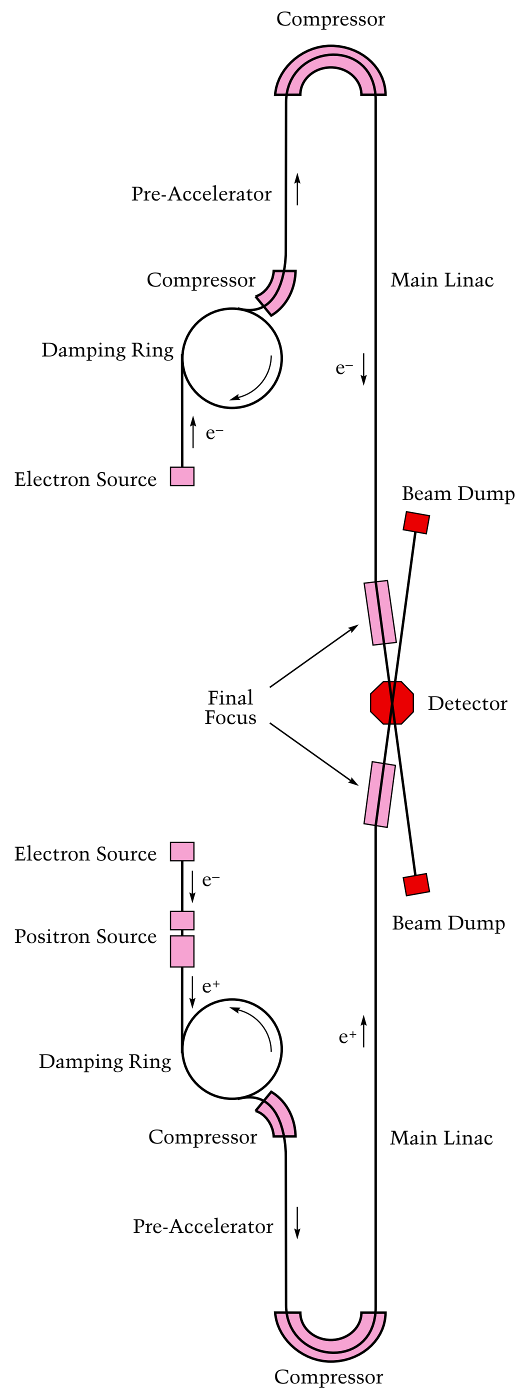
Future FFTB experiments will use the results of the previous experiments to attempt to reduce the beam size further, to below the design goal of 60 nanometers. The new beam-position monitor (BPM) will be fully commissioned and then used to control the beam position to a few nanometers, which is the level required for a high-luminosity machine such as the Next Linear Collider.

THE NEXT LINEAR COLLIDER

Currently, only one linear collider exists: the Stanford Linear Collider (SLC), which collides 50 GeV positrons and electrons. In order to study higher energy realms of physics with great precision, it is necessary to build an accelerator which can collide electrons and positrons at much higher energies—500 to 1,500 GeV. Because of the way in which circular and linear colliders scale with beam energy, only a linear collider is feasible for electrons and positrons at this energy.

In order to produce large numbers of interesting events in a reasonable time, the Next Linear Collider (NLC) must produce luminosities from 10^{33} to 10^{34} cm^{-2} sec^{-1}. Because a linear collider is limited in its collision frequency and in the charge that can be carried in a single bunch, the beam sizes at the collision point will need to be extremely small—around 300 nanometers in the horizontal and as small as 3 nanometers in the vertical! This means that the final focus of the NLC will have to demagnify the beam coming in from the linear accelerator by a factor of about 400 in the vertical. Because the beam will be 100 times as large in the horizontal, it will also be necessary to carefully adjust the beam so that it is not "rolled" at the interaction point—even 1 degree of roll will cause the focused spot to double its vertical size. Such requirements place very tight constraints on the final focus system's alignment, stability, and tunability.

For many years, physicists around the world have collaborated on the design of such a collider. Several experimental facilities have been built to determine the best technologies and techniques to use for various of the collider's subsystems. The Final



Schematic diagram of a future linear collider. Beams of electrons and positrons are accelerated separately in the two linacs, focused in the final focus systems, and brought into collision in the center of the detector. In order to provide the necessary energy to the particles, the accelerator needs to be about 20 kilometers long.

Worldwide R&D for a Future Linear Collider

THE FINAL FOCUS TEST BEAM is one experiment in a worldwide research and development effort directed towards a TeV-scale linear collider. The goal is to fully understand all the sub-systems of such a collider.

One of the most important components of a future linear collider is a pair of linear accelerators—one for electrons, one for positrons. Several different schemes for the accelerators have been proposed, and these form the basis for four of the experiments. Scientists at DESY (in Hamburg, Germany) have proposed a design called TESLA—TeV Electron Superconducting Linear Accelerator—which uses superconducting RF cavities for the necessary acceleration. Their system is being prototyped and tested at the TESLA Test Facility (TTF) at DESY. Also at DESY is the S-Band Test Facility, which is developing an extremely advanced form of the SLAC acceleration scheme, suitable for the demands of a future linear collider. Another scheme, proposed at CERN (in Geneva, Switzerland), uses a low-power, high-current "drive" beam in one accelerator to provide power for a high-power, lower-current beam in a second accelerator running alongside it. The machine which uses this scheme is called CLIC, for Cern LInear Collider. The CLIC two-beam accelerating technique is being developed at the CLIC Test Facility (CTF) at CERN. A fourth acceleration system, using a room-temperature rf system at a much higher frequency than the SLAC linac, is being developed at SLAC in the form of the Next Linear Collider Test Accelerator (NLCTA). The wakefield properties of this system were tested last year in the ASSET (Accelerating Structure SETup) experiment, also at SLAC.

A crucial element of a TeV-scale linear collider is a beam injector and damping ring system which can produce the small emittance, high-intensity bunch trains which will be accelerated by the linac. At KEK (in Tsukuba, Japan), construction has begun on the Accelerator Test Facility (ATF), a prototype for the injector-damping ring complex of a high-luminosity linear collider.

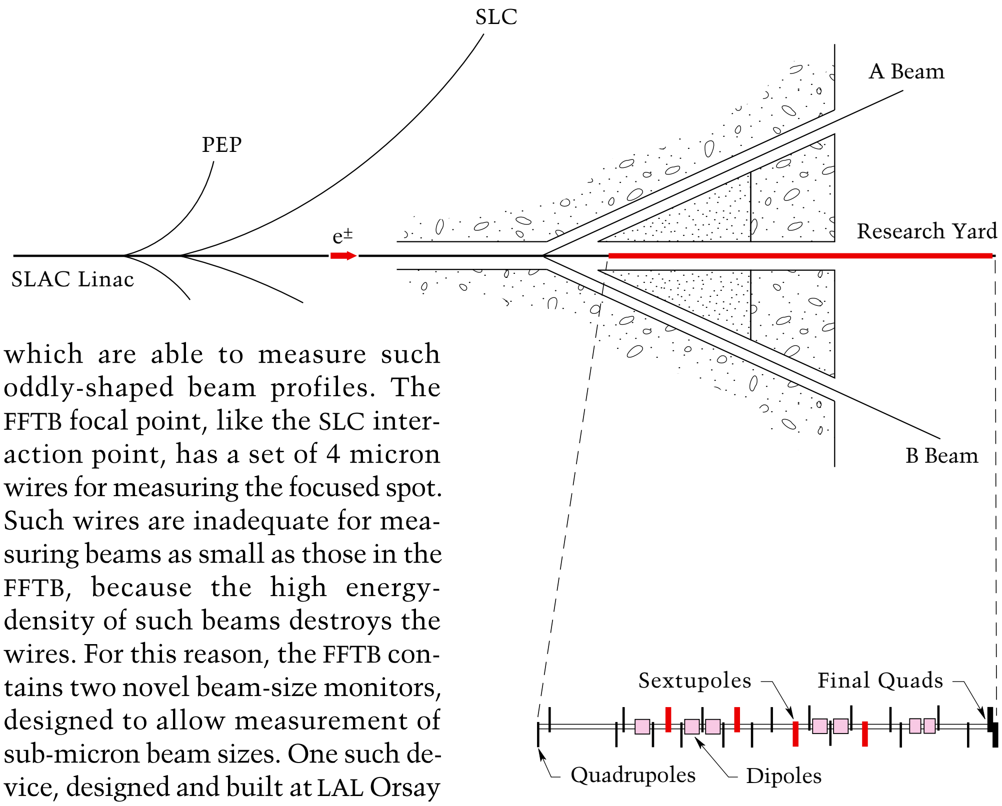
A new generation of beam instrumentation will be required to commission and tune a future linear collider. Prototypes for much of this instrumentation have been developed already for the FFTB. These include the beam position monitors and precision wire scanners (SLAC), the stretched-wire alignment system (DESY), the magnet movers (Max Planck Institute), and advanced beam size monitors (KEK and LAL Orsay). New developments include a beam position monitor of even higher resolution developed at KEK, and a "laser-wire" beam size monitor being developed at SLAC for the SLC.

Focus Test Beam is such a facility: components and ideas for the FFTB have come from KEK in Japan, Max Planck Institute and DESY in Germany, the Budker Institute in Russia, LAL in France, and Fermilab and SLAC in the United States.

DESIGN OF THE FFTB

The FFTB is designed to use the 47 GeV electron beam which is usually deflected into the SLC collider arc and sent to the SLC Interaction Point (see figure at top of next page). During FFTB experiments, the electron beam is reduced in intensity to the NLC design current of 0.7–1.0 $\times 10^{10}$ electrons per pulse, from the SLC's current of about 3.5×10^{10} per pulse. Instead of being deflected to the north, the electron beam is allowed to travel straight ahead from the linac into the FFTB itself.

The use of linear focusing magnets (quadrupoles) to reduce the size of a beam of charged particles is well understood, and in principle can be used to reduce any electron beam to any desired size. This problem is similar to creating a good image of a scene through the optical lenses of a camera. Simple focusing can only work for monoenergetic bunches, because electrons of different energies are focused by different amounts in a given quadrupole magnet. Since all real accelerators will produce electron beams with some energy spread within a bunch, and some energy jitter between bunches, it is necessary to correct this energy-dependent focusing. This is done with nonlinear focusing magnets, called sextupoles. By using a pair of sextupole magnets, with carefully tuned dipole and quadrupole magnets between them,



Overview of the end of the SLAC linac, showing the location of the FFTB in relation to the SLC arcs and end station beam lines. Also shown is the arrangement of dipoles, quadrupoles, and sextupoles that make up the FFTB.

the energy-dependent characteristics of the main focusing magnets can be corrected, without introducing additional effects which would enlarge the focused spot. The smaller the desired spot, however, the more carefully the magnets performing this correction need to be tuned. The FFTB has two such pairs of sextupole magnets: one for correcting horizontal focusing, one for correcting vertical.

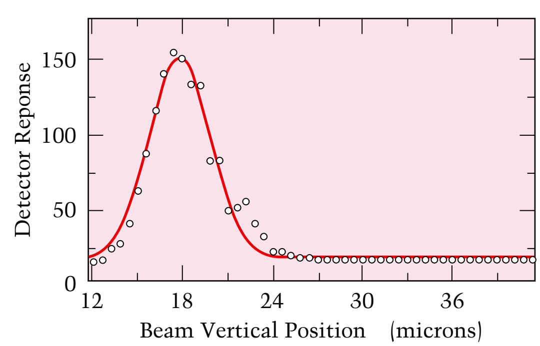
Once the nonlinear tuning described above is properly completed, the expected beam size at the focal point of the FFTB is 2 microns horizontally by 60 nanometers vertically. This represents a demagnification of the incoming beam by a factor of 380, which is the design demagnification for the NLC. While the focused spot has an aspect ratio of 32 to 1, and not 100 to 1, this still introduces all the tuning difficulties due to rolled spots. In short, virtually all of the expected challenges of the NLC Final Focus are also present in the FFTB. In order to meet these challenges, the FFTB has been built with state-of-the-art hardware, including tightly machined quadrupole and sextupole magnets on individual power supplies; a new generation of remote-controlled magnet movers with submicron step sizes; a large number of beam position monitors (BPMs) capable of resolving pulse-to-pulse beam motions of 1 micron; and an external alignment-monitoring system with similar resolutions.

A particular problem for the FFTB and NLC is measuring the beam size. At several points in the FFTB, the beam size is under 10 microns in one dimension and much larger in the other. At these points, a special set of wire scanners has been installed which are able to measure such oddly-shaped beam profiles. The FFTB focal point, like the SLC interaction point, has a set of 4 micron wires for measuring the focused spot. Such wires are inadequate for measuring beams as small as those in the FFTB, because the high energy-density of such beams destroys the wires. For this reason, the FFTB contains two novel beam-size monitors, designed to allow measurement of sub-micron beam sizes. One such device, designed and built at LAL Orsay in France, measures the interaction between the electron beam and a sample of argon or helium gas, injected at the Focal Point. The other, built at KEK in Japan, uses the interaction between the beam and a laser beam interference pattern. Both devices are capable of measuring the beam size down to the goal of 60 nanometers, with a resolution of 10 percent.

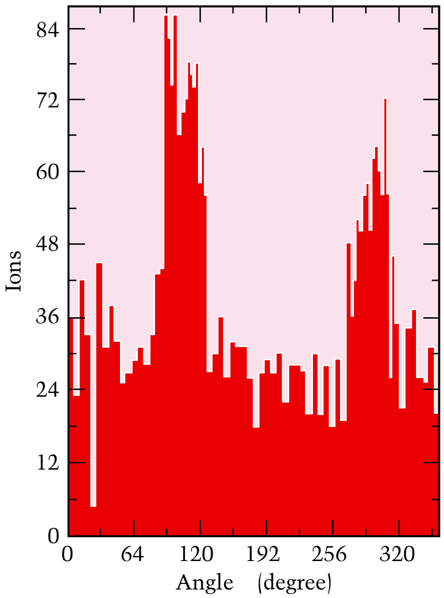
RESULTS FROM BEAM TIME

Once the beam line construction and installation was complete in the summer of 1993, several short runs were made to test the performance of the hardware and instrumentation under running conditions. The sextupole magnets were not used, so extremely small beam sizes were not possible. However, using only the quadrupole magnets, the expected vertical beam size of 1.4 microns was achieved and measured using the focal point wire scanners. This also confirmed that basic control of the beam line—the ability to achieve a given focused size, at a given location—had been accomplished.

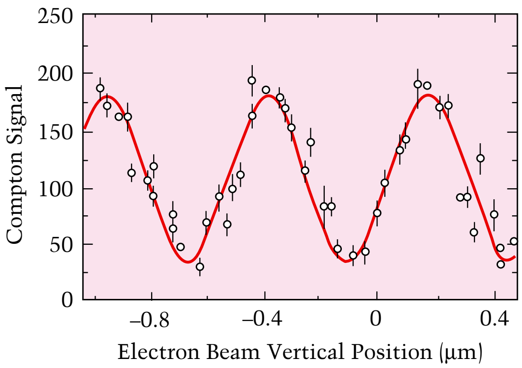
During the spring of 1994, the FFTB ran experiments for a total of



Measurement of the focused beam by a 4 micron carbon wire at the focal point of the FFTB. This measurement indicates a 3 micron vertical size. These data were taken in August 1993.



Measurement of the beam in the Gas-Jet Beam Size Monitor. The height of the two peaks relative to the rest of the signal indicates the presence of trapped ions, from which the beam size can be determined. This measurement corresponds to a size of under 100 nanometers.



Measurement of the beam in the Laser-Compton Beam Size Monitor. The electron beam interacts with an interference pattern at the focal point, causing the sinusoidal oscillation in the signal as the beam is scanned across the pattern. The beam size is determined by the height of the sine wave. This measurement corresponds to a 70 nanometer beam size.

The author and Dave Burke in the FFTB tunnel.

three weeks. This time the sextupoles were used at their design strengths, and the focused beam was gradually reduced in size at the focal point. During this time, the Gas-Jet Beam Size Monitor was able to measure focused beam sizes as small as 250 nanometers. Even more exciting, the Laser-Compton BSM succeeded in measuring beam sizes of 70 nanometers. This size was maintained for several hours, during which it was measured repeatedly and consistently found to be within 10 percent of the aforementioned 70 nanometers, with only minor adjustments needed to maintain it.

An additional three week experiment was then performed during September 1994. At this time, the beam size monitors were more fully optimized and adjusted, and an extremely vigorous program of tuning and commissioning was completed. The 70 nanometer spot was quickly restored, and measurements of the energy-dependent properties of the beam line commenced. It was found that increasing the energy spread by a factor of 5, to the NLC design value of 0.3 percent rms, only increased the focal point size by a few percent, demonstrating that the energy-dependent effects were well controlled in the FFTB. During this period of intense operation, several oddities of the beam line turned up for the first time. These issues were addressed during a two-day run of the FFTB in the beginning of January of 1995. During this time an additional piece of hardware was added: a beam position monitor capable of resolving motions of a few nanometers. First beam-based checkout of the new device was also accomplished during the January 1995 run.

FUTURE EXPERIMENTS

At this time, two additional FFTB experiments are planned, for March and December 1995. There are three main goals of these experiments. The first goal is to use the knowledge gleaned from the preceding runs to reduce the spot size to the design size or even smaller. The second goal is to fully commission the high-resolution BPM, and to use it to stabilize the position of the focused spot at the nanometer level. This is crucial to the correct functioning of the NLC, which must collide two beams which are only 3 nanometers tall! Finally, there will be a series of experiments to determine the stability of the beam line with the passage of time, and to improve this stability.

The success of the FFTB in 1994 experiments demonstrates that linear collider final focus systems with large vertical demagnifications and large aspect ratios can be constructed and tuned in a reasonable fashion. This is a major step towards the realization of a higher-energy linear collider.