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Performance of the 1994/95 SLC Final Focus System *

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Abstract

A major upgrade to the SLC final focus was installed in 1994 to eliminate the dominant third-order aberration of the system, and thereby to reduce the vertical beam size at the IP by a factor of two. At low current, the optimal beam size of about 400 nm is now routinely established, and its sensitivity to orbit variations, to changes of emittance and energy spread, and to other beam parameters has been studied. For intensities above 3×10^{10} particles per bunch, tuning is more difficult due to increased fluctuations of energy, orbit, and emittances. Nonetheless, the expected beam size of about 600 nm has been observed. New procedures and diagnostics allow easier tuning and optimization of the final focus, and also a first measurement of the emittance increase in the arcs.

I. INTRODUCTION

In the Stanford Linear Collider (SLC), electron and positron bunches are accelerated to 47 GeV by the SLAC linac, then transported through two 1200-m-long arc sections, and finally brought into collision at the interaction point (IP). The region between the arcs with the IP at its center comprises the two final foci. Their purpose is to demagnify and collide the two beams. Each SLC final focus consists of two telescopes, called the upper and the final transformer (UT and FT), separated by a chromatic correction section (CCS), which comprises two interleaved $-I$ sextupole pairs [1]. In addition, a dispersion-suppression section is located at the entrance of each final focus. Three superconducting quadrupoles (the final triplet) on either side of the IP provide the last focusing before the beams collide.

II. THE 1994 UPGRADE

In 1993, the smallest vertical single-beam sizes at the IP were of the order of 900 nm. A detailed analysis based on Lie-algebra techniques [2] revealed that the dominant contribution to the beam size (about 700 nm) was caused by a third-order chromatic term (U_{3466} in TRANSPORT notation [3]), the origin of which could be traced back to a non-optimal betatron phase between sextupoles and the final triplet [2]. The aim of the 1994 upgrade has been to correct this phase error by adding a new quadrupole close to the pre-image of the IP at the end of the chromatic correction section.

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Furthermore, in the 1994 final focus system, the role of horizontal and vertical sextupoles has been interchanged. A new quadrupole and a new skew quadrupole have been installed in the UT to facilitate an orthogonal tuning algorithm. New wire scanners have been added to measure the beam size throughout the UT.

For rms angular divergences of $\theta_x^* = 300\mu$rad, $\theta_y^* =$ 200μrad, emittances of $\epsilon_x = 600\mu$mμrad, $\epsilon_y = 60\mu$mμrad, and a relative momentum spread of $\delta = 0.2\%$, the vertical beam size calculated from the linear optics is 300 nm and the largest remaining aberration (U_{3246} in TRANSPORT notation) contributes about 200 nm to be added in quadrature. A third significant contribution of an additional 250 nm is due to synchrotron radiation in the last three bending magnets, which interacts with the uncompensated triplet chromaticity. The expected optimum single-beam spot size in 1994/95 is then of the order of 430 nm, an improvement by about a factor of two compared with the peak value of the previous year.

III. ALIGNMENT AND TUNING

Quadrupole alignment, for which the tolerance may be as tight as 100 μm [4], and the offsets of the beam-position monitors (BPMs) are controlled by a beam-based procedure [5]. The beam is steered through the center of the sextupoles with a precision better than 50 μm, using symmetric and asymmetric orbit bumps for each pair. The magnitude of these bumps is determined by the effect of different sextupole strengths on the IP spot size [7]. UT- and CCS-orbits are maintained by feedback loops. After each opening of the SLD detector and after each change of the detector solenoid field, the final triplet is realigned, again based on a beam-based measurement [6]. A sophisticated orbit-tuning scheme is adopted for the arcs, in order to generate the desired linear transfer matrix while minimizing the effect of synchrotron radiation [8].

In the new final focus, the beam matching is performed in the UT. The incoming mismatched dispersion is corrected by means of two quadrupoles and two skew quadrupoles at the entrance of the final focus. This dispersion-match is typically applied every few weeks. The betatron phase space is matched using six knobs (as suggested by Irwin), which offer orthogonal control over magnification and waist position in both planes, as well as over the coupling from the horizontal into the vertical plane [9]. Each knob simultaneously changes the strength of six quadrupoles and two skew quadrupoles of the UT in a stepwise manner calculated so as to preserve orthogonal-

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ity. The beam is matched to the design spot size on a wire scanner located at a pre-image of the IP in front of the CCS, which contains 4-μ and 7-μ-diameter carbon wires at different transverse angles [10]. The design spot size at this wire scanner is about 5 times the IP size. The Irwin knobs proved to be sufficiently orthogonal to make the UT-tuning very convenient.

Once the beam is matched in the UT, only fine tuning is necessary to minimize the IP spot size, which is estimated from scans of the beam-beam deflection angle, by maximizing luminosity-related signals. The fine-tuning with colliding beams is performed continually by the operators. Small waist shifts are obtained by changing the strength of the triplet and one quadrupole further upstream. Part of the linear coupling is corrected by means of a skew quadrupole at the triplet betatron phase. The residual dispersion at the IP is corrected using two normal and two skew $-I$ quadrupole pairs excited equally with opposite sign in the CCS. Chromaticity is compensated for by the two pairs of CCS sextupoles. Furthermore, several new sextupoles in the FT allow correction of second-order geometric aberrations.

Five new wire scanners in the UT, positioned at appropriate betatron phases, determine the emittances and the beta function mismatch of the incoming beam, as well as its energy spread. The typical rms energy spread in 1994 was of the order of 0.15% for either beam. A wire scanner in front of the final triplet measures the beam divergence, and is used to infer necessary changes of the UT magnification knob.

In order to keep aberrations small, and to preserve the orthogonality of the tuning scheme, it is essential that the phase advance between sextupoles or dispersion-correctors is exactly π. The sum-signal of two horizontal and vertical BPMs, at sextupoles that are nominally separated by a $-I$ matrix, is monitored; it reflects orbit perturbations internal to the CCS. A frequently observed diurnal variation of the sum-signal by up to 80 μm is correlated to changes of the tunnel temperature, and is presumably due to thermal expansion of the magnet supports and the tunnel floor.

IV. BEAM SIZES AND LUMINOSITY

At low current (5×10^9 particles per bunch), the design vertical (horizontal) spot sizes of 420 nm (2.2 μm), are easily achieved, as illustrated by a typical beam-beam deflection scan in Figure 1.

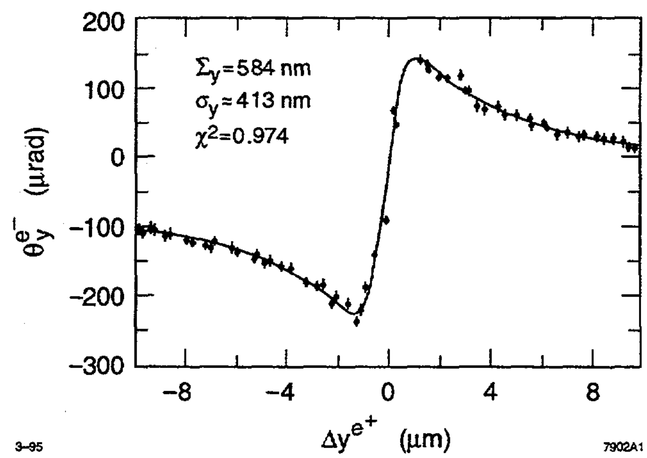

Figure. 1. Vertical beam-beam deflection scan at low current, demonstrating a single-beam size of about 410 nm.

The low-current beam sizes correspond to a normalized production rate of 11 Zs per hour per 10^{10} incident particles (the Z cross section is 30 nbarn). At this current, the transverse pulse-to-pulse orbit fluctuation in the final focus is of the order of 0.1 $\sigma_{x,y}$, and the beam-beam deflection scans agree well with the Bassetti-Erskine formula [11], from which the convoluted sizes of the two beams are easily extracted. The small spot sizes at low current were achieved while the electron damping ring was operated at twice the usual store time.

For the usual current of 3.5×10^{10} particles per bunch, the vertical emittances at the end of the linac of about 70 μmμrad are more than twice as large as for the long-store low-current mode. Furthermore, at this current, the vertical orbit variations are much larger, of the order of 0.5 σ_y. Several different sources are currently suspected to cause this transverse orbit jitter, such as magnet and structure vibrations in the linac, long-range wakefields by which a change of positron orbit or intensity affects the 60 ns delayed electron bunch, and variations of bunch length or longitudinal phase [12]. Not only does the transverse orbit motion lower the luminosity by reducing the average overlap of the two beams (a 5% effect), but more importantly it makes tuning more difficult since the beam-beam deflection scans become more erratic in the presence of jitter. Significant efforts have therefore been devoted to optimizing the quality of the fit to the beam-beam scans [13]. Pulses whose intensity, energy, or UT- and CCS-orbit deviations exceed a certain tolerance are now discarded in the scan. A first attempt has been made to adjust the fit to changes of the vertical or horizontal beam position at the IP, which are calculated from the detected beam-positions in the linac and the measured transfer-matrix between the end of the linac and the IP. Partly as a result of improved fitting algorithms, spot sizes as low as 600 nm have been achieved, which correspond to a normalized production rate of 7 Zs per hour or an absolute rate of 80 Zs per hour. The average number of produced Zs was of the order of 50–60 per hour (or 5×10^{29} cm^{-2} s^{-1}).

For typical IP beam sizes of $\sigma_x \approx 2$ μm, $\sigma_y \approx 900$ nm, and $\sigma_z \approx 750$ μm, and 3.5×10^{10} particles per bunch, the expected luminosity enhancement by disruption [14] is about 10%. This is not inconsistent with the ratio of the number of Zs recorded by the SLD detector to the number of Zs estimated from beam-beam deflection scans, which is 1.1 ± 0.1.

In addition to orbit fluctuation, there is also a pulse-to-pulse variation of the beam size. If the beams are collided vertically off center—namely, close to the maximum of the beam-beam deflection curve at about $2.5\sigma_y$—the variation of the deflection angle is insensitive to the orbit, and instead primarily reflects the variations of the beam size. Measurements for off-center collisions are consistent with

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vertical single-beam-size variations of the order 200 nm. This value is comparable in magnitude to the observed orbit jitter.

The sensitivity of the IP beam size to orbit changes induced at the entrance of the final focus system has also been measured. An orbit change of 2 mm at the vertically focusing sextupoles causes an increase of the vertical single-beam size from 400 nm to 1.8 μm. The measured dependence is consistent with simulation results except for a small asymmetry, which could indicate a skew sextupole component in the final triplet quadrupoles of about $a_3 \sim 2 \times 10^{-5}$ at a radius $r = 21$ mm.

From the dependence of the beam position at the IP wire (or at the pre-image wire) on the beam energy, the second-order vertical dispersion at the IP has been measured. It is of the order of 20 mm and, consequently, its contribution to the vertical spot size is insignificant. The measured beam size is indeed not very sensitive to the relative *momentum* spread δ in the range 0.1–0.3%.

Several attempts have been made to measure the single-beam sizes at the IP. One approach has been to greatly enlarge the spot size of the opposing beam (for instance, by increasing its emittance) and then to measure the outgoing divergence of the smaller beam as a function of its waist position. The minimum value of the divergence is a direct measure of the IP spot size, since the density of the large beam is known. At low current, this method gave promising results, but it has not been successful at high current because of the increased orbit jitter and highly distorted beam distributions after collision. In a more recent approach, the single-beam sizes are reconstructed from the measured energy spread and average energy of the two collided beams as a function of their horizontal or vertical distance during collision.

V. ARC EMITTANCE GROWTH

The new wire scanners in the UT allow a direct observation of the emittances in the final focus for the first time. It was found that the emittance-increase along the arcs depends on neither the beam current nor the initial emittance. The increase of the horizontal emittance is about $\Delta\epsilon_x \approx$ 100–120 μmμrad, while the vertical increase is about $\Delta\epsilon_y \approx$ 30–40 μmμrad. These numbers agree well with the expected effect of synchrotron radiation and linear coupling, calculated from measured arc oscillation data [8]. However, a few months after the last arc orbit-tuning, the vertical emittance increase has been much worse, $\Delta\epsilon_y \geq 70$ μmμrad, which is possibly due to degraded beta functions, coupling, and dispersion. Effort is underway to further reduce the actual emittance blowup by more local arc-tuning schemes. The minimum possible increase of the vertical emittance, due to vertical bending and rolls in the arcs, is about 10 μmμrad. There is some evidence for high-current emittance growth due to geometric or resistive-wall wakefields from collimators in the arcs and at the end of the linac [15].

VI. SUMMARY AND OUTLOOK

In spring 1994, the upgraded SLC final focus system was successfully commissioned. At low current, the new final focus routinely delivers the vertical design spot size of 400 nm. At high current (3.5×10^{10} particles per bunch), the spot size increases to values of 600–900 nm, due to deteriorating upstream emittances and to reduced orbit stability. The peak luminosity achieved corresponds to about 80 Zs per hour. The average production rate was 50–60 Zs per hour. A total of 100,000 Zs were recorded by SLD during the 1994/95 SLC run, translating into an integrated luminosity of 3.3 pbarn^{-1}.

So far, the convoluted transverse sizes of both beams have been inferred indirectly from beam-beam deflection scans. Before the next SLC run in 1996, it is planned to install a laser wire inside the SLD detector [16]. The laser wire will provide a direct measurement of the single-beam sizes at the IP, thus allowing independent fine-tuning of the two final foci, and will make diagnostics much easier.

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