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Simulation Studies of the SLC Bunch Compressor (RTL)*

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In the 1994/95 SLC run, bunch lengthening in the damping ring along with overcompression in the two ring-to-linac transport lines (RTLs) have caused a normal beam loss of about 10–20% between entrance and end of the RTLs, which constitutes a major hindrance to further luminosity increases of the SLC. This paper summarizes studies of both longitudinal and six-dimensional dynamics in the RTL, and compares simulation results with measurements. Quadratic dependence of path length on energy and higher-order multipoles in the RTL quadrupoles are shown to affect the compressor performance. Minor optics changes are suggested which may improve the transmission efficiency.

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SIMULATION STUDIES OF THE SLC BUNCH COMPRESSOR (RTL)*

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Abstract

In the 1994/95 SLC run, bunch lengthening in the damping ring along with overcompression in the two ring-to-linac transport lines (RTLs) have caused a normal beam loss of about 10–20% between entrance and end of the RTLs, which constitutes a major hindrance to further luminosity increases of the SLC. This paper summarizes studies of both longitudinal and six-dimensional dynamics in the RTL, and compares simulation results with measurements. Quadratic dependence of path length on energy and higher-order multipoles in the RTL quadrupoles are shown to affect the compressor performance. Minor optics changes are suggested which may improve the transmission efficiency.

1 INTRODUCTION AND MOTIVATION

The two SLC ring-to-linac transport lines (RTLs) connect the SLC damping rings to the SLAC linac. In addition, they serve as bunch compressors, reducing the rms bunch length from about 6–8 mm at the exit of the ring to a final length of 1 mm. The performance of the RTLs has been studied extensively before, both in experiments and in simulations, see, e.g., Ref. [2]. In 1994, the SLC damping rings were upgraded [3], resulting in a change of the incoming beam distribution. Also, over the years, several small improvements were made to the RTLs themselves. For instance, the nonlinear field components of some quadrupoles were reduced and a few limiting apertures were increased. These changes as well as recent streak-camera measurements of bunch lengths and beam losses [4] made a re-evaluation of the compressor performance desirable and motivate this report.

In the RTLs, first an S-band RF wave induces a correlated energy variation across the bunch. The bunch is then compressed by traversing a dispersive beam line with nonzero momentum compaction factor (R_{56} matrix-element in TRANSPORT notation [1]). Parameters for the present RTLs are listed in Table 1. Figure 1 shows the magnet configuration and the first and second order dispersion. Both in front and behind the high-dispersion point, several optical $-I$ transforms exist, which simplify orthogonal tuning and reduce the effect of systematic field errors.

During the 1994/95 SLC run, 10–20% of electrons and positrons were routinely lost in the RTLs. Reasons for the beam loss are: 1) bunch lengthening in the damping ring, 2) overcompression, and 3) limited energy aperture. At high current the damping-ring bunch length increases and the longitudinal beam profile becomes asymmetric, due to

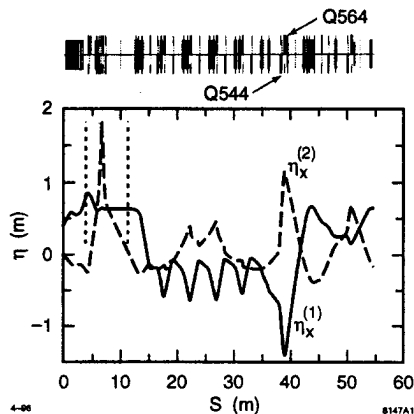


Figure 1: Magnet configuration and first & second-order dispersion in the SLC bunch compressor (RTL).

Energy E	1.19 GeV
Bunch length σ_z	6.8 mm \rightarrow 1.2 mm
Relative energy spread σ_e	0.09% \rightarrow 1.1%
RF voltage V_{RF}	41 MV
RF frequency f_{RF}	2.8 GHz
RF structure length L_{RF}	2.17 m
R_{56}	-0.6 m
T_{566}	-1.1 m

Table 1: Parameters of the SLC bunch compressor (RTL)

potential-well distortion. As an example, for $N = 4 \times 10^{10}$ particles the rms bunch length of 7 mm is about 30% larger than at low current, and, if we divide the bunch distribution at its peak, the leading half is shorter than the trailing half by more than a factor of 2 [4]. In 1994, the compressor RF voltage was raised so as to overcompress the bunch, which reduces the beam energy spread at the end of the linac [5]. Both increased bunch length and overcompression produce a larger energy spread in the RTL, where a significant fraction of the beam is lost because of a large dispersion and a restricted aperture. The energy acceptance, relative to the damping-ring energy, was measured to be -2.1% and +2.35% [6]. Due to possible calibration errors, the uncertainty in the measurement is $\pm 0.1\%$, but the measured relative asymmetry is believed to be fairly accurate.

2 TRACKING SIMULATIONS

For longitudinal tracking studies a modified version of the code LITRACK [7] is used. Initial particle positions are chosen according to an asymmetric Gaussian, which approximates the measured distribution (see Ref. [4]). The simulation includes the quadratic path length dependence

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on energy (T_{566} in TRANSPORT notation), the wake fields of the compressor RF, and a realistic energy cut of 2.2–2.4%. In accordance with real operation, the compressor RF phase is adjusted such that the average beam energy is unchanged by the compressor RF. Figure 2 a shows the longitudinal beam profile at the exit of the compressor, as obtained by the simulation for nominal conditions (negative z is towards the front). The bunch exhibits a steeply rising leading edge and a long trailing tail. For a purely linear compressor, exactly the opposite bunch shape is expected, since overcompression should reverse the potential-well distorted initial distribution. This expectation is confirmed by Fig. 2 d, which shows the distribution simulated for a more linear system, where, as an exercise, the T_{566} is set to zero and the RF wavelength is doubled (L-band). Figures b and c illustrate the individual effects of the T_{566} and the S-band RF curvature, respectively. The figures demonstrate that the RF curvature and the nonzero T_{566} contribute about equally to the observed asymmetry. Serendipitously, the actual bunch shape with a sharper leading edge (Fig. a) results in a smaller energy spread at the end of the linac than that expected for a purely linear system (Fig. d).

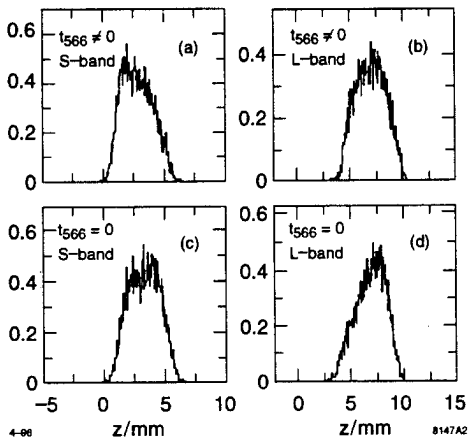


Figure 2: Effect of T_{566} and RF curvature on final bunch shape; a) expected bunch shape, b) λ_{RF} doubled, c) $T_{566} = 0$, d) $T_{566} = 0$, λ_{RF} doubled.

In 1994/95 SLC operation, the pulse-to-pulse orbit, energy and intensity variations in the linac and final focus [9] have been a major concern and their origin has not been fully identified. One possible source are phase or energy errors at extraction from the damping ring. By simulating particle transport through both the RTL and the SLAC linac we study the sensitivity of the transmission, final energy and energy spread at the end of the linac to initial phase or energy errors and to intensity fluctuations. In Fig. 3 a) the relative change of the final beam energy is depicted as a function of the initial phase in degrees S-band. For a 20° phase error, roughly equivalent to the initial rms bunch length, the resulting energy change at the end of the linac is about 0.5%. Figure 3 b) shows an increase in the rms energy spread from a nominal 0.1% to about 0.4% over the same phase range. The measured rms phase variation is only about 0.25° , and, therefore, its effect should be insignificant. Figure 3 c) shows the relative transmission as a

function of the initial phase. The asymmetric curve reflects both the asymmetric energy acceptance and the asymmetric bunch shape. In a similar way, the effect of an energy

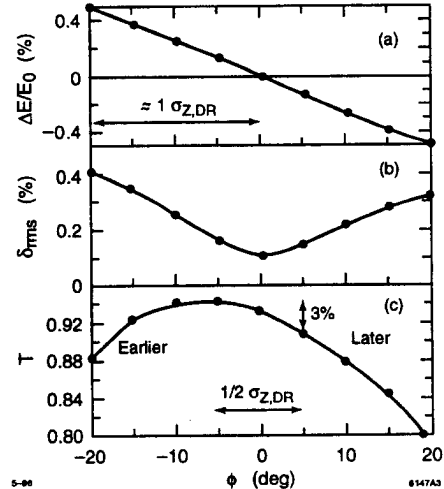


Figure 3: Sensitivity to initial phase errors; a) mean energy at end of linac, b) energy spread, c) relative transmission.

error can be determined. An initial error of 1 MeV, equal to the rms energy spread in the ring, is found to cause an energy change by only 0.3% at the end of the linac, while the transmission stays almost constant. Also we find that intensity variations of a few percent have little effect on the final beam energy.

Six-dimensional tracking studies have been performed with a modified version of MAD [10]. These simulations include the apertures of all quadrupoles and bending magnets, multipole field errors of critical quadrupoles, and transverse and longitudinal wake fields in the compressor RF. Typical quadrupole half apertures are 2.57 cm; at the peak-dispersion point they increase to 3.85 cm. Measured multipole-field errors were available only for the two quadrupoles Q544 and Q564 in the high dispersion region (see Fig. 1). The dominant multipole components are a 12-pole of 0.052% (0.012%) and a 20-pole of 0.028% (2.5×10^{-6}) for Q544 and Q564, respectively; all numbers are referred to the main field and to a radius of 9.65 mm. To estimate the final emittances (or bunch length) in the six-dimensional simulation, the particle distribution is fitted to a Gaussian (or exponential). Such a fit avoids complications arising from particles far in the tail of the distribution, and its result can directly be compared with a real emittance measurement, which would not be true for the rms value. For a typical RF voltage of 41–42 MV, the bunch length fitted to the simulated distribution is 1.15–1.35 mm. The simulations show that the wake fields in the RF section are insignificant.

In the absence of multipoles, the energy acceptance in the six-dimensional simulation for 3.7×10^{10} particles is $\pm 2.46\%$ in relative units, and the transmission is 0.94. Particles are primarily lost after about 16 m, at the first dispersion peak. When 12-pole and 20-pole in Q544 are included in the simulation, additional particle losses occur at Q564, the transmission reduces to 0.92 and the corresponding en-

ergy acceptance of -2.31% and $+2.44\%$ is smaller and asymmetric. The latter values are in qualitative agreement with the observed asymmetry, but not quite as large. The remaining difference could be due to unknown multipole errors in other RTL quadrupoles. In addition to increased beam loss, the multipole fields also cause an increase of the horizontal emittance by about 15%, which is not inconsistent with observations. We have also performed simulations for higher beam intensities, using predicted damping-ring beam distributions [11]. For 5×10^{10} particles per bunch, the simulated beam loss is still only about 10%.

3 COMPARISON WITH MEASUREMENTS

Figure 4 compares the bunch length measured with a streak camera at the end of the linac [12] with the simulated one as functions of compressor voltage. Qualitatively the two curves agree well, but the simulated bunch length is larger by about 0.05–0.1 mm. This difference is reminiscent of a discrepancy between streak camera and wire scan measurements [3], and could point to a systematic offset of the streak-camera results. Figure 5 compares the simulated

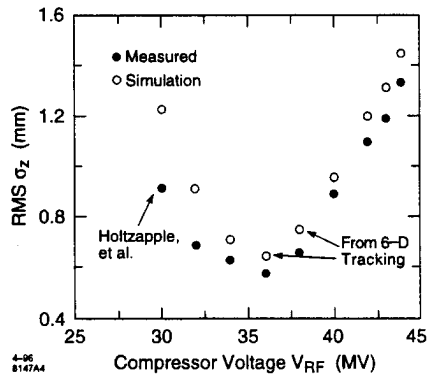


Figure 4: Bunch length versus compressor voltage

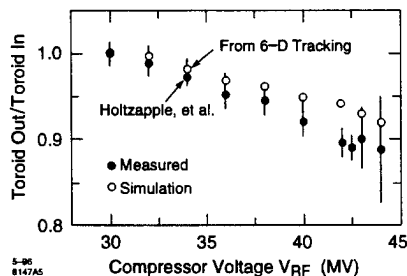


Figure 5: Transmission versus compressor voltage.

and measured [12] transmission as a function of compressor voltage. For higher voltages, the actual transmission appears worse by about 3%. A possible explanation for the discrepancy are nonlinear field errors in quadrupoles other than Q544 and Q564, or magnet misalignments and a reduced physical aperture.

4 POSSIBLE CURES

There are several alternative approaches to improving the RTL transmission: a) increasing the magnet apertures, b)

rotating the bunch in longitudinal phase space prior to extraction, via sudden changes of damping-ring cavity voltage (so-called 'bunch munching' [13]), c) installing a new chicane-based compressor in Sector 2 of the SLAC linac [14]. A fourth, cheaper approach would aim for small changes to the RTL optics, following either of two different strategies: i) to reduce the dispersion at the four most critical locations and, thereby, increase the energy acceptance of the RTL; so far, no optical solution along this path has been found; ii) to increase the R_{56} , lower the RF voltage and reduce the energy spread. Changing six quadrupoles by about 10% increases the R_{56} from 0.6 m to 0.7 m, while maintaining the $-I$ sections. The RF voltage for a final bunch length of 1.23 mm is then 37 MV (reduced from 42 MV). As expected, the simulated transmission improves, by about 4%, to a value of 0.96. However, the horizontal emittance growth is also increased, from 15% to about 30%, due to residual chromaticity and mis-matched second order dispersion. This emittance growth cannot easily be corrected by the RTL sextupoles. Nevertheless, if one is willing to accept a 15% larger horizontal emittance in exchange for 4% less beam loss, this would be one option.

5 CONCLUSIONS AND THANKS

Tracking simulations suggest that the SLC bunch compression is rather insensitive to initial phase and energy errors. While the simulations reproduce qualitatively and semi-quantitatively most of the observations, they appear to predict slightly less beam loss than observed, which could be due to unmeasured multipole errors or due to magnet misalignments in the real machine. There does not seem to be an easy and cheap solution for improving the performance of the compressor, though beam losses may be reduced easily by changing the R_{56} , at the expense of an increased horizontal emittance. The author thanks P. Krejcik for suggesting this study, P. Emma, B. McKee and M. Woodley for helpful informations, and K. Bane for a very careful reading of the manuscript.

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