OPERATION AND PERFORMANCE OF BUNCH PRECOMPRESSION FOR INCREASED CURRENT TRANSMISSION AT THE SLC *

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Abstract

As the beam currents at the SLC are increased, transverse aperture restrictions in the ring-to-linac transport line (RTL) become increasingly important. The RTL contains a bunch compressor which introduces a large energy variation across the bunch and hence a larger transverse beam size. Since 1994 the compressor amplitude has been operating at higher than design voltage. While advantangeous for shaping the bunch distribution, this increased the bunch energy spread and therefore resulted in more beam loss. Moreover, due to current-dependent bunch lengthening in the damping ring, the higher the beam current, the more the current loss. To avoid such losses, the bunch length may be precompressed in the damping ring. Until recently, bunch precompression with high beam currents was not stable. In this paper we identify the reasons for the difficulties, describe the changes made to accomodate bunch precompression, and discuss performance aspects after implementation. The estimated increase in current at the interaction point is 15%.

1 INTRODUCTION

The current loss in the RTL is shown in Fig. 1. This loss has two identified sources: current-dependent bunch lengthening in the damping ring and bunch compression in the RTL. As shown in the measurements by Holtzapple [1], the scaling of the bunch length σ_z on damping ring cavity voltage V_c is $\sigma_z \propto V_c^{\frac{1}{4}}$ at high current. This is weaker than the usual square root law (which was shown to be valid at low beam current). The data of Fig. 1, which were obtained with $V_c = 680$ kV, show a 28% transmission loss (23% taking into account the relative calibration between the toroids) at a beam current consisting of two bunches of 4.5×10^{10} particles per bunch (ppb). At a nominal operating voltage of 800 kV and 4.0×10^{10}, the loss was 13%.

The second source of current loss is related to (standard) bunch compression in the RTL which takes place in two steps: first, a cavity is used to introduce an energy-phase correlation within the bunch, then in the high dispersion region following the cavity, the bunch length is compressed due to the energy-dependent path length. Letting z_r, δ_r and z_l, δ_l denote the longitudinal position z and relative energy δ in the ring (r) and linac (l), respectively, a particle within the bunch is transported as

$$z_l = z_r + R_{56}\delta_l \ \text{ and } \ \delta_l = \delta_r + \frac{eV}{E}\cos\phi, \qquad (1)$$

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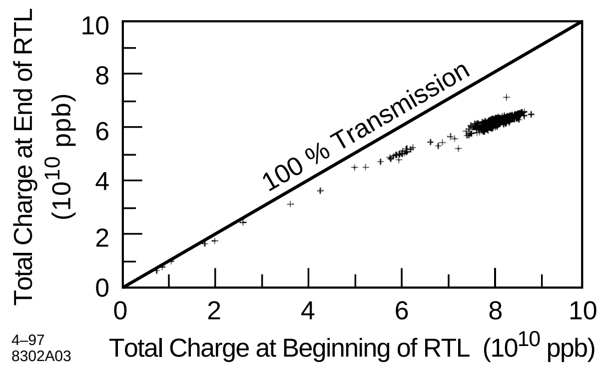

Figure 1: RTL transmission without precompression.

where R_{56} is a lattice parameter which maps phase into energy from the compressor cavity to the linac, e is the electron charge, V is the compressor voltage, $E = 1.19$ GeV is the beam energy, and ϕ is the relative phase of the particle with respect to the zero crossing of the compressor voltage. Recently the compressor amplitude has been operated at higher than design voltage [2]. While advantageous for shaping the longitudinal beam distribution, this increased the energy spread of the bunch by about 30%. From Eq. (1) beam losses can occur in regions of high dispersion η and limited horizontal apertures (since $x = \eta\delta$).

2 BUNCH PRECOMPRESSION ANALYSIS

To minimize these losses, the bunch length may be precompressed [3] by manipulation of the cavity voltage in the damping ring. Previous studies have shown that a single step change in the cavity voltage results in a longitudinal phase space mismatch which elongates the bunch and that the resulting beam phase oscillation may be eliminated while amplifying the bunch length oscillation by application of a second, appropriately timed, step change to the cavity voltage. Implementation of bunch precompression was only moderately stable, however, due to unexplained beam variations.

To better understand the source of the observed instabilites, bunch precompression was subsequently analyzed using a more detailed model [4] of the damping ring rf system including feedback loops, which are used to regulate the cavity voltage and beam phase, and a realistic (nonlinear) klystron. Within that model, the centroid motion of the beam phase ϕ in the damping ring is given by the harmonic solution

$$\ddot{\phi} + \frac{\alpha\omega e\dot{V}}{E\omega T}\phi = 0, \qquad (2)$$

where $\alpha = 0.0147$ is the momentum compaction factor, $\omega = 2\pi \times 714$ MHz is the angular rf frequency, and $T =$

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117.6471 ns is the revolution period.

Simulations showed that the newly incorporated direct loop [5] (which is used to regulate transient beam loading[6]) caused the klystron to saturate due to the effective increase in cavity bandwidth: at high gain, therefore, the cavity voltage could not track the requested change. Simulations showed that would be no significant compromise if the loop gain were reduced. As shown in Fig. 2, a factor of 2 reduction in loop gain hardly affects the cavity voltage or beam phase regulation.

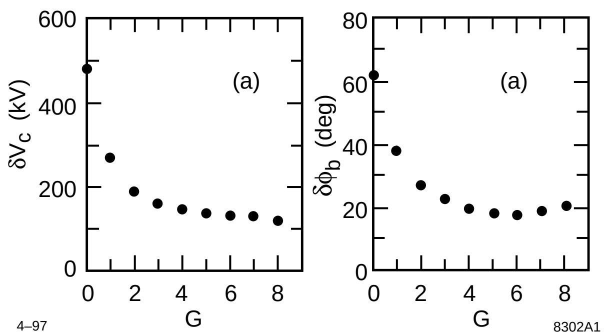

Figure 2: Simulation of peak-to-peak cavity voltage δV_c and beam phase $\delta\phi_b$ variations at injection as a function of direct loop gain G with $V_c = 800$ kV and 2 bunches containing 4×10^{10} ppb.

Following the derivation in Ref. [7], the single-particle model of the rf system was expanded to include estimates for the bunch length and energy spread. Defining the longitudinal emittance ϵ as $\epsilon^2 = \langle\phi^2\rangle\langle\delta^2\rangle - \langle\phi\delta\rangle^2$ and defining the second moments of the distribution to be ${\sigma_\phi}^2 = \langle\phi^2\rangle$, and ${\sigma_\delta}^2 = \langle\delta^2\rangle$, the equation of motion for the bunch length and energy spread are

$$\begin{aligned} \ddot{\sigma_\phi} - {\omega_s}^2\sigma_\phi &= (\alpha\omega_s)^2\frac{\epsilon^2}{{\sigma_\phi}^3} \\ \ddot{\sigma_\delta} - {\omega_s}^2\sigma_\delta &= \frac{(e\dot{V})^2}{E\omega T}\frac{\epsilon^2}{{\sigma_\phi}^3} \end{aligned} \quad (3)$$

with $\dot{V} = \omega V \sin\phi_b$. In deriving Eqs. 3 has been assumed, as in Ref. [7], the commutativity of the time derivative and average over the bunch distribution, which is valid ignoring intrabunch beam dynamics. The effect of short-range wakefields are analyzed in Ref. [8].

Using the reduced direct loop gain to avoid klystron saturation, the predicted cavity voltage and observables are shown in Fig. 3 as a function of time. The double-impulse step changes in the cavity voltage result as expected in an coherent bunch length reduction while the coherent dipole rotation is cancelled.

3 IMPLEMENTATION

Shown in Fig. 4 (to be compared with Fig. 3) are the measured cavity voltage (measured using a diode detector), bunch length (obtained from a peak current measurement,

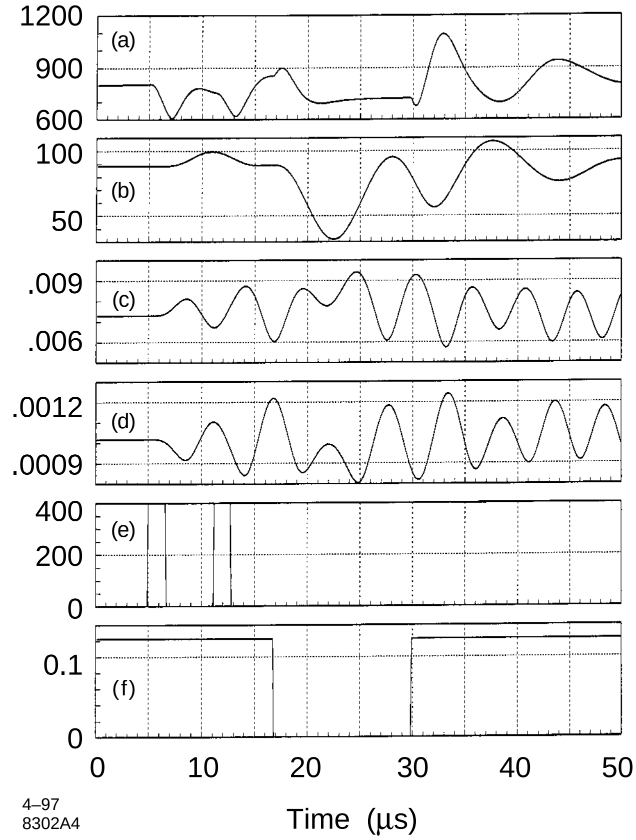

Figure 3: Simulations of bunch precompression parameters. Plotted as a function of time are the cavity voltage [kV] (a), the beam phase [deg] (b), the bunch length [m] (c), the relative beam energy [%] (d), the command for the requested voltage change [kV] (e), and the dc beam current [A] (f).

which is inversely proportional to bunch length, using a single stripline of a position monitor), and mean energy of the beam during precompression. The centroid energy was measured using a horizontal beam position monitor in a region of high dispersion in the damping ring. In the future, we plan to digitize the beam centroid and energy to monitor stability and compare with expectation. The increase in transmission measured during preliminary tests is shown in Fig. 5.

4 PERFORMANCE

When precompression was turned on with reduced direct feedback gain, we detected no change in the beam jitter (position, intensity, and energy) or in the backgrounds at the interaction point (IP). Shown in Fig. 6 is the electron charge at the IP and the precompression command signal; the increase in the average electron beam current is about 10% with precompression. In addition, since electron pulses are used to make positron pulses, the increased electron current yielded higher positron current. The positron current at the IP was observed to increase gradually over a time period of about one week.

Bunch precompression was later implemented in the

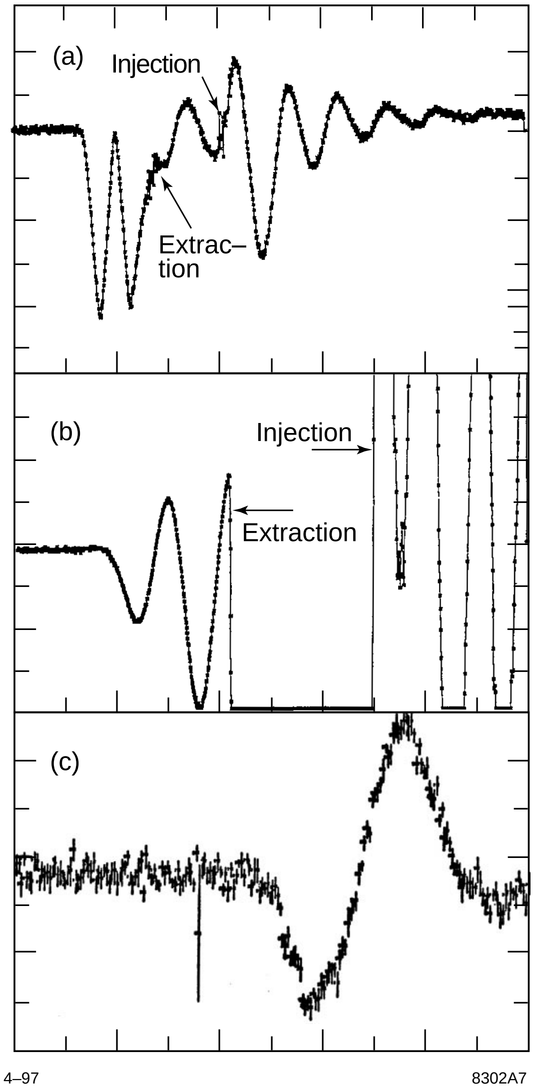

Figure 4: Measured cavity voltage [50 kV/dvsn, 10 μs/dvsn] (a), peak current [10%/dvsn (based on cross-reference with Fig. 3), 5 μs/dvsn] (b), and centroid energy [50 μm or 0.77%/dvsn, 20 turns or 2.34 μs/dvsn] (c).

positron damping ring. Unlike with electrons, however, the luminosity was not observed to increase. The reason for this is not understood. Possible reasons include increased wakefield effects (by the leading positron bunches on the trailing electron bunches), increased bunch length jitter (which is predicted [9] to result in increased orbit jitter), or to a yet undetermined effect.

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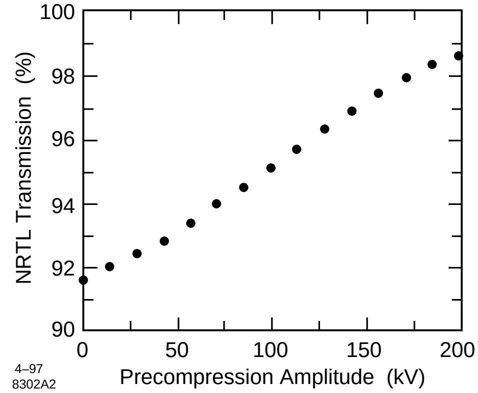

Figure 5: Increase in transmission in the RTL as a function of precompression depth. During the measurement, the timing parameters (i.e. the duration of each step change in the cavity voltage and the spacing between each of the two step changes) were held fixed.

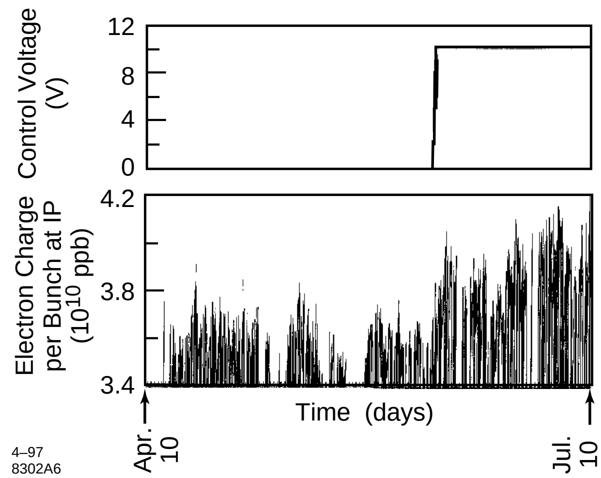

Figure 6: Precompression command signal and electron beam current measured at the IP as a function of time.

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