Beam-Based Analysis of Day-Night Performance Variations at the SLC Linac

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Abstract

Diurnal temperature variations in the linac gallery of the Stanford Linear Collider (SLC) can affect the amplitude and phase of the rf used to accelerate the beam. The SLC employs many techniques for stabilization and compensation of these effects, but residual uncorrected changes still affect the quality of the delivered beam. This paper presents methods developed to monitor and investigate these errors through the beam response. Variations resulting from errors in the rf amplitude or phase can be distinguished by studying six different beam observables: betatron phase advance, oscillation amplitude growth, rms jitter along the linac, measurements of the beam phase with respect to the rf, changes in the required injection phase, and the global energy correction factor. By quantifying the beam response, an uncorrected variation of 14º (S-band) during 28ºF temperature swings was found in the main rf drive line system between the front and end of the linac.

1 INTRODUCTION

Since the SLC now produces flat beams with emittances as low as $\gamma\varepsilon_y = 0.2*10^{-5}$ m-rad at the end of the linac, stability of the hardware has becomes increasingly critical. Slow variations coming from day-night temperature swings make it difficult to maintain the best emittances. It has previously been shown that the largest variations are caused by the accelerating rf system, but it was unclear whether the amplitude (A) or the phase (ϕ) of the rf was varying. An earlier paper [1] described sources of amplitude variations, while this paper concentrates on the more serious effect of rf phase variations. In particular, beam-based measurements were used to distinguish between the two (A, ϕ). First we discuss the stability requirements, then the beam-based signals and simulations, and finally the primary problem source, the main drive line which distributes the rf synchronization.

2 STABILITY REQUIREMENT

If the linac alignment and beam orbit were perfect, the requirements for rf stability would be relaxed. Changes in longitudinal phase space parameters (energy, phase, bunch length, and energy spread) would not couple into the transverse phase space. Improved alignment is clearly desireable (see [2]). In reality there are transverse offsets and the resulting wakefields must be canceled at the SLC by compensating orbit bumps [3]. Typically a bump spans about six betatron wavelengths. An initial emittance of $1.0*10^{-5}$ m-rad without bumps can be reduced to $0.2*10^{-5}$ m-rad. To control transverse jitter, the SLC uses BNS [4] damping which introduces a large energy spread in the beam. This causes the wakefield cancelling bumps to be very sensitive to energy and phase changes. An energy change of 1%, or a phase change of 1.5º over the region of the bump can change the phase advance by 22º. This disturbs the wakefield-tail cancellation and generates an emittance growth of $\Delta\varepsilon = (1.0 * \sin 22^\circ) = 0.4$ m-rad. Similar effects occur if the energy gain of one klystron (out of 30) is unknown to 30%.

3 BEAM BASED SIGNALS

After stabilizing the rf amplitudes [1], it was recognized that there were still large daily variations in the betatron phase advance of the beam, as measured by oscillation data taken automatically with a diagnostic pulse [5, 6] (Fig. 1).

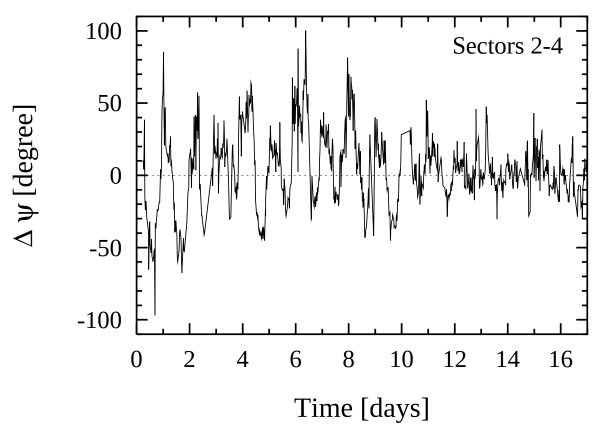

Figure 1: Diurnal betatron phase advance variation. The overall phase measured from the beginning of the linac to this point is 2800º, so a -100º phase change corresponds to 3.5% energy gain. After day 10 it was compensated.

To distinguish between rf amplitude and phase as the source of the drifts, additional diagnostics were required. Table 1 summarizes the observables used.

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Indications	Variation	Reasons
global energy correction	+1.5%	*A*, ϕ
betatron phase advance	at 500 m: –100˚	*A*, ϕ
injection phase	e^-: +7˚, e^+: +4˚	ϕ, cable
oscillation amplitude growth	50%	ϕ
transverse rms jitter	100%	ϕ
beam phase monitors	Li2: 7˚, L28: –7˚	ϕ, cable

Table 1: Beam parameters studied and possible causes (*A*: rf amplitude, ϕ: rf phase, cable: cable length). The amount of the variation is the day/night ratio, or for phases the day minus night difference.

The global linac energy correction accounts for the integrated sum of all energy errors. A 1.5% diurnal change corresponds to 1.5% more or less spare energy available. If this were due to rf amplitude changes, it could not explain the 100º phase advance change (equivalent to 3.5% of the energy) measured after 500 meters of linac.

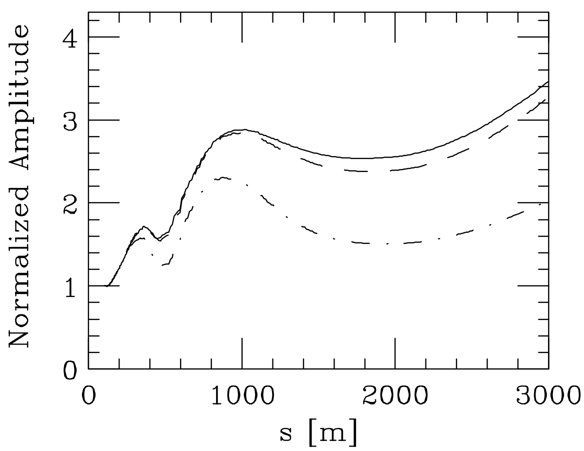

Figure 2: Simulated amplitude growth factor along the linac (solid) compared with 2% energy reduction (dashed) or +3º phase variation (dash-dotted).

An indication that phase variations were dominant came from simulations of the amplitude growth of betatron oscillations which showed a different sensitivity to energy or phase variation (Fig. 2). For a single particle, the amplitude growth factor of an oscillation scales as $(\det(R)\, E/E_o)^{1/2}$, where R is the effective matrix of the beam transport elements including wakefields and E/E_o is the energy normalization. For a BNS damped beam, the energy spread will cause the amplitude to decrease through filamentation. In the presence of transverse wakefields, the tail of the bunch is excited to even larger amplitudes than the head and the amplitude grows. Oscillation amplitudes were found to change by up to 50% between day and night (see Fig. 3). Similar behavior was observed in the rms of the transverse beam jitter measured by the feedback systems located along the linac. The jitter changed as much as 100% diurnally. If the source of the jitter is constant, this indicates that the BNS damping has become weaker.

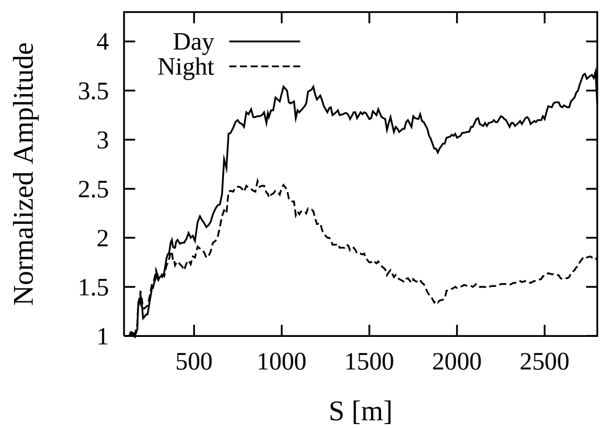

Figure 3: Measured oscillation amplitude growth factor plotted versus location in the linac for day and night. At 1000 m the variation is 50% larger in mid-day (3.6/2.4).

Another indication of these problems was given by monitors which measure the beam phase with respect to the rf near the beginning and end of the linac. A diurnal difference of ±7º (or 14º over the whole linac) was seen (Fig. 4). In principle this change could be due to measurement systematics such as cable length changes. However, the simulations below indicated that the observed variation was consistent with the other measured effects.

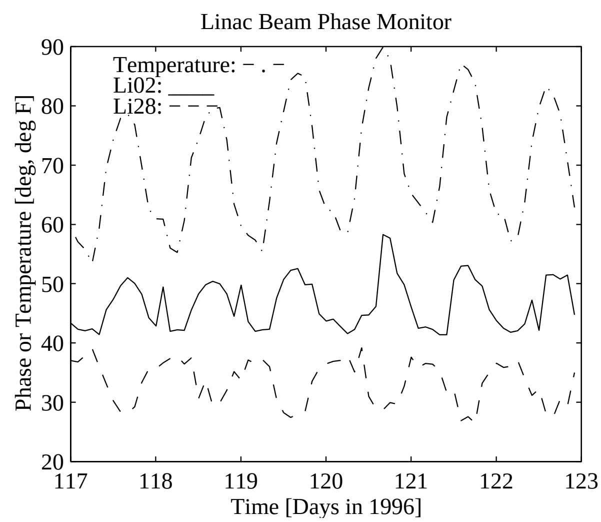

Figure 4: Beam phase in sector 2 and 28 and outside temperature showing an anticorrelation and a phase variation of 7º. The temperature swing during that period was about 28ºF daily.

4 SIMULATIONS

Simulations were performed to understand if the various observations were consistent with the hypothesis of a 14º phase variation of the main drive line that synchronizes the linac rf. The simulation assumed an ideal energy profile with a BNS configuration of 22º for the first 700 meters and –16.5º for the rest of the linac at night. If the phase length changed by 14º during the day, the initial BNS phase would decrease by 7º (to 15º) and the final phase would increase by 7º (to –9.5º). These variations weaken the BNS damping and provide less suppression of beam jitter. With weaker BNS phases, the beam is closer to the crest of the rf and the total energy available is larger. The beam energy at the end of the linac is held constant by feedback but the error is reflected in the global energy correction required. If one calculates the energy gain for the weaker daytime BNS phases (from cos 15º to cos (–9.5º)) and compares it to the ideal night value, there is an energy discrepancy of 1.4% (see Fig. 5). This is consistent with observed behavior.

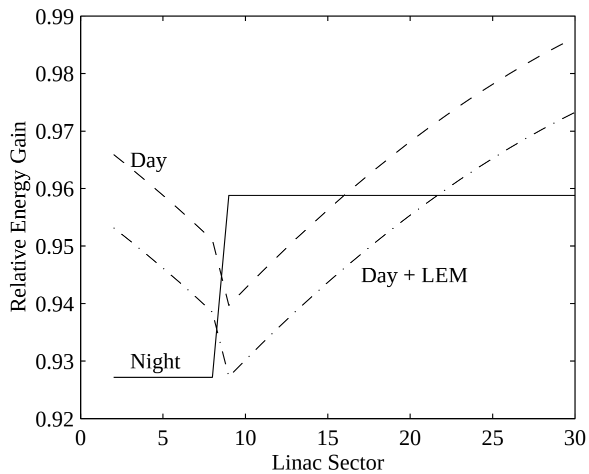

Figure 5: Relative energy gain along the linac for different main drive line conditions: At night the energy gain per sector is reduced by the cos (22º) and cos (–16.5º), while during the day it varies along the length of the linac by a factor between cos (15º) and cos (–9.5º). The third curve shows the day curve scaled down by 1.4% to reflect the effect of the global energy feedback which holds the mean energy constant.

5 MAIN DRIVE LINE

The main drive line (MDL) which synchronizes the linac rf phases was found to be a major source of the observed sensitivity to diurnal temperature variations. The phase length of the MDL is affected by external temperature and barometric pressure variations. This length is monitored by an interferometer [7] and a feedback system then adjusts the linac rf phases to correct for the measured length changes. The various diurnal effects described here indicated that temperature variations of the MDL were not fully compensated by the interferometer feedback. An additional ad hoc temperature correction was applied to alleviate the symptoms while the true source of the error was being investigated. This correction effectively doubled the feedback response to temperature change (see day 124 in Fig. 6), and it successfully reduced the diurnal variation in the beam parameters discussed (see day 10 in Fig. 1). Further investigations of and improvements to the rf hardware are discussed in another paper [8].

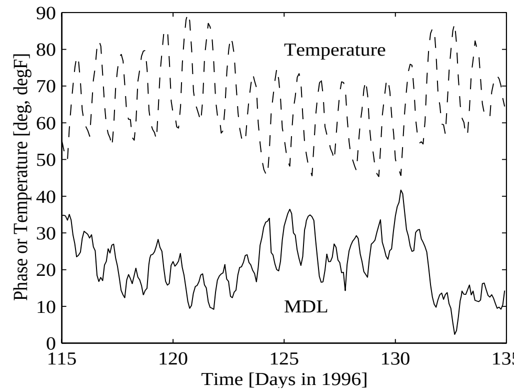

Figure 6: MDL interferometer phase versus time. The phase length may vary by up to 30º with barometric pressure swings, and up to 15º with diurnal temperature cycles. Before the correction at day 124, only half of the temperature dependence, about 7º, was being compensated.

6 SUMMARY

Diurnal variations of linac energy profile were traced to uncorrected phase length changes in the main drive line which synchronizes the rf. The residual phase variation of up to 14º was compensated by applying an additional temperature correction while the true source of the error was investigated.

7 ACKNOWLEDGMENTS

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