

## Beam-Based Monitoring of the SLC Linac Optics with a Diagnostic Pulse\*

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### Abstract

The beam optics in a linear accelerator may be changed significantly by variations in the energy and energy spread profile along the linac. In particular, diurnal temperature swings in the SLC klystron gallery perturb the phase and amplitude of the accelerating RF fields. If such changes are not correctly characterized, the resulting errors will cause phase advance differences in the beam optics. In addition RF phase errors also affect the amplitude growth of betatron oscillations. We present an automated, simple procedure to monitor the beam optics in the SLC linac routinely and non-invasively. The measured phase advance and oscillation amplitude is shown as a function of time and is compared to the nominal optics.

*Presented at the 17th IEEE Particle Accelerator Conference (PAC 97): Accelerator Science, Technology and Applications, Vancouver, B.C., Canada, May 12-16, 1997*

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\*Work supported by Department of Energy contract DE-AC03-76SF00515.

# BEAM-BASED MONITORING OF THE SLC LINAC OPTICS WITH A DIAGNOSTIC PULSE<sup>1</sup>

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## Abstract

The beam optics in a linear accelerator may be changed significantly by variations in the energy and energy spread profile along the linac. In particular, diurnal temperature swings in the SLC klystron gallery perturb the phase and amplitude of the accelerating RF fields. If such changes are not correctly characterized, the resulting errors will cause phase advance differences in the beam optics. In addition RF phase errors also affect the amplitude growth of betatron oscillations. We present an automated, simple procedure to monitor the beam optics in the SLC linac routinely and non-invasively. The measured phase advance and oscillation amplitude is shown as a function of time and is compared to the nominal optics.

## 1 INTRODUCTION

The SLC linac is subject to large variations of its optics. Most of those variations occur on a day-night basis and are strongly correlated with the outside temperature. A diagnostic pulse was first implemented in 1995 [1] and then used extensively during the 1996 run in order to monitor the behavior of the SLC optics.

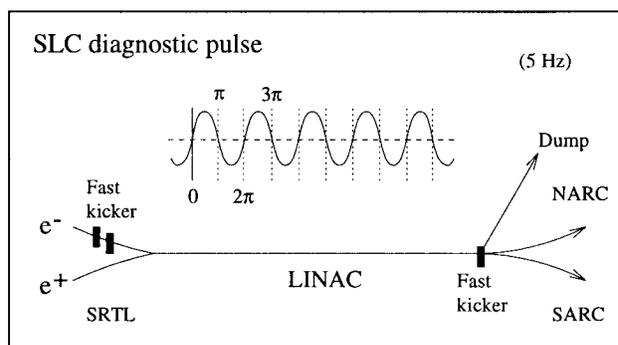
We distinguish between the *machine* and the *beam optics*. The former is defined by the magnet strengths and the design beam energy, while the latter describes the multi-particle behavior of the beam in the presence of strong wakefields. The diagnostic pulse measures the beam optics. The variations in beam optics that are shown in this paper are caused by two different mechanisms.

1. The beam energy along the linac is not constant. As some of the 230 klystrons switch on and off, the local beam energy changes while the final beam energy is kept constant. The lattice strength in SLC is adjusted in order to minimize this effect. In addition, the accelerating gradient at a single structure can vary due to undetected errors.

2. The transverse beam dynamics in the SLC linac is dominated by wakefields. Wakefield effects cause both a change in phase advance and the amplification of betatron oscillations. The wakefield effects on the optics depend on beam current, RF phases, bunch length and bunch distribution. Any change in those parameters will change the beam optics. For a detailed description of the multi-particle beam dynamics see [2].

## 2 IMPLEMENTATION

In standard SLC operation electron bunches are sent down the linac with a rate of 120 Hz. The sophisticated timing and triggering system of the SLC allows one to automatically kick selected pulses with 5 Hz, measure the induced betatron oscillations and dump them at the end of the linac. The positrons are not affected. In 1996 the SLC diagnostic pulse used 10 pulses every 15 minutes. The loss in integrated luminosity is negligible. The 1996 implementation was restricted to the vertical plane of electrons. It is illustrated in Figure 1.



**Figure 1** Schematic illustration of the SLC diagnostic pulse implementation.

The data was processed with two different methods. A simple online algorithm fitted the locations where the betatron oscillations crossed the zero axis (zero-crossing method). The phase advance is determined in 180 degree intervals and is almost independent of the knowledge of the optical functions. The method is simple, fast and robust. The average of two initial phases were saved into history plots that allowed tracking of the stability of the phase advance for a number of different regions in the linac. In this simplified model the amplitude of the oscillations was defined as the maximum BPM amplitude between zero-crossings.

A more complete analysis was suggested in [3]. This algorithm was implemented into the online analysis during the 1996 run and was used for the offline analysis presented in this paper. A complete description can be found in [4]. Here we merely outline the principle. For a single measurement, the diagnostic pulse acquires two

<sup>1</sup> Work supported by the Department of Energy, contract DE-AC03-76SF00515

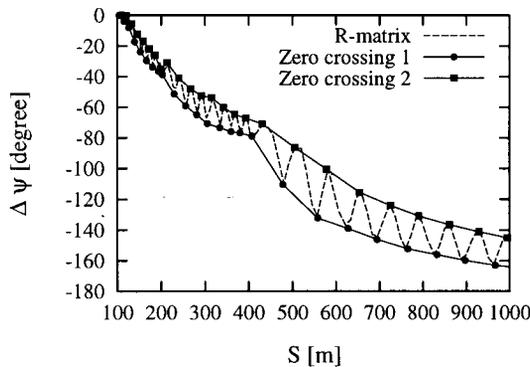
betatron oscillations  $(x_1, x_1')$  and  $(x_2, x_2')$  with different initial phases. The same  $\mathbf{R}$ -matrix transports both betatron oscillations from the initial point “0” to all downstream locations “i”:

$$(x_1, x_1')_i = \mathbf{R} \cdot (x_1, x_1')_0 \quad \text{and} \quad (x_2, x_2')_i = \mathbf{R} \cdot (x_2, x_2')_0$$

This allows reconstruction of the full  $\mathbf{R}$ -matrix. Assuming that the single-particle Twiss functions apply locally, the  $\mathbf{R}$ -matrix is then transformed into normalized coordinates. The two main observables, phase advance  $\psi$  and normalized amplitude  $A$ , are then obtained as:

$$\psi = \arctan\left(\frac{R_{12}}{R_{11}}\right) \quad \text{and} \quad A = \sqrt{\det(\mathbf{R})} \cdot \sqrt{\frac{E}{E_0}}$$

The amplitude is corrected for adiabatic energy damping. Without wakefields,  $A$  is equal to one along the whole length of the linac. BNS damping aims at keeping  $A$  close to one in the presence of wakefields [4]. In addition, the beam Twiss functions  $\beta$  and  $\alpha$  can be determined from the diagnostic pulse data.



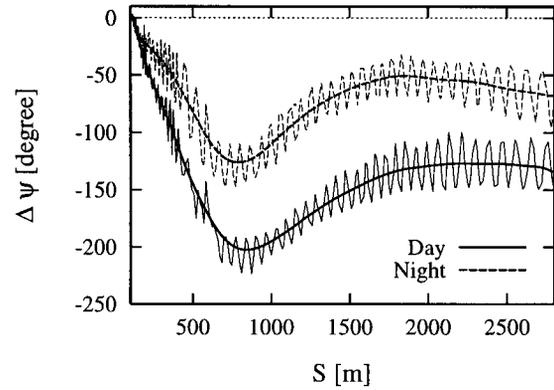
**Figure 2** Phase advance difference with respect to the machine optics along the SLC linac (simulation). The “zero crossing” results are compared to the result of the  $\mathbf{R}$ -matrix algorithm.

The results for the phase advance from the two methods are compared in Figure 2. As expected, the results agree very well. The average of the two “zero-crossing” results gives an accurate measure of the beam phase advance. The total oscillation swing in the  $\mathbf{R}$ -matrix result in Figure 2 is a measure of the beta mismatch over all possible initial phases.

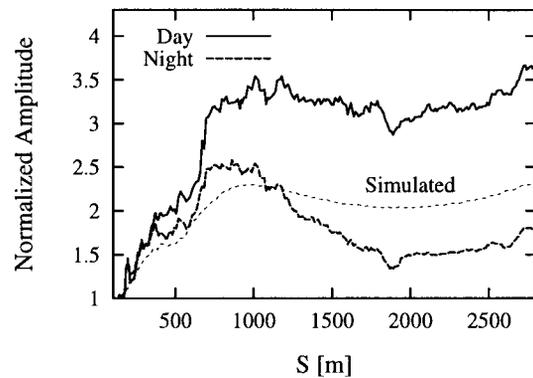
### 3 STABILITY

The phase advance and the normalized oscillation amplitude were monitored for the whole 1996 run, from March to August 1996. A major goal for those measurements was to identify the temperature dependent day-night stability problems affecting the SLC performance. As soon as the outside temperature began to rise in May, large day-night variations were observed indeed. Figures 3 and 4 show the measured beam phase advance and normalized oscillation amplitude on May 11<sup>th</sup> for two periods called “day” and “night”. The “night” period

contains data from 1:12h to 5:31h, while the “day” period contains data from 12:14h to 14:38h.



**Figure 3** Measured beam phase advance difference in the SLC linac with respect to the machine optics during day and night of May 11<sup>th</sup>, 1996



**Figure 4** Measured normalized oscillation amplitude in the SLC linac during day and night of May 11<sup>th</sup>, 1996.

It is seen that the beam optics changes from day to night. The total phase advance varies by up to 100°, while the normalized amplitude changes by almost a factor of 2. The beam-based emittance optimization for the SLC linac is heavily affected by those changes.

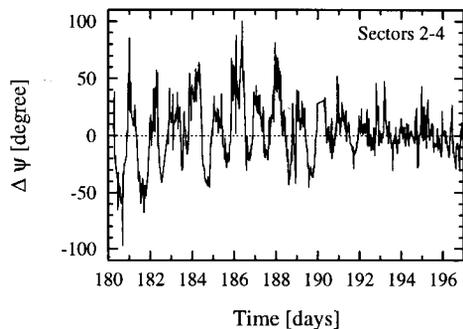
Once the beam signature of the day-night variation was measured with the diagnostic pulse it could be traced to an uncorrected temperature-dependent variation of the RF phase synchronization system in the linac [5,6]. A simple model was developed that simultaneously explained several outstanding stability problems in the SLC linac. For more details see [5].

Figures 5 and 6 show the variations in phase advance and normalized amplitude before and after a temperature correction was applied to the phase distribution system (on day 191). Day-night variations in the beam optics were significantly reduced.

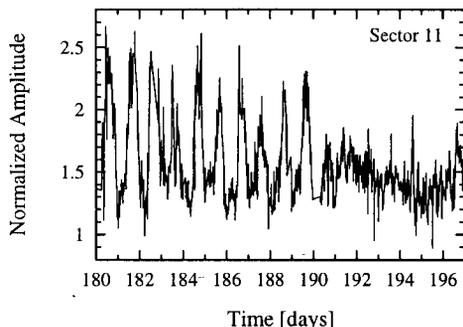
### 4 ABSOLUTE ERRORS

The measured multi-particle beam optics can be compared to the expectations. Detailed simulations were performed with the LIAR computer program [4]. The simu-

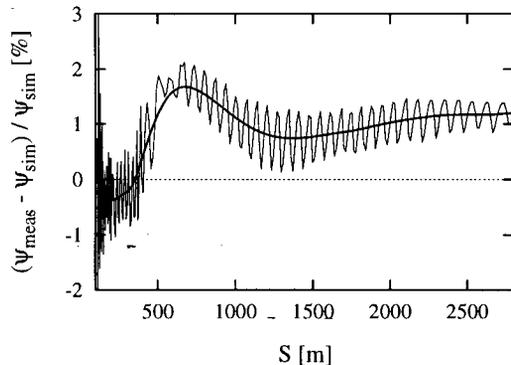
lations used the measured quadrupole settings, the actual SLC beam energy and the measured beam profile and current, to the known accuracy.



**Figure 5** Measured variation of the beam phase advance in sectors 2-4 from June 28<sup>th</sup> to July 16<sup>th</sup>.



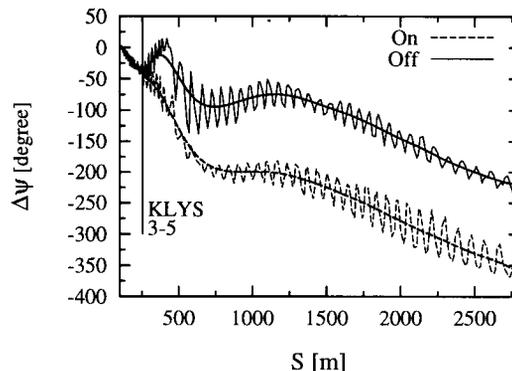
**Figure 6** Measured normalized amplitude in sector 11 from June 28<sup>th</sup> to July 16<sup>th</sup>.



**Figure 7** Relative difference between measured and simulated beam phase advance along the SLC linac on the night of July 31<sup>st</sup>.

Figure 4 compares the measured normalized amplitude to the simulation result. The amplitude at night shows reasonably good agreement with the expectation. Figure 7 shows the relative difference in phase advance between a measurement on July 31<sup>st</sup> and the simulation. The agreement between the measurement and the simulation is at the 1-2% level. Taking into account uncertainties in the longitudinal beam profile, the RF phases, etc. this agreement is remarkably good.

It is important to point out that the diagnostic pulse also allows one to locate large setup errors. An example is shown in Figure 8. The phase advance changes by about 130° when a klystron early in the linac is switched off.



**Figure 8** Measured phase advance before and after switching off a klystron in the beginning of the linac. The lattice was not rescaled.

## 5 SUMMARY

A diagnostic pulse was developed and used successfully in the SLC linac for monitoring and checking of the multi-particle beam optics. The measured signature of large day-night variations in the beam optics indicated a solution to a long outstanding stability problem for the SLC. The measured beam phase advance was shown to agree on the 1-2% level with detailed simulations of the multi-particle beam dynamics. In addition, the normalized oscillation amplitude shows very good agreement within its measured stability. The diagnostic pulse also provides a valuable tool to find large errors in the klystron and optics setup. It will provide an essential tool in the operation of future linear colliders.

## ACKNOWLEDGEMENTS

We would like to thank W. Spence for his help and important contributions.

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