SLAC–PUB–7580
July 1997

Observation and Analysis of Static Deflections from Transverse Long-Range Wakefields in the SLC*

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Abstract

In the SLC main linac a train of three bunches is accelerated. The leading positron bunch is followed by two bunches of electrons. When the positron bunch passes off-axis through the RF structures, it excites dipole modes in the structures, for example long-range transverse wakefields which deflect the subsequent electron bunches. Although the magnitude of the deflections is small one can infer the deflections by measuring the trajectory difference while changing the spacing between the positron and electron bunches. Knowing the positron trajectory the misalignments of the accelerating RF structures with respect to the BPM's can be calculated. We present measurements from the SLC linac and discuss the data analysis and errors.

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.

OBSERVATION AND ANALYSIS OF STATIC DEFLECTIONS FROM TRANSVERSE LONG-RANGE WAKEFIELDS IN THE SLC*

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In the SLC main linac a train of three bunches is accelerated. The leading positron bunch is followed by two bunches of electrons. When the positron bunch passes off-axis through the RF structures, it excites dipole modes in the structures, for example long-range transverse wakefields which deflect the subsequent electron bunches. Although the magnitude of the deflections is small one can infer the deflections by measuring the trajectory difference while changing the spacing between the positron and electron bunches. Knowing the positron trajectory the misalignments of the accelerating RF structures with respect to the BPM's can be calculated. We present measurements from the SLC linac and discuss the data analysis and errors.

1 INTRODUCTION

A charge that is accelerated in the SLC linac excites transverse wakefields if it is misaligned with respect to the center of an RF structure. Figure 1 shows the calculated transverse wakefield $W(z)$ that is excited in an SLC S-Band structure of length L_0 from a charge Q_1 with offset δy. A charge Q_2 at position s with energy $E_2(s)$, that follows the first charge with distance Δz, then experiences a wakefield deflection

$$\theta(s) = W(\Delta z) \cdot \frac{e\,Q_1 L_0(s)}{E_2(s)} \cdot \delta y \,. \tag{1}$$

The unknown beam to structure offsets δy are caused by unavoidable alignment errors and are the cause for severe emittance dilutions in the SLC linac [1]. If they were determined accurately then the optimization and stabilization of the SLC beam emittances could be improved.

Transverse wakefields are usually distinguished into short-range wakefields that act within a bunch and long-range wakefields that act from one bunch to the next. Both are generated from beam to structure offsets. However, it is important to note that differently from the short-range case, long-range wakefields remain only in the first third of a structure and decohere afterwards. We are going to show how to determine the beam to structure offsets from long-range wakefields. In the presence of large internal structure misalignments those offsets will differ somewhat from the ones important for short-range wakefields.

The SLC beam consists of three bunches: 1) a positron bunch, 2) an electron bunch, and 3) an electron bunch for positron production. Here we consider the first two bunches. The electron bunch witnesses the transverse long-range wakefields from the leading positron bunch. With Equation 1 it is seen that a change in Δz changes the wakefield deflection θ. For a single structure and if Δz is changed in many steps the wakefield can be mapped out and the beam to structure offset is determined. Here we consider many superimposed errors and only a few possible settings for Δz. Assuming that the wakefield function is known, a single change in bunch spacing then allows to calculate the beam to structure offsets from the measured change Δy_2 in the trajectory of the second bunch:

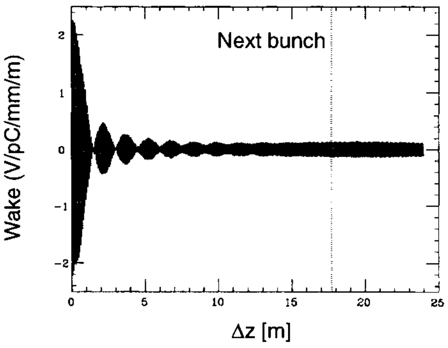

Figure 1: Transverse wakefield as a function of distance Δz for the SLC S-Band structures. The nominal bunch spacing is indicated by the dotted line.

$$\begin{aligned} \Delta y_2(s) &= \int_0^s ds' R_{12}(s,s') \cdot \Delta\theta(s') & (2) \\ &= \int_0^s ds' R_{12}(s,s') \cdot \frac{eQ_1 L_0(s')}{E_2(s')} \\ &\quad \cdot W_0 \cdot f_\phi(s') \cdot \delta y(s') \,. & (3) \end{aligned}$$

The long-range wakefield function $W(\Delta z)$ for SLC is dominated by a 4140 MHz mode and can be approximated with good accuracy by $W_0 \cdot f_\phi(s')$ where $W_0 \approx$ 0.13 V/pC/mm/m and

$$f_\phi(s') = \cos\left[\phi_d(s') - \Delta\phi + \phi_0\right] - \cos\left[\phi_d(s') + \phi_0\right] .$$

The change in distance Δz is expressed through an offset $\Delta\phi = \Delta z/7.2\text{cm} \cdot 360°$ in the long-range wakefield phase. ϕ_0 is the nominal phase between the second bunch and the long-range wakefield. The analysis is slightly complicated by the fact that the long-range dipole-mode frequencies of the SLC S-Band structures have been adjusted

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

by a technique called "dimpling". This was done in order to avoid beam breakup with continuous beam operation in the SLAC linac. The "dimpling" is taken into account by a phase offset ϕ_d that is a function of position s and takes the values 0°, 45°, and 90° for the modes 4140 MHz, 4142 MHz and 4144 MHz. Figure 2 illustrates the dipole mode frequencies for all structures in the SLC linac.

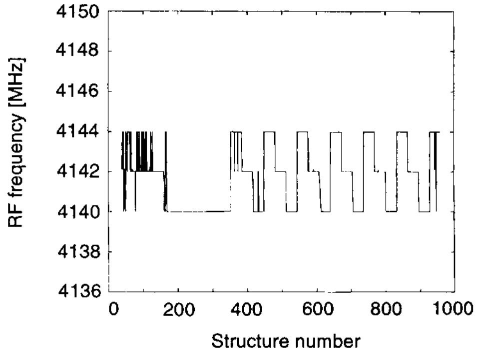

Figure 2: Dipole mode frequencies for the SLC S-Band structures. The effect of "dimpling" is illustrated.

All terms in Equation 3 can be measured or calculated except the beam to structure errors $\delta y(s)$. This allows to solve for $\delta y(s)$. Note, that due to the energy dependence in Equation 3 the sensitivity of the method changes widely along the linac. The wakefield deflections at injection energy are almost a factor of 50 stronger than the deflections at the end of the linac. A part of this difference is compensated by stronger focusing in the beginning of the linac.

2 MEASUREMENTS

The fundamental mode of the SLC S-Band structures is 2856 MHz. The corresponding wavelength is 0.35 ns which defines an RF bucket. In order to change the bunch spacing between the positron and the first electron bunch, the positrons were not moved while the timing of the electron bunch was moved in two steps of 1 RF bucket. The corresponding changes in $\Delta\phi$ are 160° and 320°, allowing for a significant change in the phase factor $f_\phi(s)$ and the measured electron trajectory.

The measured trajectory change from a 1 bucket movement of the first electron bunch is shown in Figure 3. The positron trajectory remained unchanged within its stability. Measurements were done repeatedly with 1 and 2 RF bucket changes for the electrons. Each measurement was calculated from three online measurements, each the average of 30 beam trajectories. The spread within the three average measurements was used to determine the systematic measurement error to be roughly 20 μm.

3 ANALYSIS

Starting from Equation 2 the problem to be solved is

$$R_{12} \cdot \alpha = b\,, \tag{4}$$

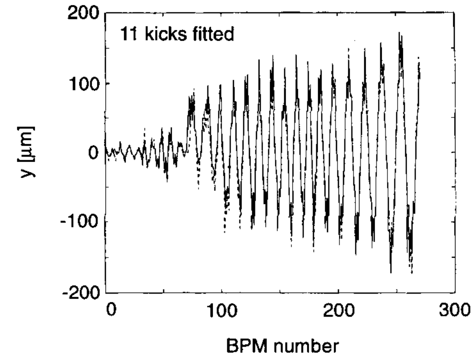

Figure 3: Measured change Δy_2 in the electron trajectory due to moving the electron bunch 1 RF bucket (10.5 cm) closer to the positrons. The measurement (solid) is compared to a fit (dashed) for 10 wakefield deflections and an average offset of all structures (compare next section).

with b being the array of BPM measurements Δy_2, α the array of wakefield deflections θ and R_{12} the relevant transport matrix. Note that for most of the linac, kicks from four structures between neighboring BPM's are lumped together into a single effective kick.

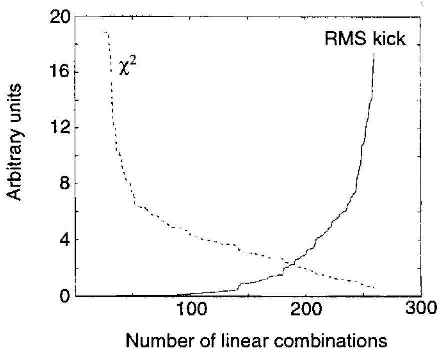

Figure 4: The χ^2 and the RMS kick found by SVD as a function of the number of linear combinations that are included into the solution. The χ^2 can be greatly reduced with just a few kick combinations. If too many combinations are included, unphysically strong kicks are introduced that reduce the χ^2 only slightly.

For the data analysis we used the method of singular value decomposition (SVD). SVD factorizes $R_{12} = U \cdot S \cdot V^T$ with $UU^T = 1$ and $VV^T = 1$. The matrix S is diagonal with the diagonal elements W_i sorted in descending order. A number W_i indicates something like the effectiveness of a combination of kicks to change the trajectory. Putting a "threshold" on W_i will force the solution to use the most effective combinations of kicks and the RMS kick of the solution is reduced. Unphysical kick combinations can such be avoided. This is illustrated in Figure 4. The solution is obtained as $\alpha = VS^{-1}U^Tm$ with the error $(\delta\alpha)^2 = \left(V^T/W\right)^2$. The knowledge of the error $\delta\alpha$

allows to iterate the result while disregarding the most insignificant kicks with large relative errors. In Figure 5 it is shown that about 15 kicks are sufficient to explain the measured data within its resolution. The agreement between the fit and the measurement is illustrated in Figure 3 for just 11 kicks. Though some differences are left, the data is well explained within its resolution and possible errors in the used optics R_{12} model. The data also allows to determine the phase ϕ_0 between the electron bunch and the long-range wakefield. Figure 6 shows that a minimum fitted χ^2 is obtained for $\phi_0 \approx 15°$.

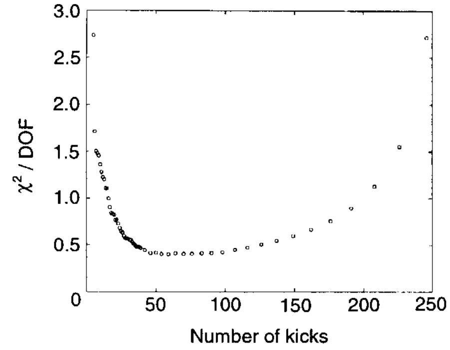

Figure 5: The χ^2 per degree of freedom as a function of the number of kicks that are included into the solution. About 15 kicks are sufficient to obtain a χ^2/DOF of 1.

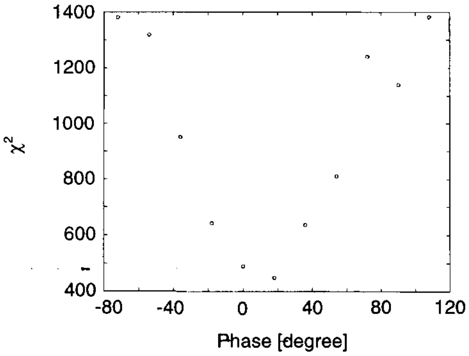

Figure 6: The phase ϕ_0 between the electron bunch and the long-range wakefield is indicated by a minimum χ^2 of the fitted solution.

For the final results, the 1 and 2 bucket data sets were fitted simultaneously. The structure misalignments were calculated from the fitted wakefield kicks and the results were compared to conventional survey data. We drew the following conclusions:

1. The measured trajectory changes can be explained within the noise of the measurement by 15-20 large structure misalignments with an RMS of 1.5 mm. In addition an average offset of $\approx$ 120 μm of all structures is needed to explain the data.
2. Due to the limited stability and BPM resolution, it is difficult to resolve single errors. The errors are lumped together into a few large ones.
3. The LRWF results depend on the model used for the wakefield optics. We obtained consistent results with a modified model.
4. There is no strong correlation between misalignments found by long-range wakefield and survey measurements. However, large offsets from the long-range wakefield analysis tend to coincide with problems in the survey. About 25 out of 263 survey measurements (about 10%) have large uncertainty errors. Assuming no correlation with the LRWF results, we would expect that about 2 out of 20 LRWF kicks coincide with the survey problems. However, we find 7 coincidences that might indicate real problems.
5. Twelve out of twenty large misalignments obtained from the long-range wakefield analysis occur at the end of a sector (instrumentation section).

4 SUMMARY

During the 1994/1995 run transverse long-range wakefields were studied in the SLC. Changing the distance between the e- and e+ bunches, the static wakefield kicks from the leading positrons on the electrons were changed and the corresponding change in the electron trajectory was measured. A significant change in the electron trajectory was indeed observed, indicating several large transverse structure offsets in the SLC. A detailed data analysis was done for the vertical plane.

Though limited in their accuracy, the long-range wakefield analysis pointed to the instrumentation sections at the end of linac sectors as the likely locations of large structure misalignments. Because the regular lattice is interrupted there, traditional alignment and survey methods are limited in their accuracy, explaining the possibly large misalignments. Also, an average structure offset of about 120 μm is needed to explain the measured electron trajectory.

The available signal to noise ratio from the long-range wakefield measurements is not large enough to resolve all important structure errors with the required accuracy. Within the available resolution, errors are lumped together into a few large kicks. Although sufficient for a steering minimization, the accuracy is not sufficient for a mechanical realignment of the RF structures. A related approach [2] to determine the structure alignment with a better signal to noise ratio has been proposed and will be tested in the SLC linac during the 1997 run.

5 REFERENCES

[1] R. Assmann, "Beam Dynamics in SLC". These proceedings.

[2] F.J. Decker et al, "Super-ASSET: A Technique for Measuring and Correcting Accelerator Structure Misalignments at the SLC". These proceedings.