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MEASUREMENTS OF LONGITUDINAL PHASE SPACE IN THE SLC LINAC*

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INTRODUCTION

In the Stanford Linear Collider the beam leaves a damping ring and then enters the Ring-to-Linac (RTL) transfer line. In the RTL it is compressed in length by a factor of 10 by means of an rf section, with which a longitudinally correlated energy variation is induced in the beam, and a following beam line which has non-zero momentum compaction. The compressed beam then enters the linac proper. In this paper we describe three measurements of longitudinal properties of the beam in the SLC linac. We present measurements of (i) single bunch beam loading, of (ii) the energy spectrum at the end of the linac, and of (iii) the linac bunch length. Since the results of all three measurements depend on the beam's longitudinal charge distribution in the linac they, in turn, also depend on the bunch lengthening that occurs in the damping rings, as well as on the behavior of the compressor. The results of the first two measurements, in addition, depend critically on the strength of the longitudinal wakefields in the linac.

The results of these three measurements are compared with simulations. For these calculations, at any given current, the potential well distortion in the damping ring is first computed (see Ref. 1). The compression process is then simulated to obtain the longitudinal charge distribution in the linac. For the first two measurements this distribution is then convolved with the calculated longitudinal wake function of the SLAC linac[2] in order to obtain the induced voltage. Finally, the induced voltage is combined with the effect of the linac rf wave to give the final energy spectrum. (More details of this calculation procedure are given in Ref. 3.)

SINGLE BUNCH BEAM LOADING

When an electron (or positron) bunch passes through the acceleration structure of the SLAC linac it excites electromagnetic fields which are called wakefields. These wakefields react back on the beam and, among other things, result in the beam losing energy. The lost energy is referred to as "single bunch beam loading." We want to measure this energy loss in order to estimate the extra gradient that is needed to achieve a given final beam energy. Another motivation for performing this measurement is that it is a test of the validity of the calculated longitudinal wake function of the SLAC structure, a function which has been used extensively for predicting the high current behavior of the linac beam. As mentioned above, if we convolve the wake function with the beam charge distribution we obtain the beam induced voltage. The average value of the beam induced voltage should, then, equal the losses that we measure.

In order to measure the single bunch beam loading for the linac the beam was steered onto a phosphor screen positioned at a point of high horizontal (x) dispersion at the end of the linac. Thus the x position of the beam's centroid on the screen, when divided by the dispersion there (η), gives the beam's final energy with respect to a reference energy. The measurements were begun at a relatively high value of current, $N = 3.5 \times 10^{10}$ electrons per bunch. The current was then decreased, in steps of $\Delta N = 5 \times 10^9$, with the beam's centroid measured at each step. For these measurements the rf phase of the beam in the linac was not changed. The voltage of the compressor rf V_c was also kept fixed, at 29 MV. The nominal final energy E_0 = 47 GeV and η = 72 mm. In Fig. 1 we display the measurement results

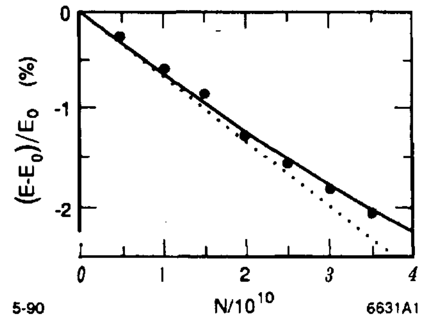

Fig. 1. The change in final beam energy measured as function of beam current (the circles). The compressor voltage V_c = 29 MV, the reference energy E_0 = 47 GeV. The solid curve gives the calculation results, the dotted line the calculated results assuming there is no bunch lengthening in the damping rings.

(the circles). The x-coordinate gives the bunch population N; the y-coordinate the relative change in final energy $(E-E_0)/E_0$.

Also displayed in Fig. 1 (by the solid line) are results of calculations. We clearly see good agreement between the measurement and the calculation results. From the calculations we find that the bunch shapes are nearly gaussian at V_c = 29 MV. If we take these shapes and fit them to gaussians we find that the rms length of the fits vary from 0.60 to 1.15 mm as the current is increased from zero to $N = 4 \times 10^{10}$. Additional calculations assuming no bunch lengthening in the ring are given by the dotted line in Fig. 1. We see that the two curves differ significantly only at the higher currents.

The good agreement between measurement and theory indicates that the calculated longitudinal wake function for the SLAC structure is accurate, at least when applied to bunches with rms length $\gtrsim$ 0.6 mm. We should mention, however, that the single bunch beam loading in the SLAC linac has been measured before, but for a very short bunch, one with an rms length of 0.3 mm.[4] For that measurement the loss was found to be 35% above the value expected from calculations. However, the estimated errors of that measurement were very large, on the order of 20%.

THE FINAL BEAM ENERGY SPREAD

In the SLC, for good luminosity we want the beam's energy spectrum at the end of the linac to be essentially contained within an aperture of $\pm 0.3\%$ $\Delta E/E$. The final energy spectrum of the beam is determined by its position on the rf wave and by the shape of the beam induced voltage. During normal SLC operations the final spectrum is often adjusted by the machine operators by varying the overall rf phase of the linac. The hardware that measures the spectrum is a nondisruptive version of the hardware described in the previous section:() At a dispersive region near the end of the linac the beam enters a wiggler magnet. The resulting synchrotron radiation is imaged on a phosphor screen, thus providing a measure of the beam's energy spectrum. Currently the resolution of the hardware is limited to an rms value of about 0.15% $\Delta E/E$. However, with the new wire monitor that will soon be installed we hope to reduce this number by a factor of 10.

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For the present measurement we varied the overall linac phase and measured the full-width-at-half-maximum of the spot on the screen x_{fw}. The spectrum width is then defined by $\delta_{fw} = x_{fw}/\eta$ with η the dispersion at the wiggler. For this measurement N = 1.5 x 10^{10}, V_c = 28.8 MV, $E \sim 47$ GeV, and η = 72 mm. Fig. 2 displays the results (the circles). In our convention a more positive value of phase is toward the front of the rf crest. The absolute zero of phase, however, is not known. In the-plot we have shifted the measured phase values by an amount that causes the position of the minimum in the data to agree with that in the simulation results (discussed below). Note that, in theory, if we measured the centroid positions of the spectra as function of phase and then fitted the results to a cosine wave, we could accurately determine the zero of phase. However, in the SLC it is impractical to perform this experiment with the energy feedback off. The feedback was on during our measurements; thus the centroids of our measured distributions have no significance. We should also point out that the areas under the spectral curves, which are proportional to the beam current, should all be equal. In fact, we found variations of up to 15% from the mean value in the areas of the data, indicating that there is some nonlinearity in the response of the hardware.

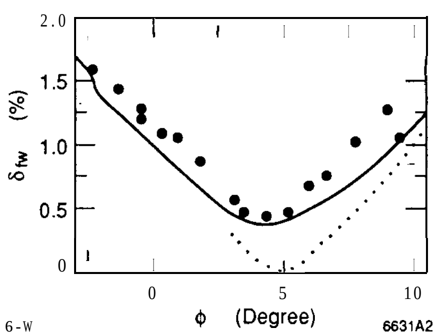

Fig. 2. The spectrum width δ_{fw} measured at the end of the SLC linac as function of overall linac phase for N = 1.5 x 10^{10} (the circles). Also shown on the plot are the calculated results when the resolution of the hardware (0.15%) is included (the solid curve) and when it is not (the dots). Here V_c is assumed to be 27.4 MV.

The spectral shapes were also obtained from simulations, again assuming the wakefield effect is described by the calculated wake function for the SLAC linac. In order to include the effect of the limited harware resolution, each calculated spectrum was first convolved with a gaussian with rms of 0.15% before comparing it with the measurements. The full widths of the calculated spectra δ_{fw} were then plotted as function of linac phase. We found that the shape of this curve is very sensitive to small changes in compressor voltage. When using V_c = *28.8* MV the curve cannot be made to match the data very well; in this case there is a descending portion of the curve, with a minimum near 5°, which is then followed by a very flat region. For a good match to the measurements we needed to reduce V_c in the calculations by 5%, to 27.4 MV. This conclusion--i.e. that there is a 5% discrepancy between the actual output of the compressor and its readout value-is supported by another linac measurement that was performed near in time to this one.[6]

The calculated results, when V_c = *27.4* MV, are given by the solid curve in Fig. 2. The phase ϕ is given with respect to the rf crest. That the minimum value of the curve agrees with the minimum of the data confirms that the resolution is about 0.15%. The spectral widths before the resolution convolution was performed is given by the dotted curve. The minimum value of this curve, δ_{fw} = 0.04%, is just given by the component of the beam energy spread that is uncorrelated with longitudinal position. (We should point out that this small value of δ_{fw} does not mean that the spectrum is almost monochromatic. In this case the calculated spectrum consists of a sharp central spike and long energy tails, representing a good fraction of the beam.) In Fig. 3 we show the measured spectral shapes when the linac phase reading (which we-denote by ϕ') was 58.2°, 64.9°, and 67.2° (the left column). The abscissas give the position on the screen, with higher energy particles displayed more to the left in the plots. The ordinates give the intensity in units that are arbitrary, except insofar as one unit signifies the same intensity in each plot. The calculated spectra that correspond to these measurements, with $\phi = -2.3°$, 4.3°, and 6.6°, are given in the right column. For these plots the horizontal scale is Ax = $-\eta\Delta\delta$. We see that the calculated shapes agree well with the measurements.

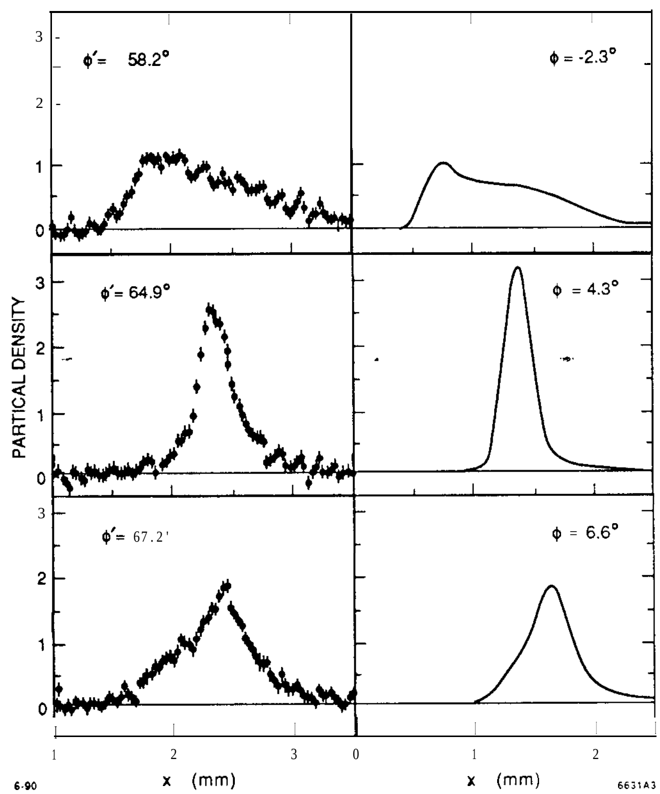

Fig. 3. The shape of the spectra for three of the data points given in Fig. 2 (the left column). The calculated spectra that correspond to these measurements are given in the right column.

BUNCH LENGTH MEASUREMENTS

The SLC linac bunch length is sufficiently short so as to be difficult to measure with a streak camera. Instead, we employed another method to measure the bunch length:[7] First, over a portion of the linac the rf was phased at 90° to the beam, so that a roughly linear correlation between longitudinal position and energy was induced within the bunch. The beam was then bent into a beam line with a known dispersion and was observed on a screen. From the width of the digitized spot the bunch length was obtained. This method is similar to one that was used for measuring the longitudinal charge distribution in the SLC damping rings.[8] At high currents, however, it is more difficult to obtain a good measurement of the bunch length for the linac in this way than it was for the damping rings for two reasons: (i) In the linac the bunch is 5-10 times shorter than it is in the damping ring. The longitudinal wakefield is therefore much stronger. And its contribution to the beam's energy spectrum will no longer be insignificant, as it was for the damping ring bunch length measurements. (ii) In the linac slight orbit errors will lead to single bunch beam break-up-and therefore emittance growth-which will tend to complicate the measurements,

For the present measurement only Linac Sectors 2-9 (out of 30) were employed. At the beginning of the measurement a dipole magnet was activated at the end of Sector 9, in order to kick the beam to an off-axis screen. Each bunch length measurement then consisted of two parts. First, with the Sector 9 rf turned off, the phase of the remaining sectors was adjusted to minimize the spot size on the screen; the distribution was fit to a gaussian and the rms width of the fit σ_{x0} was recorded. For the second part the Sector 9 rf was turned on, but phased at $90°$ to the beam. The new distribution was then measured, and again was fit to a gaussian. Finally, the two width measurements were subtracted in quadrature to give σ_x. For a good measurement we need σ_x to be significantly larger than σ_{x0}. The corresponding bunch length is then given by $\sigma_z = [E/(\eta e V_9 k_{rf})]\sigma_x$, with E the beam energy, η the dispersion at the screen, V_9 the peak rf voltage of Sector 9, and k_{rf} the rf wave number. For the present measurements E = 12.4 GeV, η = 67 cm, V_9 = *1.64* GV; for the SLAC linac k_{rf} = 60 m^{-1}.

The measured bunch length σ_z is shown as a function of compressor amplitude in Fig. 4 (the circles), for currents of N = 1.0 (the top frame) and 2.1 x 10^{10} (the bottom frame)! The curves in the two plots are the simulation results. To obtain these, the longitudinal charge distribution was first computed, and then lit to a gaussian. The curve gives the rms width of the fit. Below $V_c = 35$ MV the measurements and simulations agree reasonably well. The discrepancy at higher values of V_c may be due to the compressor not reaching the peak voltages that the readout suggested. The crosses in Fig. 4 give the results when the Sector 9 rf was off.

The bunch length was also measured as function of current, at V_c = 32.5 MV (see Fig. 5). This compressor setting should yield almost maximum compression, therefore the behavior of the bunch length in the linac should reflect the behavior of the energy spread in the damping ring. In Ref. 8 the energy spread in the ring was reported to be flat up to the turbulent threshold current (somewhere near N = 1.5 x 10^{10}) and then to increase approximately as $N^{1/3}$. The data of the present measurement has quite a bit of scatter in it (see Fig. 5). But the data does show an increase in bunch length near N = 1.5 x 10^{10}, which could be the signature of the onset of turbulence in the damping ring. This increase, however, is much more rapid than is predicted by the calculation (the curve). More measurements will be needed to decide this issue. Note that the measured widths with Sector 9 off (again the $+$'s) increase with current. We expect this to be the case, since the minimum energy spread tends to increase with current if the bunch length is largely unchanged.

We hope to repeat this measurement. We also plan to attempt this measurement in a different way. By performing the bunch length measurement at two different, properly chosen, rf phases. we should be able to separate the contribution to the energy spectrum at the screen of the longitudinal wakefield from that of the longitudinal charge distribution. In this way we will not only obtain a more accurate measurement of the bunch shape, but also a direct measurement of the induced voltage (see Ref. 3).

★ These bunch length measurements were performed at a different time than the energy spread measurements described earlier, and the controller for the compressor voltage was also different. Therefore, the conclusion, stated earlier, of a 5% shortfall in compressor output should not be applied here.

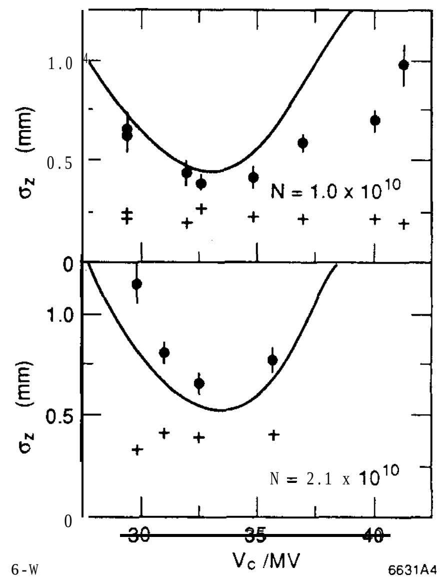

Fig. 4. The bunch length σ_z measured as function of compressor voltage V_c for bunch populations N = 1.0 x 10^{10} (top) and 2.1 x 10^{10} (bottom). (The data is given by the circles.) Also shown is the results with Sector 9 turned off $(+)$. The calculated bunch length is given by the curve.

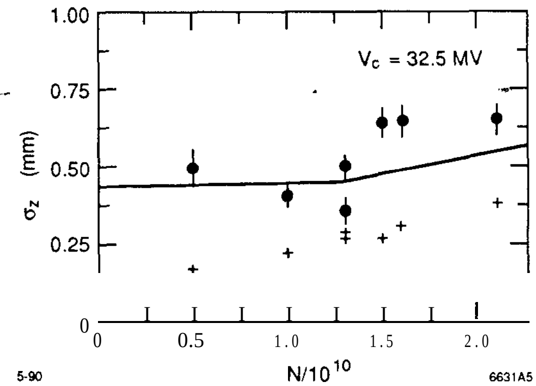

Fig. 5. The bunch length σ_z measured as function of current (the circles). The compressor voltage V_c = 32.5 MV. Also shown are the measurements with Sector 9 off $(+)$ and the calculated bunch length (the curve).

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