MEASUREMENT OF WAKEFIELD SUPPRESSION IN A DETUNED X-BAND ACCELERATOR STRUCTURE*

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Abstract

Research is underway at SLAC to develop accelerator structures for the next generation linear collider. A full-scale prototype X-band structure has been built in which the dipole mode frequencies were detuned to suppress the long-range transverse wakefield by about two orders of magnitude. To verify that the detuning works as expected, a facility to measure the long-range wakefield, called the Accelerator Structure SETup, or ASSET, was constructed in the SLAC Linear Collider (SLC). This paper presents the results from the measurement of the prototype X-band structure with this facility.

Introduction

The designs being considered at SLAC for the Next Linear Collider (NLC) employ multi-bunch operation in a high acceleration gradient X-band linac [1]. The largest contribution to the transverse wakefield generated in the X-band structures is expected to come from the lowest band of dipole modes. If the structures were built with identical cells, the transverse wakefield would be dominated by the few near-synchronous dipole modes in this band, and would produce an enormous blowup of the transverse motion of the NLC bunch train. In a detuning strategy to reduce the wakefield, the 206 cells of the structure were instead designed with a smoothly varying geometry to produce a constant accelerating mode frequency (11.4 GHz) in the structure, but a Gaussian distribution in frequency of the product of the dipole mode density and the mode coupling strength to the beam. The resulting dipole wakefield, which evolves in time essentially as the inverse Fourier transform of this product, also falls off in a Gaussian manner, and is about two orders of magnitude smaller by the time of the next bunch (1.4 ns) in the NLC design. However, at times comparable to the length of the bunch train, which is nominally 126 ns, the wakefield is expected to recohere to several percent of its initial strength as a result of the discreteness of the mode frequencies. A further order-of-magnitude suppression of the wakefield on this time scale is required for the NLC, and can be achieved by using several structure types with interleaved mode frequencies, or by the addition of mode damping.

ASSET Facility

A full-scale (1.8 m long) prototype X-band structure has been built with detuning and successfully operated at high power [2]. In searching for a means to verify the effect of the detuning on the long-range transverse wakefield, it was realized that the SLC was well suited as a test bed because the two bunches, electrons and positrons, can be independently injected into the main linac to serve as drive and witness bunches for wakefield measurements. Consequently, the Accelerator Structure SETup, or ASSET, was constructed near the beginning of the main linac in the SLC for the purpose of measuring the wakefield generated in a single X-band structure [3]. Fig. 1 shows a plan view sketch of this facility.

For the transverse wakefield measurements, the positron bunch served as the drive bunch, and was extracted from the South Damping Ring and injected into the main linac via the South-Ring-To-Linac (SRTL) transport line. In the linac, the bunch passed through the X-band structure and was then steered into a dump. The magnet used for this purpose is also the first bend of a chicane that transported electrons back onto the linac axis. The electron bunch served as the witness bunch, and was extracted from the North Damping Ring at a later time (≡ t) and injected on-axis into the linac via the North-Ring-To-Linac (NRTL) transport line. In traversing the test structure, the witness bunch was deflected by the wakefield generated by the drive bunch. The witness bunch then passed though the chicane and down the linac where its trajectory was recorded by beam position monitors (BPMs) located in each of the quadrupole magnets.

The changes in the witness bunch vertical deflection that resulted from controlled changes to the drive bunch vertical offset in the structure were used as the basis for determining the transverse wakefield. The deflections were computed from betatron oscillation fits to data from 24 BPMs downstream of the chicane, and corrected for incoming orbit jitter using the results from similar fits to data from 17 BPMs in the NRTL.

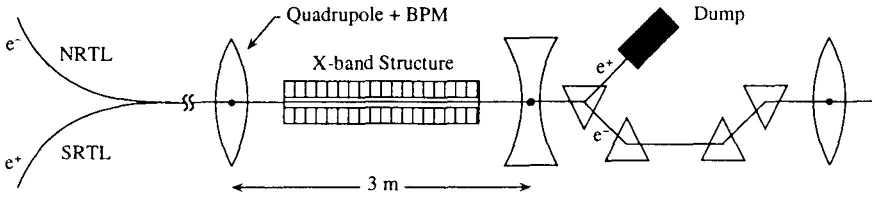

Fig. 1. Layout of the Accelerator Structure SETup (ASSET) in the SLC

During the measurements, the X-band structure was maintained at its nominal operating temperature, and its input and output rf couplers were terminated with matched loads.

To formulate the measurement approach, we let Δy_d denote a change in the vertical trajectory of the drive bunch in the structure, parallel to its axis. The corresponding change to the witness bunch vertical angular trajectory, $\Delta\theta_y$, due to the dipole modes is

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$$\Delta\theta_y = A\, W_\perp(t)\, \Delta y_d \qquad (1)$$

where $W_\perp(t)$ is the integrated dipole transverse wakefield in the structure at the time, t, behind the drive bunch. For convenience, $W_\perp$ is normalized in units of the drive bunch offset, drive bunch charge, and structure length. The proportionality factor, A, is

$$A = e^2 L_s I_d f_s / E_w \qquad (2)$$

where L_s is the structure length, I_d is the drive bunch intensity (i.e., the number of particles in the bunch), E_w is the witness bunch energy (1.2 GeV), and f_s is a factor that accounts for the averaging of the drive and witness bunch wakefield interaction over the longitudinal distribution of the particles in the bunches. As discussed below, the 15.1 GHz central frequency of the lowest dipole band was the dominant wakefield component observed, so the dilution factor corresponding to this frequency, $f_s = .90$, was used in the calculations.

The positron intensity was not recorded pulse-to-pulse but sampled every two minutes. The value sampled nearest in time to the wakefield measurement was used to compute the wakefield strength. Unfortunately, the positron intensity was unstable for most of the running period, which led to uncertainties in the inferred wakefield strengths that varied from a few percent up to 10%. Also, the average positron intensity decreased from about 2×10^{10} to 5×10^{9} during the run, and thus reduced the sensitivity to the wakefield proportionally. The electron bunch intensity, however, was fairly stable at about 1×10^{10}.

Measurements and Results

During the two day period that was allotted to do the measurements, data were taken at 17 settings of the bunch timing that were configured by changing the SLC timing system in multiples of 1.4 ns and/or 8.4 ns. At each setting, a much finer scale bunch timing control was used, and several measurements of the wakefield were made as part of a two step approach to determining the dipole amplitude, $|W_\perp|$. In the first step, the drive bunch offset relative to the structure axis, y_d, was set to 2.2 mm using the two neighboring BPMs as an absolute reference. Data were then taken in which the bunch timing was varied over a few oscillation periods of the wakefield. The measured changes in the witness bunch deflection were used to map the local wakefield function, and in particular, to find the time settings corresponding to its peak values, both positive and negative. In the second step, data were taken at a few of the peak time settings where y_d was varied from −2.0 mm to 2.0 mm at three settings of the witness bunch offset, y_w = −0.2, 0, 0.2 mm. Here the $\Delta\theta_y$ results were fit to determine $|W_\perp|$ as well as the integrated quadrupole wakefield strength, for which $\Delta\theta_y \propto \Delta y_d^2\, \Delta y_w$. This two step approach to measuring the amplitude, while much quicker than doing the offset measurements at many time settings, assumes in the first step that the dipole component dominates the total wakefield, and that the structure is well aligned (<< 2.2 mm) to the two neighboring BPMs. As measurements were made, the data in fact justified these assumptions and so the acquisition continued in this manner.

Figure 2 shows two examples of measurements made by varying the bunch timing, one near the bunch crossing (t = 0), and one where the bunches are about 92 ns apart. The data points were computed using Eq. 1, where Δy_d was assumed to equal the absolute drive bunch offset of 2.2 mm. The solid line in Fig. 2a is a prediction of the short-range wakefield, while that in Fig. 2b is a fit to the data of a sine function with a fixed period. Because of an uncertainty in the bunch timing calibration for the small time changes, the time scale was adjusted so that the period of the observed oscillations, such as seen in Fig. 2b, corresponds to the central dipole mode frequency of 15.1 GHz. This same scale factor was used for all fits.

The predicted wakefield in Fig. 2a is based on a calculation of the dipole modes in an equivalent periodic structure [4]. The prediction includes the effect of the ≈ 1 mm rms Gaussian bunch length profiles, which further reduces the already small higher band contributions. The t = 0 point of data was defined as the best match to the prediction (note that the data are causal in that the values at negative times are consistent with zero). The error bars on the data points in this figure include the contribution from the positron intensity jitter, which is generally much larger than that from the $\Delta\theta_y$ measurement error.

Figure 2b is typical of the measurements at later times in that there are no apparent contributions from higher frequency modes. The dipole wakefield amplitudes measured from the sine curve fits in fact agree with the results from varying the bunch offsets. This agreement is consistent with the finding of no significant quadrupole contributions in the offset analyses,

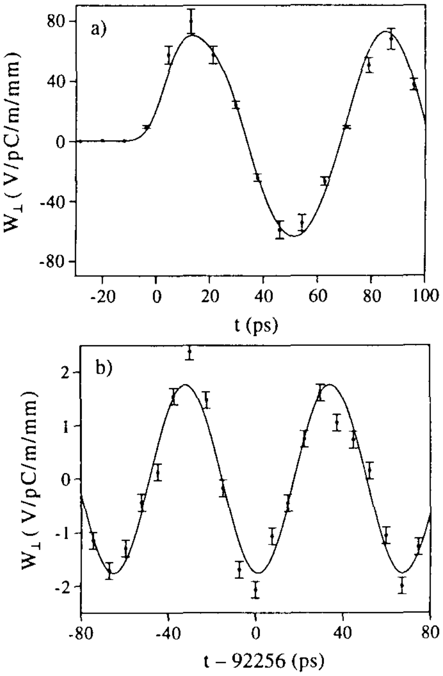

Fig. 2. Dipole wakefield measured (a) near the bunch crossing and (b) at a bunch separation of about 92 ns. The solid lines are described in the text.

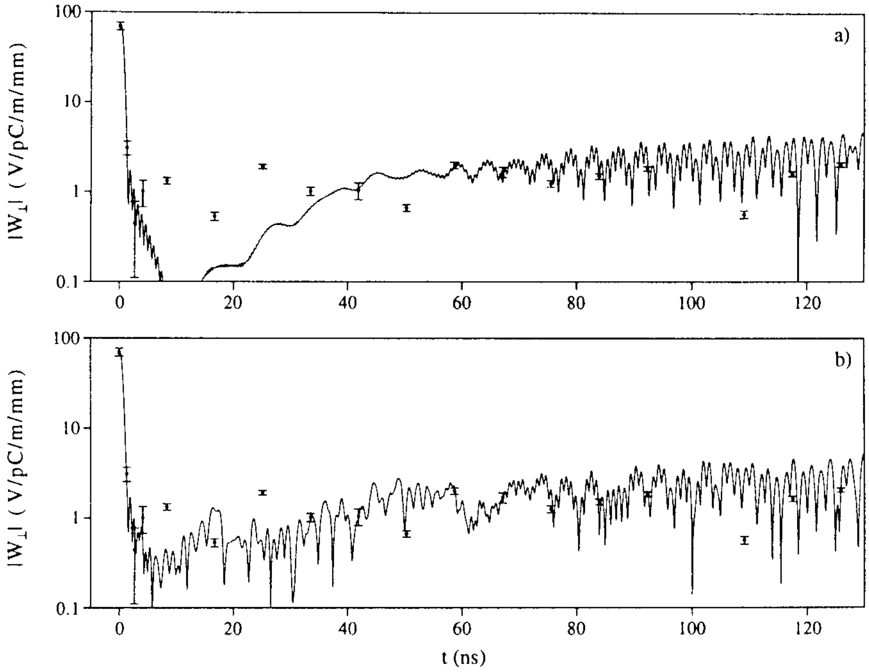

Fig. 3. Dipole wakefield amplitude measurements and prediction a) without cell frequency errors and b) with 1.5×10^{-4} rms fractional frequency errors.

as was expected. The agreement is also consistent with the 100 μm level of accuracy to which the structure was aligned to the two neighboring BPMs.

The suppression of wakefield amplitude, as evidenced by comparing Figs. 2a and 2b, is more clearly seen in Fig. 3, in which all amplitude data are plotted as a function of the bunch time separation. Each data point in this figure is typically an average of six measurements, two from repeated bunch time variation measurements, and four from two repeated bunch offset variation measurements at two of the peak wakefield time settings. The error bar on each point however is not the combined errors of the individual measurements, but an estimate based on the variation of the values averaged, and a 5% systematic uncertainty. The spread in the measured values is correlated with the size of the positron intensity jitter, and is reflected in the χ^2 of the fits. At two time settings, it appeared that a significant amplitude change occurred over a time period of about two oscillations. In these cases, the mean amplitude was plotted.

The solid line in Fig. 3a is a prediction of the long-range wakefield amplitude based on an equivalent circuit model of the structure that characterizes each cell as a two mode oscillator that is weakly coupled to its neighbors [5]. One sees that the data are consistent with the initial rapid fall-off in the predicted wakefield amplitude, but that subsequent points up to about 40 ns are much larger than the predications, while points at later times are smaller on average by about a factor of two. Part of this disagreement is believed to be due to the effect of the residual errors in the cell cavity diameters from the fabrication process. Measurements of the cells made before the structure was assembled show a Gaussian-like error distribution in the diameters that would produce a 1.5×10^{-4} rms fractional smearing of the synchronous cell dipole mode frequencies. Recomputing the wakefield with different sets of frequency errors, each drawn from a Gaussian distribution with this rms width, produces results closer in size to the $t < 40$ ns data. The solid line in Fig. 3b is an example.

At later times, the addition of the frequency errors does not greatly change the results. Here the predictions would better agree with the data if the Q of the modes used in the calculations were lowered from the assumed value of 6500 to about 4000. Measurements of the loaded Q of the modes using a network analyzer, however, show no evidence for the smaller values. Cross-plane coupling of the wakefield modes, which would also reduce the measured wakefield, has been ruled out from an analysis of the horizontal witness bunch orbit data taken during the measurements. Theoretical work is continuing in an effort to better model the structure to see if the match to the data can be improved.

Summary

Using the ASSET facility in the SLC, we have verified the suppression of the long-range transverse wakefield in an X-band structure built with detuning. The measured wakefield amplitudes are in fair agreement with predictions that include the effect of cell fabrication errors. The short-range wakefield prediction, which is less theoretically uncertain, is in good agreement with the data.

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