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Measurement of Wakefield Suppression in a Damped and Detuned X-Band Accelerator Structure*

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Abstract

As part of the SLAC program of X-band accelerator structure development for a future linear collider, a new method of damping the structure dipole modes has been developed to augment the wakefield supression that has been achieved with the use of mode dentuning. To test this concept, a prototype Damped-Detuned Structure (DDS) was built. In addition to having cells whose dimensions vary along the structure to generate the detuning, it has four parallel manifolds that couple to the cells to provide the damping. The transverse wakefield generated by a beam in this structure was measured using the Accelerator Structure Setup (ASSET) facility in the SLC. This paper presents these results together with spectrum measurements of the beam induced by manifold signals and comparisons with the theory.

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As part of the SLAC program of X-band accelerator structure development for a future linear collider, a new method of damping the structure dipole modes has been developed to augment the wakefield suppression that has been achieved with the use of mode detuning. To test this concept, a prototype Damped-Detuned Structure (DDS) was built. In addition to having cells whose dimensions vary along the structure to generate the detuning, it has four parallel manifolds that couple to the cells to provide the damping. The transverse wakefield generated by a beam in this structure was measured using the Accelerator Structure Setup (ASSET) facility in the SLC. This paper presents these results together with spectrum measurements of the beam induced manifold signals and comparisons with theory.

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Nearly all designs being considered for future linear colliders employ multibunch operation to improve efficiency. This introduces coupling of the bunch motions through the transverse wakefields generated as the beam traverses the linac accelerator structures. Unless suppressed, these fields are generally large enough to resonantly amplify the betatron motion of the bunches by many orders of magnitude. For the Next Linear Collider (NLC) design, there has been an active program to address this problem for more than six years. A milestone occurred three years ago with the construction and successful testing of a detuned structure [1]. The geometry of its 206 cells varies smoothly over the length the structure to yield a frequency distribution of modes in the lowest dipole band, which when weighted by the mode coupling strength to the beam, is approximately Gaussian with a mean of 15.1 GHz and a sigma of 2.5%. This detuning results in the destructive interference of the mode contributions, yielding a Gaussian falloff in the net wakefield generated after each bunch. The design parameters were chosen to produce about a two orders of magnitude reduction by 1.4 ns, the nominal NLC bunch spacing. However, due to the finite number of modes, the wakefield reduction does not continue indefinitely. By 126 ns, the NLC bunch train length, the mode contributions partially recohere, yielding a wakefield at the several percent level.

Although the detuning would significantly reduce the betatron amplification that would occur in an NLC-like linac, the resulting level would still not be readily manageable. This has prompted the development of a damping scheme to suppress the wakefield rise at longer times [2]. For this scheme, four parallel rectangular wave guides, referred to as manifolds, are added to the structure and couple via radial slots to all but 3 cells at each end. Their layout, excluding external terminations, is illustrated in Fig. 1. The manifolds propagate a single band of modes in the frequency range of the lowest band of dipoles modes and are cutoff to the fundamental accelerating mode (11.4 GHz). The objective in this scheme, which is only possible with the detuning, is to couple each dipole mode to the manifold through that portion of the structure where the dipole mode has the same phase advance per cell as the propagating mode in the manifold at that frequency. The manifold dimensions are varied along the structure to better tailor the coupling with the design goal of lowering the mode Q's from about 6500 to 1000.

The theory used to model the structure for this design is quite complex [3]. Basically, it is an extension of the two-band equivalent circuit model that has been used to model the detuned structure [4] with the addition of an equivalent circuit to represent the manifolds and their couplings to the cells. The inputs to this model are nine parameters per cell that were interpolated from MAFIA analyses of equivalent periodic structures made from 11 representative cells. The dimensions of the 206 cells were chosen to produce a truncated Gaussian distribution ($\pm 2\,\sigma$ where $\sigma = 2.5\%$) of the synchronous mode frequencies of the equivalent

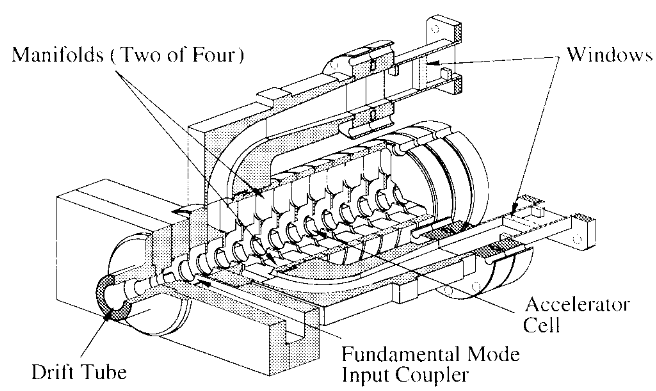

FIG. 1. Cutaway view showing two of the four manifolds and their output ports at the upstream end of the DDS.

periodic structures, the same as was done for the detuned-only structure. And as before, this included the constraint of a $2\pi/3$ phase advance per cell for the 11.4 GHz fundamental mode.

Designing the manifold connection to the structure exterior was a difficult task as well. One wants a good match over the 14 to 16 GHz range so that power is not reflected back into the manifolds where it can couple back into the cells. This is mainly important for the downstream couplers where nearly all the manifold power propagates. Here the best match achieved for the bends corresponds to a reflection coefficient that is less than 0.1 above 15 GHz but increases below 15 GHz to 0.8 by 14 GHz. The vacuum windows, which were added so the manifold signals could be measured, unfortunately worsened the reflection coefficient above 15 GHz, increasing it to 0.4 by 16 GHz. Because of time constraints, these windows could not be improved before the wakefield tests. However, the net match of the manifolds was well measured and included in the wakefield modeling.

To test the agreement with theory, the DDS was installed in the Accelerator Structure SETup (ASSET) facility which is located in the upstream end of the main SLC linac. This facility, which is illustrated in Fig. 2, uses the SLC bunches to 'drive' and 'witness' structure wakefields. During the test, the 1.8 m long DDS was maintained at its design operating temperature of 45 °C. The 8 manifold outputs were connected via 20 dB cross-guide couplers to 17 m long Heliax cables which ran to the Klystron Gallery above the linac tunnel. Here the signals could be measured with a spectrum analyzer. The fundamental mode input and output couplers were also terminated, either through similar cable connections or a matched load.

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 DDS and was then steered into a dump. The magnet used for this purpose is also the first bend of a chicane which 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 ($\equiv$ t) and injected on-axis into the linac via the North-Ring-To-Linac (NRTL) transport line. In traversing the DDS, 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 transverse wakefield was determined by measuring the change in the witness bunch deflection per unit change in the drive bunch offset in the structure. The measurement process was optimized for the vertical plane, and unless

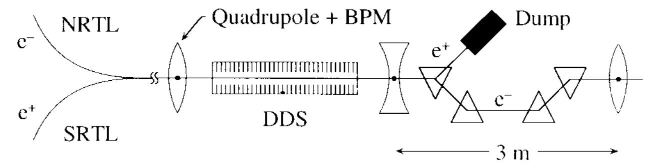

FIG. 2. Layout of ASSET in the SLC.

noted otherwise, we will consider only these measurements. To formulate the measurement approach, let Δy_d denote the change in the trajectory of the drive bunch in the structure, parallel to its axis. The resulting change to the witness bunch angular trajectory, $\Delta\theta_y$, due to the dipole modes is

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

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 frequency dependent factor that accounts for the averaging of the drive and witness bunch wakefield interaction over the longitudinal distribution of the particles in the bunches. For our tests, the NRTL and SRTL bunch compressors were adjusted to produce the minimum possible bunch lengths, which measurements indicate are about 550 μm rms [5]. Assuming this value and Gaussian bunch profiles, $f_s = .97$ for the 15.1 GHz mean frequency of the lowest dipole band.

The witness bunch deflections, $\Delta\theta_y$, 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 19 BPMs in the NRTL. The transport matrix elements needed to do the fits were computed from oscillation data generated by changing the strength of two dipole corrector magnets near the beginning of the NRTL. Also, the BPM resolutions were computed from goodness-of-fit analyses of BPM data taken during nominal beam operation. Four-pulse averaging was used to improve the resolution, which was about 5 μm in the linac and 17 μm in the NRTL.

The positron intensity was measured with a toroid in the SRTL that has about a 1% percent absolute accuracy. The toroid data were recorded on the same pulses as the BPM measurements and averaged in the same manner. Over the course of the run, the positron intensity, which is generally hard to keep stable, varied in the range of 2×10^{10} to 3×10^{10}. The electron bunch intensity, however, was fairly stable at about 1.6×10^{10}. The transverse widths of both bunches were $\approx$ 100 μm rms, much smaller than the $\approx$ 10 mm structure iris diameters.

To measure the temporal dependence of the wakefield, control of the relative bunch timing was required. Three methods were used, each of which provided a different level of control. The coarsest level was the 8.4 ns clock period of the SLC timing system. By programmed changes to all pulsed systems affecting the witness bunch, its timing could be shifted in multiples of this period. A finer level of control was achieved by unlocking the South Damping Ring phase feedback loop for short periods of time so the positrons would 'slip' by multiples of the 1.4 ns ring rf period. An oscilloscope display of the electron and positron signals from a linac BPM was used to verify the relative bunch timing at this level.

Finally, the South Damping Ring rf phase control that synchronizes the positron bunch, while stored, to the linac rf phase, was used to achieve continuous time changes in the range of one S-band period (350 ps). This phase locking system, which is used for electrons as well, is stable pulse-to-pulse at the sub-picosecond level as evidenced by the SLC longitudinal interaction point stability during colliding beam operation. This control was calibrated by moving it in steps and measuring the relative phase shift of the 4.1 GHz components of the electron and positron signals from a linac BPM.

The wakefield measurements were made over a two day period in which the relative bunch timing was stepped in 8.4 ns multiples from 0 to 150.1 ns, and by 1.4 ns multiples in regions of interest. At each setting, the continuous bunch timing control was used to locally map $W_\perp(t)$ at 31 points in a ±90 ps range. For each of these 31 measurements, the drive beam was moved transversely relative to the structure in 2 mm increments from −2 mm to 2 mm using dipole corrector magnets in the SRTL that were calibrated against the two BPMs nearest to the structure. The measured deflections, $\Delta\theta_y$ and intensities, I_d, were then used in a straight-line fit based on the above equations to extract $W_\perp$. For this result to be accepted, the data had to pass cuts based on the goodness of the fit and on the excursions of the bunch intensities and the NRTL electron orbit during the three measurements. We note that in this measurement procedure one makes no assumption about the absolute alignment of beam in the DDS. However, one does assume that the higher moment wakes, such as quadrupole, are relatively small as expected theoretically and confirmed by separate analyses of these and other data.

Figure 3 shows two examples of the local wakefield mapping, one near the bunch crossing (t = 0), and one where the bunches were about 118 ns apart. The solid line in Fig. 3a is a fit to the data. The fit function is a prediction for the short-range wakefield of a point charge that was obtained by summing the synchronous mode contributions from a periodic structure with an iris radius equal to that of the middle cell in the DDS [6]. Here the damping and detuning are ignored since their effect is small on this time scale. The fit allows for a scale factor, which has been applied to the prediction, and for a relative time shift, which has been applied to the data. Also, the prediction was smeared assuming longitudinal Gaussian bunch profiles with sigmas equal to 470 µm, a value obtained from a fit to just the $t < 10$ ps data in which the bunch length was allowed to vary as well. This result, which has error of 50 µm, is consistent with the value of 550 µm expected from SLC bunch length measurements. However, the resulting scale factor of 85% is not consistent with unity. We do not yet understand the cause of this disagreement.

Figure 3b is typical of the measurements at later times in that there are no apparent contributions from higher frequency dipole bands (one exception occurs at 25.2 ns where the data show a 25 GHz oscillation which likely originates from modes in the third dipole band [7]). The solid line in the figure is a fit to the data of a sine function with a 15.1 GHz frequency, the mean value for the first dipole band. In some data sets, one sees a variation of the oscillation amplitude which can be as large as 50% over a few periods. This beating effect is an expected result of the mode detuning.

From the oscillation fit, which averages over any beating, a wakefield amplitude, $|W_\perp|$, was obtained for each local mapping. At most time settings, at least two

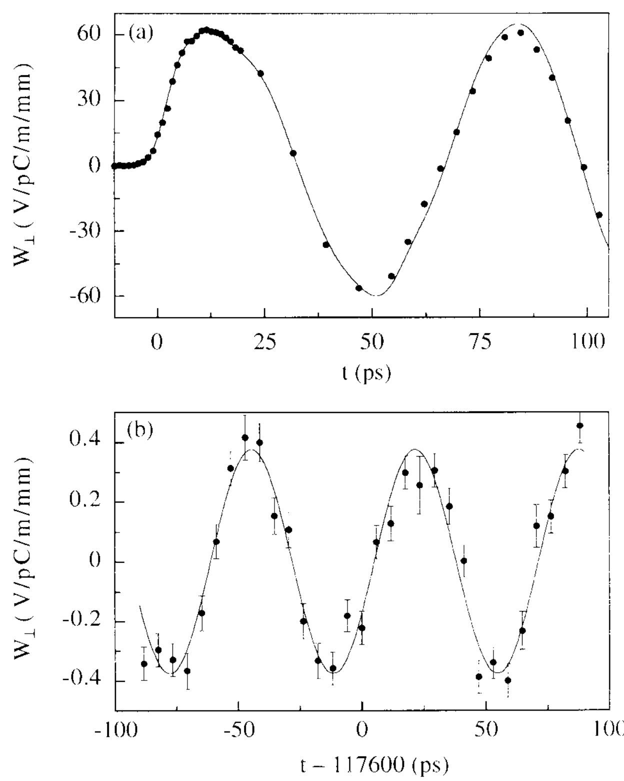

FIG. 3. Dipole wakefield measured (a) near the bunch crossing and (b) at a bunch separation of about 118 ns. The measurement errors in (a) are less than the size of the data point plot symbols. The solid lines are described in the text.

measurements were made of the vertical amplitude and one of the horizontal. The averaged vertical results are shown in Fig. 4 together with the prediction from the model described earlier. One sees that the data agree reasonably well with the theory although the recoherence point around 120 ns is about 10% later than predicted. The horizontal results shows a similar agreement and in most cases are consistent with the vertical results within the measurement errors. These data are expected to be similar since the structure is x-y symmetric except for the fundamental mode input and output couplers which should not greatly affect the dipole modes.

The beam induced manifold signals provide an additional probe of the wakefield and were processed to obtain information on the structure alignment as well [8]. Here we examine just the spectrum and compare it to the prediction from the same model that was used to compute the wakefield. This is shown in Fig. 5 for data taken with the electron beam 1.3 mm off-axis in the structure. The prediction has been scaled to match the data and corrected to simulate the sampling characteristics of the spectrum analyzer. One sees that the general shape of the spectra agree but not the details. In particular, the mode spacing near the center of the band, which is inversely proportional to the recoherence period, is about 10% smaller than predicted and thus consistent with the wakefield result.

In summary, the DDS transverse wakefield measured in the ASSET facility is in reasonable agreement with predictions. The addition of the damping has improved the long-range wakefield suppression by about a factor of four relative to detuning only. Improvements to the manifold matching should yield at least an additional factor of two suppression, making the structure suitable for use in an NLC-like linac.

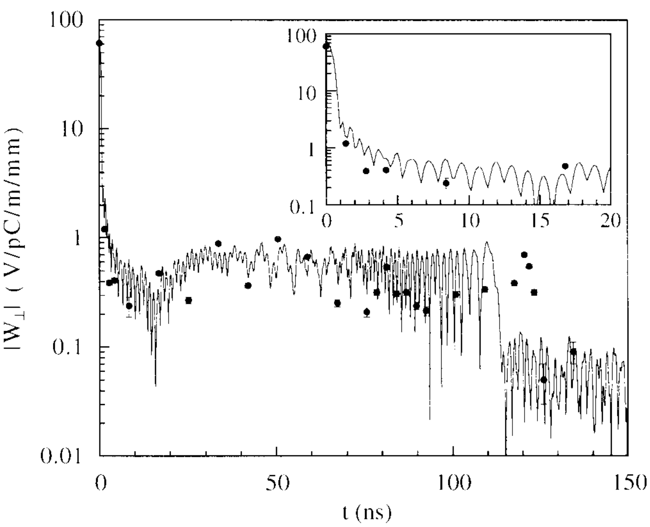

FIG. 4. Vertical wakefield amplitude measurements (data points) and prediction (solid line). The insert shows an expanded view of the first 20 ns.

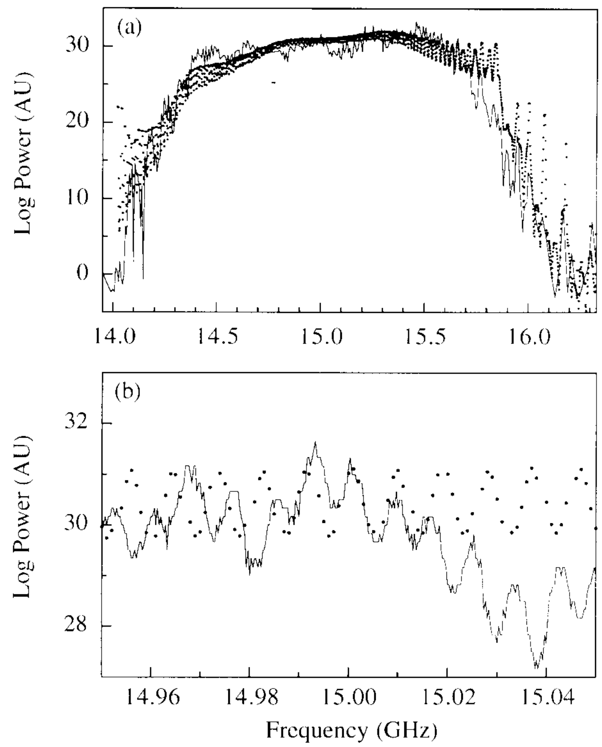

FIG. 5. Measured (solid line) and predicted (dots) signal power spectrum from a downstream manifold port (a) over the width of the dipole band (b) and near the center of the band.

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