*DIRECT MEASUREMENT OF TRANSVERSE WAKEFIELDS IN THE SLC LINAC**

P. Krejcik, R. Assmann, F.J. Decker, S. Hartman, R. Miller, T. Raubenheimer,
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309 USA

The transverse wakefields that generate tails in the beam distribution of an off-axis bunch can be viewed as resonant dipole modes in the structure. These same dipole modes were responsible for beam break up of long bunch trains during the early operation of the SLAC linac. This paper describes the excitation of these modes by the single, high-intensity bunches used in SLC operation. Both time and frequency domain measurements were made of the beam induced signals to identify the dipole modes. The amplitude of the measured dipole mode signal is found to be proportional to the bunch's offset in the structure. The utility of this technique for obtaining alignment information of the linac structure is discussed for both the SLC and future linear colliders.

I. INTRODUCTION

The largest contribution to emittance growth at the SLC comes from the transverse wakefields generated when a bunch is off-axis in misaligned accelerating structures. The head of the bunch generates fields which deflect the tail of the bunch and even the following bunches. In frequency domain these deflecting fields can be recognized as higher-order modes excited in the structure. These dipole-mode signals are readily discernible, occurring at a different frequency from the fundamental mode in the structure. This paper covers the techniques used to detect the dipole modes generated by the single bunch SLC beams, and shows that the signals are linearly related to the beam position within the structure.

The presence of dipole modes is well known in the history of SLAC as they were responsible for the beam break-up intensity limit during the early days of long bunch train operation of the linac [1]. The beam break up phenomena is a resonant process whereby the transverse oscillation of the leading bunches amplify along the bunch train as a result of the dipole mode excitation. Structure measurements and calculations of the first-order dipole modes are detailed in ref. [1].

At the SLC our interest has been in directly observing the wakefields responsible for emittance growth and to test whether practical information can be inferred about the alignment of individual accelerating sections. The dipole modes generated in the structure provide a sensitive structure beam position monitor (BPM), compared to normal linac BPM's that typically measure beam position with respect to the center of a discrete quadrupole.

II. ACCELERATOR LAYOUT AND SIGNAL ACQUISITION

It is of interest to observe the signal from both the output end of the structure and from the input end since the dipole modes propagate backwards and can be trapped within a few cells from the end of the structure. The SLAC structure, shown in fig. 1, has a 20 dB coupler attached to one of the four RF loads attached to the ends of the four 10′ accelerating sections driven by one klystron. The signal from the coupler is transmitted via coaxial cable to a phasing station above ground where it was originally used as part of the klystron phasing system. The signals from these cables allow us to sample one in every four of the individual structures at their output end. There are no individual signal couplers on the input couplers to the accelerating sections so we can only observe these signals as they propagate back towards the klystron where the waveguides from four accelerating structures combine. A convenient signal coupler is located on the SLED cavity

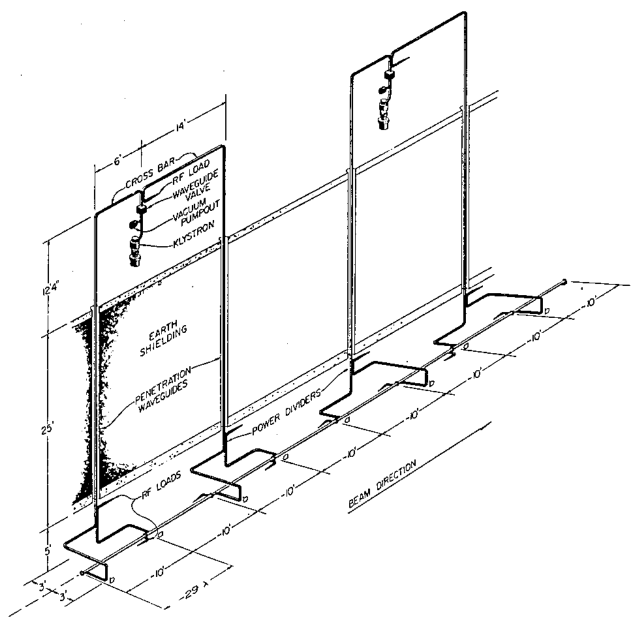

Figure 1: Layout of the accelerator and klystrons (reproduced from ref. 1). Signals were taken from the output load shown at the end of each 10′ accelerator section, and from a coupler on the SLED cavity (not visible) located above each klystron.

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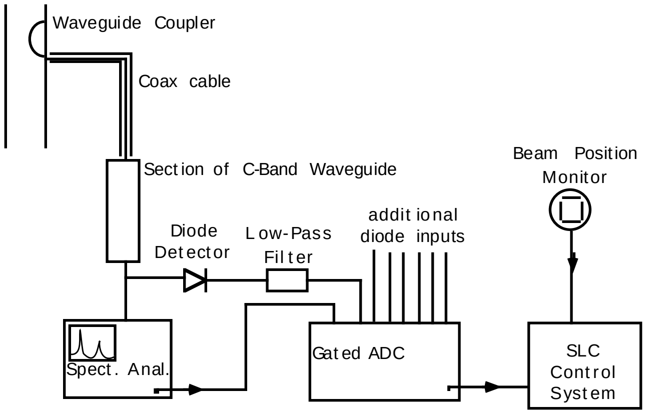

Figure 2: Layout of the instrumentation used for sampling the beam-generated modes in the structure.

(not shown in detail in the figure) which is mounted above the klystron shown in fig. 1.

The signal from the couplers is dominated by the fundamental mode at 2856 MHz. A short section of C-band waveguide, shown in fig. 2, effectively cuts off all of the signal at the fundamental mode giving us good signal to noise ratio for the higher-order modes of interest. As shown in fig. 2, this high-pass filtered signal can be diode-detected immediately and further filtered [2], or it can be analyzed with a spectrum analyzer. The mode spectra can be recorded or the spectrum analyzer can be operated as a narrow band receiver to look at the time and amplitude response of a specific line in the spectrum. In the latter mode the video output of the spectrum analyzer is sampled by a gated ADC (GADC) so that the signal amplitude may be correlated with a BPM signal via the SLC control system. The diode-detected signal is low-pass filtered and

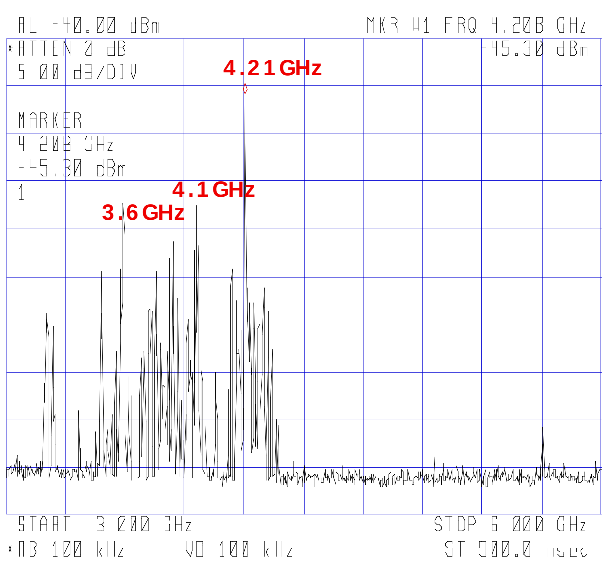

Figure 3: Beam-induced mode spectrum observed from the input couplers, measured from 3 to 6 GHz.

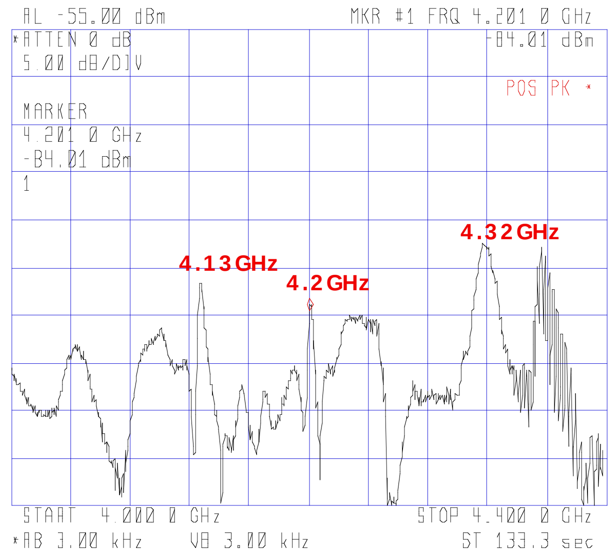

Figure 4: Beam-induced mode spectrum observed from the output couplers, measured from 4 to 4.4 GHz.

also sampled by the GADC for similar correlation measurements. Although this signal is not as selectively filtered as the spectrum analyzer output, it does have the advantage of requiring much simpler instrumentation which can be duplicated to analyze the signals from several sections of waveguide at once.

III. RF MODES GENERATED BY THE BEAM

The spectra of modes induced by a single bunch of $8x10^9$ electrons are shown in fig. 3 for the input coupler in the range 3 to 6 GHz and in fig. 4 for the output coupler in the range 4 to 4.4 GHz. The general features common to both spectra are the large number of frequency lines clustered around 4.1 GHz where the dipole modes are expected.

IV. DIPOLE MODE RESPONSE TO BEAM POSITION

The results of the correlation measurement between the horizontal beam position, as measured on an adjacent BPM, and the amplitude of the mode at 4.21 GHz, measured at the input coupler, is shown in fig. 5. The beam was moved with respect to the structure by steering local bumps into the orbit. A linear response is observed and the resolution of the signal is of the order of 20 microns. The standard linac BPM against which the signal is calibrated does not have a resolution much beyond this, so we can not expect to observe a greater resolution in the present experiment. The correlation experiments were repeated at several different mode frequencies at both the input and output couplers for both horizontal and vertical beam motion and are summarized in table 1.

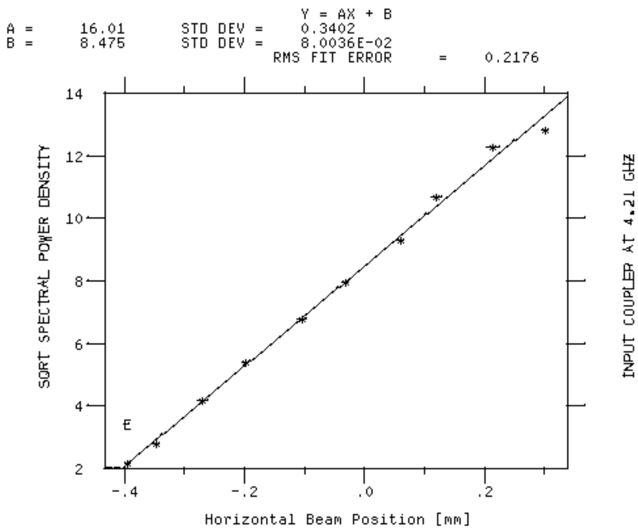

Figure 5: Structure BPM linearity measured at 4.21 GHz at the input coupler.

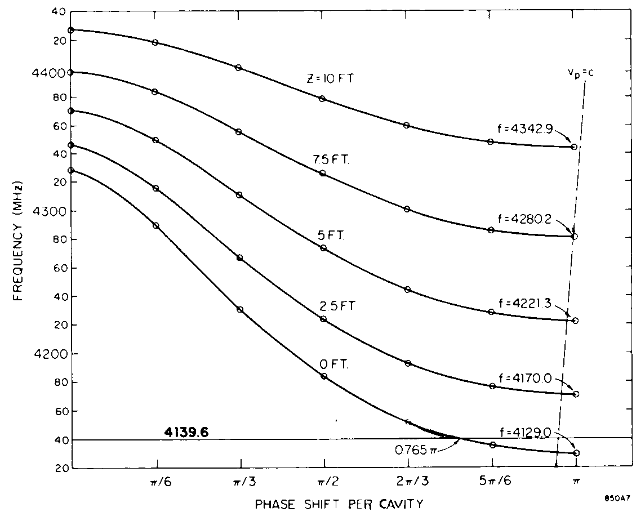

Figure 6: Dispersion diagram for dipole modes in the SLAC structure (reproduced from ref. 1).

The strongest correlations occurred at frequencies with the largest amplitude in figs 3 and 4. The frequencies at which the horizontal correlation was greatest were also those showing the strongest vertical correlation. The vertical signals were much smaller than those generated by horizontal offsets in the beam position. However, if the dipole mode signal was first nulled by appropriate horizontal steering of the beam it was then possible to clearly resolve the correlation to vertical motion of the beam.

Table 1: Measured correlation of mode with beam position.

input coupler	X Correlation	Y Correlation
4.1396 GHz	none	none
4.169	weak	none
4.2105	strong	weak
4.2931	weak	none
8.42	none	none
8.6	none	none
output coupler		
4.1037	strong	none
4.1279	strong	none
4.22525	not measured.	none
4.31463	not measured	none
4.3563	not measured	none

V. COMPARISON TO EXPECTED MODES

The SLAC structure is designed for a constant gradient, so the cells are not exactly periodic. From the dispersion diagram for the dipole modes given in ref. [1], and reproduced in fig. 6, we can see that the dominant 4.21 GHz signal is originating about 4′ in from the end of the structure. The solutions found for these dipole modes are for backwards propagating waves. Some of the modes are trapped implying that some of the energy is reflected in the forward direction again, which accounts for their presence at the output coupler.

The horizontal and vertical dipole modes are very close in frequency, as one would expect in an axially symmetric structure, where the only asymmetry comes from the couplers. The couplers are horizontally polarizing and so incapable of transmitting vertical modes. The fact that we still obtain a correlation between the observed dipole mode signal and the vertical beam position indicates that the vertical modes couples some of their energy to the horizontal modes within the structure. The observed strength of the horizontal mode therefore has contributions from both the horizontal and vertical beam offset. This means that if we try and use the signals as a structure BPM it is important to realize that the horizontal and vertical are not orthogonal.

VII CONCLUSION

The structure BPM data is helping us learn to improve the linac alignment and reduce SLC emittances [2]. We have been limited to using existing couplers in the linac to avoid interfering with the ongoing physics program. Future linear colliders, with tighter alignment tolerances, will invariably incorporate structure BPM's, but more efficient higher-order mode couplers can be incorporated in their design.. Never-the-less, these experiments are a significant validation of the technique for future linear collider design.

VIII ACKNOWLEDGMENTS

We gratefully acknowledge Harry Hoag and Marc Ross are for sharing their knowledge and experience of the SLAC linac.

IX. REFERENCES

[1] The Stanford Two-Mile Accelerator, ed. R.B. Neal, 1968 W.A. Benjamin, Inc., N.Y.

[1] D. Whittum et al, to be published.