BEAM PIPE HEM11 PROBES FOR TRAVELING WAVE LINAC SECTION*

A. M. Vetter, J. L. Adamski, and W. J. Gallagher

Boeing Aerospace Company
P.O. Box 3999
Seattle, Washington 98124

Abstract

The HEM11 modes responsible for beam breakup [1,2] instabilities in electron linacs are generally standing wave excitations even in traveling wave linac structures. In constant gradient structures, moreover, the modes which couple most strongly with the beam tend to be concentrated in the upstream end of the section[1]. If the upstream beam pipe of the section is made appropriately large, these dipole modes can be coupled out without coupling appreciable accelerator mode power. We describe such an arrangement, in which we incorporate antenna probes to enhance the loading of the dipole modes and enable observation of higher order modes (HOMs) excited by the beam.

Introduction

Average beam current in electron linacs is limited by the beam breakup instability which results from interaction between the beam and the HEM11 (dipole) modes of the accelerator structure. In single pass accelerators, this interaction gives rise to two types of instability, regenerative and cumulative.

The regenerative instability occurs within the confines of a single linac section. In the steady-state limit, it can easily be shown that there is a threshold or "starting" beam current I_S above which the instability grows until limited by beam loss, and that this starting current is inversely proportional to the loaded quality factor Q_L of the HEM11 mode[2]; i.e.,

$$I_S Q_L = K \qquad (1)$$

where K is determined by other system parameters including the details of the accelerator structure geometry and the beam energy profile in the section.

The cumulative instability involves the action of many accelerator sections, each of which slightly amplifies the transverse modulation of the beam at the HEM11 frequency. The increase of beam displacement amplitude with position along the accelerator is generally characterized by an e-folding factor which depends on the product of beam current and quality factor of the HEM11 mode[1] (as long as the HEM11 resonant frequencies of different sections differ by amounts small compared to the bandwidth). Therefore, for a given acceptable total gain in the displacement amplitude, the product of allowed beam current and loaded quality factor is fixed and eqn. (1) above describes cumulative as well as regenerative beam breakup.

When this inverse proportionality between limiting beam current and Q_L holds, reducing Q_L for the HEM11 mode will result in a corresponding improvement in starting current, independent of whatever other measures are taken to raise it (through increasing K in eqn. (1)).

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Characteristics of the HEM11 Mode

Even in traveling wave structures, the HEM11 excitation is generally a standing wave because the structure terminations are matched only for the accelerator (TM01) mode. Traveling wave accelerator structures are generally of the constant gradient type characterized by a programmed taper of the beam hole. This taper is again determined by TM01 mode considerations, and typically has drastic effects on the HEM11 band. Often the two or three lowest frequency (highest phase shift/cell) HEM11 modes will be below the low edge of the band for the downstream end of the structure where the cell-to-cell coupling is low, and the excitation profile of these modes will be weighted towards the upstream cells of the structure[2].

It is important to keep in mind that the dipole excitations of the structure exist in two orthogonal polarizations, and that both of these must be successfully loaded in order to improve the starting current. The input and output couplers of a traveling wave accelerator structure are generally coplanar and probably constitute the dominant departure from azimuthal symmetry. The dipole mode polarization axes will then be aligned with the coupler plane and the couplers will couple preferentially to one of the two polarizatons.

Techniques for Loading HEM11 Mode

The general problem in HOM loading is to couple effectively to the HOM without coupling much power from the accelerator mode. In standing wave accelerating structures, this may be done by placing loop coupling probes in cells which are unexcited by the accelerator mode[3]. Another technique employs coupling loops in excited cells, but the loops are fitted with band stop filters[3] which do not pass power at the accelerator mode frequency.

An alternative loading technique, which does not require placing probes in the accelerator structure proper, allows the higher order mode to propagate down the beam pipe to a load external to the structure. The beam pipe is sized to be above cutoff for all but the accelerator mode. The cutoff frequencies for the TM01 and TE11 modes of a circular waveguide are given by

$$f_c(\mathrm{TM01}) = \frac{0.383}{a\ c} \qquad (2)$$

and

$$f_c(\mathrm{TE11}) = \frac{0.293}{a\ c} \qquad (3)$$

where a is the radius of the waveguide and c is the velocity of light. Evidently, dipole excitation can propagate down the beam pipe at even lower frequency than monopole excitation, yet the lowest frequency HEM11 modes of the accelerator structure are typically at half again the accelerator mode frequency.

This suggests that there should be an appropriate beam pipe size which is well below cutoff for

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the accelerator mode, yet well above cutoff for the HEM11 mode. One might forsee some problem in arranging for the HEM11 mode, which is generally thought of as resembling the TM110 mode of a pillbox cavity, to couple to a TE-type excitation of the beam pipe. However, the hybridization due to the beam apertures allows this coupling to occur.

Beam Pipe Loading of HEM11 Modes in the Boeing Linac

Our particular accelerator structure is a 35-cell, 3-meter, constant gradient, traveling wave structure which operates at 1.3 GHz, with a cell-to-cell phase shift of $3\pi/4$. The cells of this structure have a rounded contour, nose cones, and relatively large beam apertures (tapering from roughly 2.5 in to 2.0 in). Beam excitation studies on an S-band scale model of this structure were reported at a previous conference[4]. Bench tests on the S-band model, which was equipped with coupling loops in each cell, show the characteristic front end concentration of the lowest frequency dipole modes.

Our dipole mode loading method employs an oversize beam pipe on the front end of the structure. This pipe is a 4-in O.D. by 1/16-in wall stainless steel tube which flanges to a multi-ported vacuum chamber built of similar sized tube, as shown in figure 1. The vacuum chamber connects to a cryopump and contains sundry vacuum gauges, viewscreens, a viewport, and ports for four electric probes which couple to RF fields propagating through the tube. Application of eqns. 2 and 3 give cutoff frequencies of 2.34 GHz and 1.79 GHz for the TM01 and TE11 modes respectively, taking the 1/16-in wall thickness of the chamber into account (inside diameter is 9.83 cm). The tube is therefore above cutoff for the HEM11 mode, but below cutoff for the accelerator mode, whose strength falls off at a rate of 3.5 dB/cm as one moves down the beam pipe away from the structure.

Experimental Technique

The four electric probes in the 4-in vacuum chamber are numbered 1 through 4, with even numbered probes on the top and bottom, and odd numbered probes on the sides. The top and bottom probes couple effectively to one of the two polarizations of the HEM-11 mode, while the left and right probes couple to the other. The main input coupler on the side of the first cell of the structure couples strongly to the left-right polarization and weakly to the up-down polarization.

Stimulus-response measurements were made by driving the structure with a leveled signal from a Hewlett Packard Model 8341A synthesized sweep generator applied to one of the electric probes or to a small loop placed in the main input coupler waveguide, while analyzing the signal present in one of the other probes with a Hewlett Packard Model 71200A modular RF spectrum analyzer. This spectrum analyzer is equipped with digital storage and a maximum hold function which retains the highest response seen in each frequency bin. The spectrum analyzer display was copied using a Hewlett Packard Model 7475A digital plotter connected directly to the spectrum analyzer.

Figure 2 shows the response of the system when a 0-dBm signal was injected at the main coupler and the spectrum analyzer was connected to one of the side electric probes (no. 3). The signal generator swept slowly over the 200-MHz frequency span, requiring 100 s to complete the sweep, while the spectrum analyzer swept rapidly (50 ms sweep time) over the same span. At a typical point during the measurement, the spectrum analyzer display was as shown in the bottom trace in figure 2. The width of the response was determined by the 300-kHz resolution bandwidth of the spectrum analyzer, the injected signal being very narrow in frequency. The upper trace in figure 2 shows the maximum signal retained during previous sweeps of the signal generator.

Observations

Figure 2 shows the spectrum of HEM11 modes in the polarization which couples more strongly to the main input coupler. An enlarged view of the band of HEM11 modes in this polarization can be seen in figure 3, where a 0-dBm signal was again injected at the main input coupler, and where the response spectra of probes no. 3 and no. 1 appear as the top and bottom traces. Although the probes themselves are practically identical, they yield somewhat different spectra, probably because of the departure from symmetry of the 4-in vacuum chamber introduced by the tee to the cryopump flange on the bottom of the chamber. As a general rule, however, the transmission loss for the stronger modes could be roughly set at 35 dB or so.

The corresponding spectra for the top and bottom probes are shown in figure 4. For these spectra, the input power was increased to +10 dBm. The transmission loss for the lower modes in the band was on the order of 50 dB, or 15 dB more than for the other polarization.

The loading of an HEM11 mode due to the lossy vacuum chamber can be calculated from the 3-dB bandwidths of the mode. We selected modes which coupled weakly to the main input coupler in order to avoid measuring loading due to the coupler. For example, the next to the lowest frequency peak in figure 4 is shown in figure 5, where the two diamond shaped markers are positioned 3 dB below the peak. The readout shows that they are about 140 kHz apart, indicating a loaded quality factor of Q_L = 1955/0.15 = 13000. In the S band model structure, the HEM11 modes all showed Q_L values of about 13000, which we can take to be approximately the Q_o of the mode in that structure (external coupling being very weak). Scaling to L-band, we expect the Q_o to rise in inverse proportion to the root of the frequency ratio

$$Q_o(\text{L-band}) = Q_o(\text{S-band})\sqrt{2856\ \text{MHz}/1300\ \text{MHz}}$$

$$= 21000$$

The reduction in Q_L from the unloaded value is therefore a factor of .62 for the measurement in figure 5.

Conclusions

From the simple observations reported above, it appears that the use of a large diameter beam pipe can appreciably reduce the Q_L of the unwanted dipole modes associated with the beam breakup instabilities. As no effort was expended in optimizing the interface between the coupler cell and the beam pipe for HEM11 coupling, we expect that substantial further improvement can be realized, for example by making the aperture between the beam pipe and the coupler cell somewhat larger than its present size.

The electric probes in the beam pipe will provide a very useful diagnostic indication of any beam-induced HEM11 modes during operation of the accelerator, as they show very good rejection of the 1300-MHz accelerator mode.

References

[1] R. H. Helm and G. A. Loew, "Beam Breakup," in Linear Accelerators, P. M. Lapostolle and A. L. Septier, eds.; North-Holland Publishing Company, Amsterdam, 1970.

[2] P. B. Wilson, HEPL-297, High Energy Physics Laboratory, Stanford University, 1963.

[3] K. Mittag, H. A. Schwettman, and H. D. Schwartz, IEEE Trans. Nucl. Sci., NS-20, p. 86, June 1973.

[4] A. M. Vetter, J. L. Adamski, and W. J. Gallagher, IEEE Trans. Nucl. Sci., NS-32, p. 2329, October 1985.

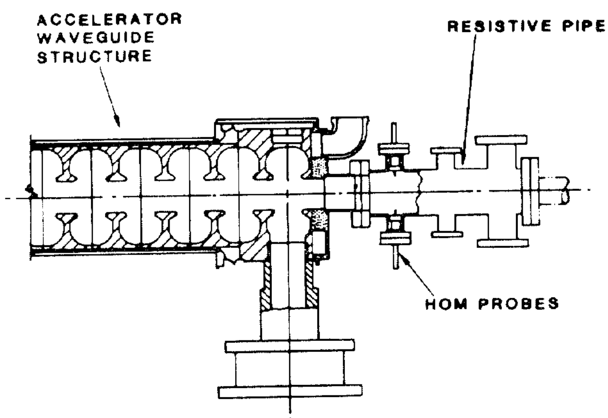

Fig. 1. Schematic of the Boeing contoured cell traveling wave accelerator structure and the large diameter vacuum chamber containing electric antenna probes.

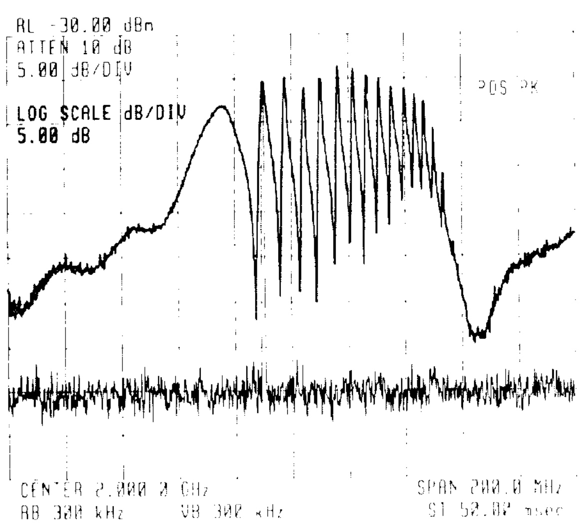

Fig. 2. HEM11 band observed with 1 mW signal injected at the main coupler and spectrum analyzer connected to electric probe no. 3.

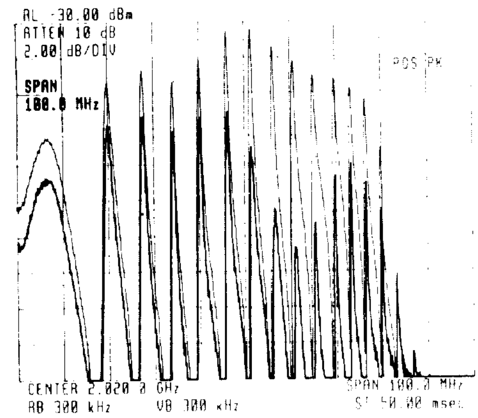

Fig. 3. Enlarged display of HEM11 band with 1 mW (0-dBm) signal injected at the main coupler and spectrum analyzer connected to electric probes no. 3 (top trace) and no. 1 (bottom trace).

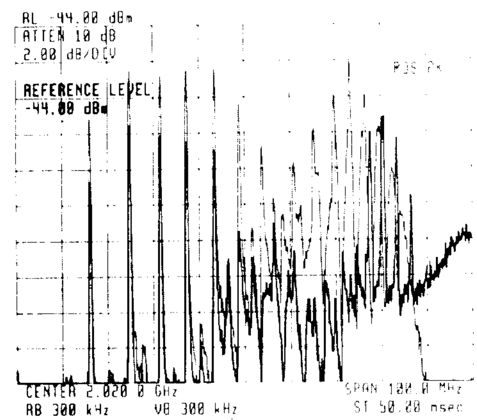

Fig. 4. Similar to Fig. 3, except input power is 10 mW and top trace shows signal in probe no. 2. bottom trace shows probe no. 4.

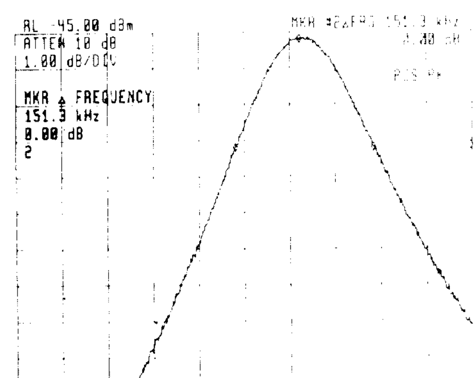

Fig. 5. High resolution display of HEM11 mode at 1995 MHz (next to left peak in Fig. 4), showing signal in probe 2 with probe 4 terminated.