MICROWAVE MEASUREMENTS OF ENERGY LOST TO LONGITUDINAL MODES BY SINGLE ELECTRON BUNCHES TRAVERSING PERIODIC STRUCTURES*

J. W. Wang,§ G. A. Loew, J. N. Weaver and P. B. Wilson
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

SUMMARY

In the design of future linear colliders, it will be important to minimize the loss of beam energy due to the excitation of higher-order modes in the accelerator structure by single bunches of electrons or positrons. This loss is not only detrimental in itself but also gives rise to energy spectrum widening and transverse emittance growth. This paper describes microwave measurements made on disk-loaded and alternating-spoke structures to determine the loss to the longitudinal modes. In these measurements the Gaussian bunch is simulated by a current pulse of the same shape transmitted through the structure on an axial center conductor. Results to date are presented for the total longitudinal loss parameter per period K in volts per picocoulomb.

INTRODUCTION

Future $e^{\pm}$ linear colliders, to become technically and economically feasible at energies of several hundred GeV, will require accelerating structures with a new set of properties. These properties together with the RF systems needed to power these structures have been described elsewhere.[1,2] The requirements are summarized below:

a) High accelerating field gradient E_a to minimize machine length. This implies structures with a low ratio of peak-to-accelerating electric field E_p/E_a to minimize the risk of electrical breakdown.

b) High ratio E_a^2/w where w is the energy stored in the structure per unit length. This ratio, which is equal to $\omega r/Q$ for the fundamental mode of the structure, is a measure of the efficiency with which the available microwave energy is used.

c) High group velocity v_g to reduce the filling time t_f, where $t_f = \ell/v_g$ for each section of length ℓ.

d) Low content of transverse and higher-order longitudinal modes that can be excited by single bunches traversing the structure. The longitudinal modes cause beam loading and energy spectrum widening while the transverse modes cause emittance growth.

Except for electrical breakdown, these properties can be calculated for simple structures with cylindrical symmetry such as the disk-loaded waveguide. Properties (a), (b) and (c) traditionally are also measured by microwave bench tests. The longitudinal and transverse wake fields under (d) can be measured with an electron beam,[3,4] but these measurements require that a long length of accelerating structure already be available. Thus to test and select new structures, it is desirable to have a bench test in which the turn-around time is short and the cost is low. The work described in this paper used such a test to measure the longitudinal higher-order mode content of structures which may also be desirable with respect to the other above listed properties. A conceptual method to measure the transverse modes has also been proposed[5] but has not yet been tried experimentally at SLAC.

Experimental Method

When a single e^+ or e^- bunch of charge q traverses a structure on its axis, typically at the velocity of light, it deposits in the structure an energy per unit length $u = kq^2$. The total loss parameter k is summed over all the synchronous longitudinal modes and depends on the axial charge distribution in the bunch. If we assume a Gaussian bunch with standard deviation σ_z,

$$k = \sum_{n=0}^{\infty} k_n e^{-\left(\frac{\omega_n \sigma_z}{c}\right)^2} \qquad (1)$$

where k_n is given by $[\omega_n/4](r/Q)_n$ for each mode of frequency ω_n. The figure of merit of the structure is then designated by $B(\sigma_z) = k/k_o$, where a low value of B indicates a low content of higher-order modes which do not participate in the acceleration process and are thus parasitic.

The method used in this paper is that originally proposed by M. Sands and J. Rees[6] and which was used extensively for the optimization of PEP vacuum chamber components.[7,8] The electron bunch is simulated by a current pulse of the same shape transmitted on an axial wire stretched through the structure. The measurement layout is illustrated in Fig. 1.

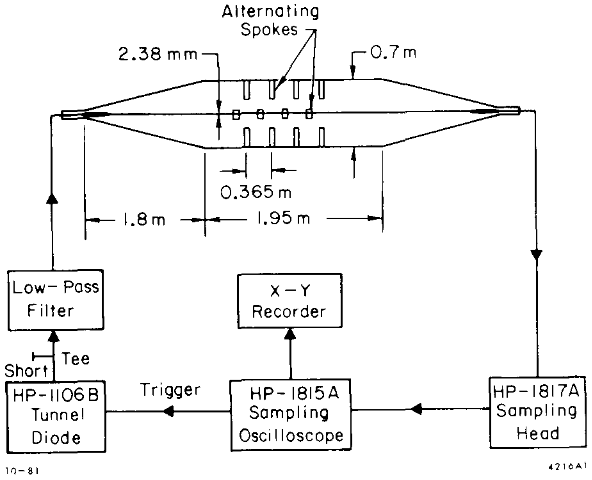

Fig. 1. Measurement layout

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§ On leave from Tsinghua University, Beijing, China

Conical tapers and extended cylinders are provided on each side of the test piece to connect it to 50Ω lines and to minimize the effect of internal reflections. The Gaussian pulse generator on the left consists of a tunnel diode step generator, a tee-junction with a shorted stub (available in several lengths) by means of which a short pulse of desired duration is produced. A low-pass filter is used to make the pulse Gaussian. On the right a sampling head and oscilloscope is connected to an X-Y recorder which plots the transmitted pulses. In order to minimize jitters and drifts, all active components are thermally stabilized by means of water cooling.

The measurement is made in two steps. In the first step, the test piece is simply a hollow pipe of inner diameter proportional to that of the accelerator structure (commonly called 2b, see Fig. 2). The current pulse transmitted through the system to the recorder is $i_o(t)$.

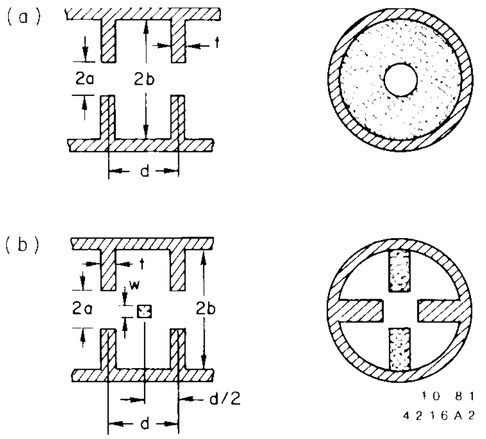

Fig. 2. a) Disk-loaded structure,
b) Alternating-spoke structure.

In the second step, the internal periodic elements of the structure are added one by one (the total length is kept constant), and the transmitted pulses $i_m(t)$, modified by the addition of each successive obstacle, are recorded. As shown in Refs. 6-8, the experimental value of k is obtained for each $i_m(t)$ from:

$$k = \frac{2Z_o}{q^2} \int [i_o(t) - i_m(t)] [\frac{i_o(t) + i_m(t)}{2}] \, dt \tag{2}$$

where

$$q = \frac{1}{2} \int [i_o(t) + i_m(t)] \, dt$$

and Z_o is the characteristic impedance of the pipe without periodic elements. The curves obtained from the X-Y recorder are digitized by means of a graphic-to-digital converter and the integration is performed by computer. For all structures measured here, it was found that the results converged in a satisfactory manner after 3 or 4 periods and an average k was obtained.

One of the most important features of these tests has to do with the σ_z of interest in future colliders. If one assumes an S-band structure like at SLAC (2856 MHz), then σ_z = 1 mm or 3.33 ps. Unfortunately, the best available step generator has a rise time with a lower limit of 20 ps, leading to a Gaussian pulse with a σ_z of at least 28 ps. For this reason, it was necessary to scale all the dimensions of the test piece from S-band by an enlargement factor S between 8 and 11. This resulted in a test cell with an I.D. of 70.8 cm and a periodic length of about 30 cm. Although somewhat cumbersome, the structure is not too costly to build from aluminum sheet and extruded parts. Referring to expression (1) and rewriting it for the loss per period K, we obtain

$$K = \sum_{n=o}^{\infty} \frac{\omega_n}{4} \left(\frac{R}{Q}\right)_n e^{-\left(\frac{\omega_n \sigma_z}{c}\right)^2} \tag{3}$$

where $(R/Q)_n$ does not change if we scale our structure in all dimensions. If then we choose to scale σ_z inversely with ω_n so as to keep $\omega_n\sigma_z$ constant, the measured K scales directly with frequency and is simply lower than the K of interest by the factor S.

In addition to this scaling problem, it is necessary to correct all the obtained i(t) waveshapes to account for the finite rise time t_r of the sampling head and oscilloscope (t_r = 38 ps). This is done by correcting the measured σ_m by the expression $\sigma = (\sigma_m^2 - \sigma_r^2)^{1/2}$ where $\sigma_r = 0.39\, t_r$.

Measurements and Results

Measurements were performed for two types of structures. The first was the disk-loaded waveguide (2π/3 mode) used at SLAC. This measurement was made for two (scaled) values of the dimension 2a (see Fig. 2a) corresponding to the 45th (average) cavity of the constant-gradient structure (2a = 2.325 cm) and the largest cavity (2a = 2.622 cm). The change in the corresponding 2b (8.265 cm to 8.346 cm or about 1%) was neglected. The measurement for each structure was made for four different values of σ_z as shown in Table I

Table I. Results of Measurements for Disk-Loaded Structures

σ_z(mm)		Scaled Loss per Period K(V/pC)		α
Measured	Scaled to 2856 MHz	2a=2.325 cm $v_g/c=0.0130$	2a=2.622 cm $v_g/c=0.0204$	($K \propto a^{-\alpha}$)
8.5	1.0	2.82	2.30	1.69
10.1	1.19	2.65	2.22	1.47
12.4	1.46	2.48	2.03	1.66
15.6	1.84	2.22	1.77	1.88

In each case, five data points were obtained for 1, 2, 3, 4, and 5 disks cumulatively added in succession, and an average K was recorded. The results are given in Table I and plotted in Fig. 3. It is interesting to note that the microwave measurement for the "average" (45th cavity) iris agrees very well with the single bunch measurement described in Ref. 3 when normalized to a Gaussian distribution with a σ_z = 1 mm. Both measurements give values of K that are ~35% higher than the theoretically calculated curve, also shown in Fig. 3. This discrepancy is identical

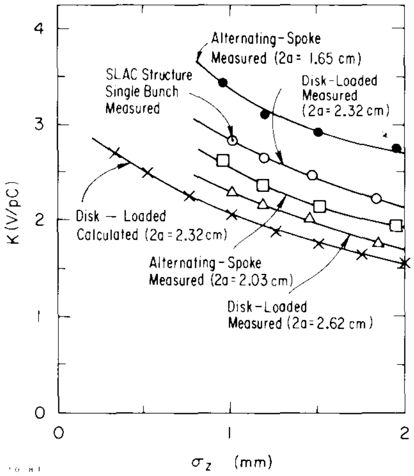

Fig. 3. Total loss parameter per period, as a function of σ_z, as obtained from computer calculations, SLAC linac beam loading measurements and bench tests normalized to 2856 MHz.

to that originally mentioned in Ref. 3. The resulting values of B with σ_z = 1 mm are 4.24 for 2a = 2.325 cm and 3.79 for 2a = 2.622 cm. In the last column of Table I, notice that the factor α, calculated for each σ_z, assumes that K varies as $a^{-\alpha}$. The average of all four values is α = 1.68, identical to the theoretically predicted value.[2] This result is reassuring because even if the microwave measurements should suffer from a systematic error, the relation between measure ments for different values of 2a seems to be consistent with theory.

The second set of measurements was made for the alternating-spoke structure shown in Fig. 2b. This structure, which is similar to the Jungle Gym, consists of a pair of radial bars which protrude into the circular guide, alternating by 90°. A complete period consists of two pairs of bars and is $\lambda_o/3$ in length ($2\pi/3$ mode): the phase shift from bar to adjacent bar is $\pi/3$. This structure was selected because of its openness, relatively high $(r/Q)_o$ [~4000 ohms/m at 2856 MHz] and high group velocity [v_g/c ~ 0.150]. The scaling parameter S was 10. The results are shown in Table II for two different values of 2a, as defined in Fig. 2b.

TABLE II. Results of Measurements for Alternating-Spoke Structure

σ_z(mm)		Scaled Loss per Period K(V/pC)	
Measured	Scaled to 2856 MHz	2a=1.651 cm	2a=2.032 cm
10.1	0.97	3.43	2.63
12.4	1.19	3.12	2.37
15.6	1.50	2.93	2.15
20.3	1.95	2.78	1.95

The results are also plotted in Fig. 3. It is seen that the lowest value of K is found for the example with 2a = 2.032 cm. Exact measurements for this structure have not yet been made at S-band but the structure seems promising. For σ_z = 1 mm and 2a = 2.032 cm, B = 3.83. In the scaled-up version, the spokes had a rectangular cross-section. Future tests will be done with cylindrical spokes which should be preferable from the point of view of electrical breakdown. A further improvement in K is expected for the π-mode, i.e., two pairs of spokes per half-wavelength. These measurements will be attempted in the near future.

CONCLUSION

The preliminary measurements presented here indicate that a microwave bench test on a scaled structure can predict, at least comparatively from structure to structure, the total energy lost per period to all the longitudinal modes by a Gaussian bunch of total charge q. Since the method requires only inexpensive models, it can be used to quickly check the design and help in the experimental selection of periodic structures for future linear colliders.

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