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SINGLE BUNCH BEAM LOADING ON THE SLAC THREE-KILOMETER ACCELERATOR*

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Summary

Since the report on single bunch beam loading experiments at SLAC at the 1975 Particle Accelerator Conference, it has been possible to obtain a much better understanding and agreement of theoretical and experimental results related to this problem. These improvements have been made possible by two developments: the generation of a "wake-field" function for the SLAC 3-km slow-wave structure and the use of this function to calculate single bunch energy spectra. The wake-field function which gives the time decay of the fields generated by the passage of a delta-function beam has been derived by summing all the TM cylindrically symmetrical modes of an equivalent accelerator cavity. By multiplying this wake-field function by a measured bunch density function and integrating along the bunch, it is possible to calculate the energy of each electron in the bunch. This in turn enables one to predict the energy spectrum for any given phase angle of the bunch with respect to the crest of the RF accelerating wave. Agreement between these calculations and experimental measurements is very good. The paper presents these results and discusses the possible sources of some of the remaining discrepancies.

Introduction

This paper is the third report on the subject of single bunch beam loading on the SLAC three-kilometer accelerator. The first series of experiments[1] was performed under less than ideal conditions and when the physical process was only poorly understood. The results showed that the energy lost by the bunch in the three-kilometer accelerator was proportional to bunch charge but independent of its energy in the range between 0.9 and 19 GeV. The second series of experiments[2] was done under significantly improved experimental conditions and with a much better understanding of the underlying mechanism. An empirical theory was developed which gave reasonable agreement with the measurements. The present paper uses much of the same experimental data but puts the theory on solid ground, based on the calculation of a wake-field function. To put this progression into focus, it is necessary to recapitulate briefly the nature of the experiment and the empirical theory.

Review of Experiment and Empirical Theory

Because of lack of space, the figure illustrating the experimental setup is not reproduced here and the reader is referred to Ref. 2. Many of the other experimental details and results can be found in Ref. 3. Briefly, a single electron bunch of adjustable charge is generated in the 35 MeV SLAC injector, accelerated to 4 GeV in the accelerator and momentum analyzed in the A-line of the beam switchyard (BSY). The single bunch is formed by the combination of two devices ahead of the 35 MeV injector. One is a grid pulser which limits the normal 1.6 μs gun pulse to approximately 7 ns. The other is a resonant system which uses transverse deflecting plates. The frequency of the system is 39.667 MHz, the 72nd subharmonic of the accelerator frequency, i.e., 2856 MHz. The voltage applied to the plates is high enough that the only bunches that reach the accelerator are the ones that pass through at zero crossing time, i.e., every 12.5 ns. The combination of the two devices working in concert generates single bunches. After these single bunches of about 5×10^8 electrons are formed, bunched and accelerated to 35 MeV, they are relativistic enough that their length (about 10 electrical degrees) and their charge distribution can no longer be affected substantially by subsequent accelerating fields. It is at this point that a "sieve" collimator is installed to control the charge of the transmitted bunch. The collimator is a slab with four "rest" positions, each consisting of an identical circular area punctured with a different set of holes. The greater the hole size and density, the greater the charge transmitted in the bunch. By choosing identical circular areas, one is certain to preserve overall beam shape. Since the beam is already "stiff", the relative charge distribution and phase remain undisturbed. The relative ratios of transmitted charge have been experimentally checked to be 0.08, 0.4, 0.7 and 1.

After the collimator, the beam is injected into the machine and accelerated to 4 GeV. This requires approximately 40 klystrons beyond which the beam is permitted to drift. The accelerator structure is entirely modular and repeats itself every 3 meters (~950 so-called constant-gradient sections with a total of ~81416 cavities). By superposition, it is assumed that the accelerating fields and the beam loading fields are set up independently. The phase θ_0 of the bunch with respect to the 4 gigavolt equivalent sinusoidal wave (see Fig. 1) can be adjusted by changing the phase of the injector klystron with respect to the other 40 klystrons treated as a block. In order to study the electron energy distribution in the bunch, the beam is momentum-analyzed in the A-line of the BSY and transmitted through a 0.1% slit. The momentum analysis is obtained by sweeping the energy of the beam by rotating the phase of a so-called vernier klystron of well-known energy by $\pm60^\circ$ around its zero-energy contribution phase. The experimental spectra (shown together with the theoretical spectra at the end of this paper) are obtained by recording energy in X (i.e., a potentiometer analog of the klystron phase) and current transmitted past the 0.1% slits through a fast beam pickup, in Y. The fast pickup output is actually fed into a sampling scope and the dc signal derived from the peak of the output is recorded. Beam charge transmission along the accelerator is measured by an array of 30 toroids and two additional fast-pickups. All RF triggers and scope signals are locked to the single-bunch timing by means of a synchronizer, as a result of which jitter is kept to a minimum.

Referring again to Fig. 1, in the absence of beam loading, i.e., small charge, the total energy of an electron is simply $E=E_0 \cos\theta$. Because of the finite slit width $\Delta E/E$,

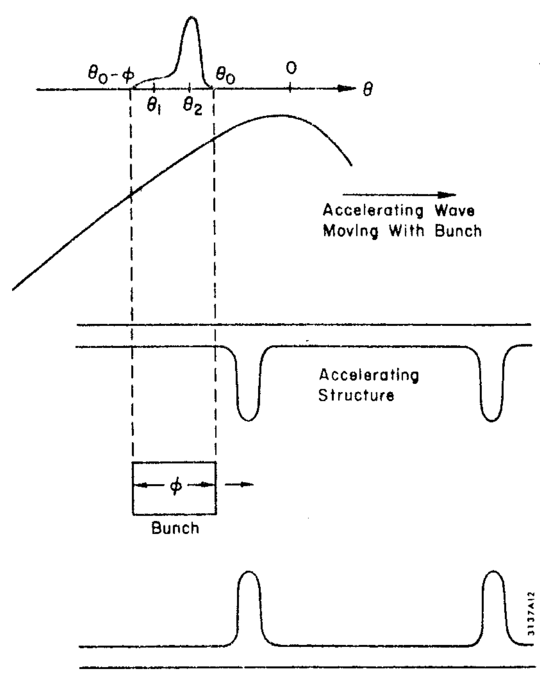

Fig. 1. Electron bunch moving along accelerator structure in synchronism with sinusoidal wave. Notice moving coordinate system along θ-axis.

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the transmitted electrons are located within an angular interval $\theta_2-\theta_1$ such that

$$E + \frac{\Delta E}{2} = E_0 \cos\theta_2 \quad \text{and} \quad E - \frac{\Delta E}{2} = E_0 \cos\theta_1 ,$$

where $\Delta E = 4$ MeV for $\Delta E/E = 0.1\%$ if one assumes a zero-diameter beam. For such a hypothetical beam, the charge transmitted through the slit is sharply cut off by both edges. Within the slit, it is proportional to the interval $(\theta_2-\theta_1)$ multiplied by a properly normalized axial bunch distribution function $f(\theta_0-\theta)$ which extends from θ_0 to $\theta_0-\phi$. Actually, because of the finite beam diameter (~3 mm) at the slit (6 mm), the charge transmitted is also multiplied by a slit function derived for a circular beam going through a straight-edge slit. This slit function has the effect of widening the momentum acceptance to 0.15% and smoothing the edges. In the presence of beam loading, the above energy equations become:

$$E + \frac{\Delta E}{2} = E_0 \cos\theta_2 + \frac{\alpha\beta}{\phi}\int_{\theta_0}^{\theta_2} f(\theta_0-\theta)\, G(\theta-\theta_2)\, d\theta$$

and (1)

$$E - \frac{\Delta E}{2} = E_0 \cos\theta_1 + \frac{\alpha\beta}{\phi}\int_{\theta_0}^{\theta_1} f(\theta_0-\theta)\, G(\theta-\theta_1)\, d\theta$$

where α is a factor proportional to bunch charge (0.08, 0.4, 0.7, 1), ϕ is the total bunch length, β is a proportionality factor and $G(\theta-\theta_{2,1})$ is the wake-field function. In Ref. 2, before any theoretically derived function was available, a half-Gaussian was arbitrarily assumed. It gave somewhat less than adequate agreement with experimental results but it was no more than an educated guess.

Wake-Field Function

Parallel work that was being done at the time for the study of beam loading in storage ring cavities and vacuum envelopes led to the idea that the wake field might be calculable from a modal analysis. The wake-field function is the energy loss as a function of time resulting from and following a unit delta-function charge impulse which transits the structure. It was computed by a method described in detail in Ref. 4 by summing the first 416 circularly symmetric synchronous modes in a periodic structure composed of 81416 identical cavities. Higher frequency modes were added by using an analytic function based on an optical resonator model of the structure. Even though each of the ~950 constant-gradient sections is made of 86 different size cavities, the computation was done by assuming an average disk-loaded cavity with 1.162 cm beam hole radius, 4.133 cm cavity radius, 2.916 cm gap length and 3.500 cm periodic length. Figure 2 gives the resulting wake-field function for 5×10^8 electrons as a function of time expressed in phase degrees at 2856 MHz.

Results and Conclusions

Experimental spectra were obtained for eight different values of θ_0 between -3° and $+10^\circ$, each for four values of α (a total of 32 cases). The maximum obtainable charge was 5×10^8 electron/bunch. The bunch shape, also shown in Fig. 2, was obtained by first calculating the predicted spectra for a bunch of uniform charge distribution at negligible beam loading ($\alpha = 0.08$) and various θ_0's, and then comparing them to the corresponding experimental spectra. A real distribution or bunch shape, properly normalized, was thus obtained, compatible for all eight low current cases.

The average experimental loss for 5×10^8 electrons was obtained by taking all 32 spectra and calculating

$$E_{AV} = \frac{\int E i(E)\, dE}{\int i(E)\, dE}$$

from E_{min} to E_{max}, and again averaging over all cases. A value of 25 MeV was found, or 50 MeV for 10^9 electrons. In order to obtain the same average value from the second term in Eqs. (1), it was necessary to make $\beta = 1.35$. The theoretical spectra of which 12 out of 32 are shown in Fig. 3

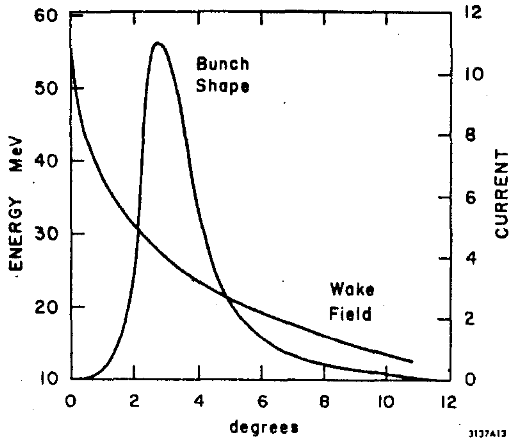

Fig. 2. Wake-field function for 3-km equivalent accelerator structure and 5×10^8 electrons, and bunch charge distribution as a function of phase degrees at 2856 MHz.

were calculated with this same value of β. With a few exceptions such as the case shown for $\theta_0=8^\circ$ and $\alpha=1$, most fits are excellent.

What conclusions can be drawn?

--The shape of the wake-field function seems to yield very good agreement with experiments as far as spectrum profiles are concerned. Hence, although there is presently some discussion[4] as to whether the modal analysis should also include a scalar potential, the shape of the present function cannot be far from correct.

--The fact that the amplitude of the calculated wake-field function seems to fall short by 35% can be explained by a number of alternate or cumulative effects:

a) Experimental current measurements may have been low by 20%.

b) The number of actual "cavities" due to discontinuities along the accelerator vacuum envelope may add another few percent to the total assumed number.

c) Transverse non-azimuthally symmetric modes which are not included in the sum, combined with the fact that the beam spends some of its trajectory off-axis where it can interact with them, may increase the loss by about 20%.

d) The effect of changes in the bunch shape can only account for small energy loss variations. Hence, a Gaussian bunch with a σ of 1° required a value of $\beta = 1.28$ to give the same average loss, i.e., only a 7% change.

Acknowledgments

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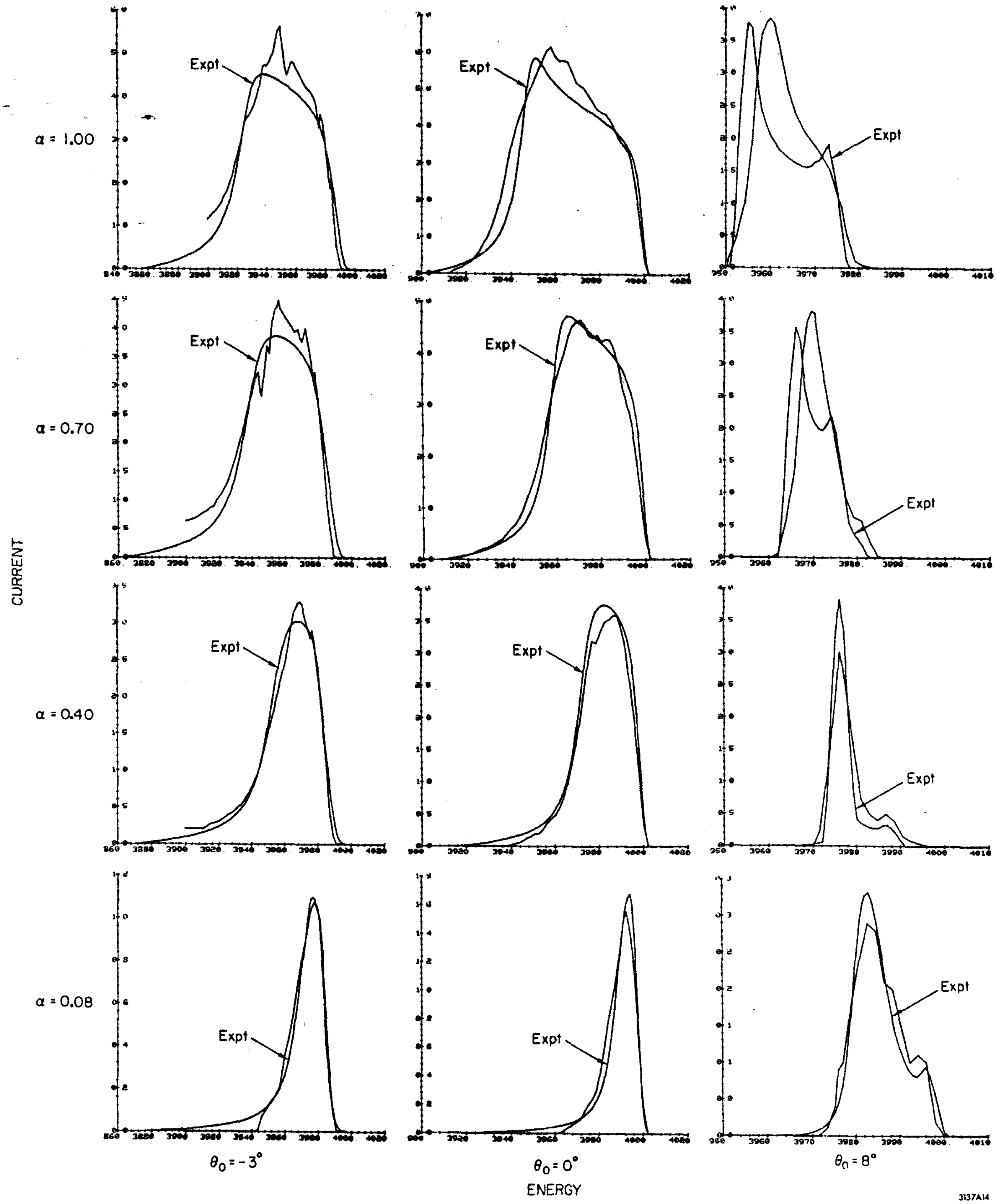

Fig. 3. Calculated and experimental energy spectra (i(E) vs. E in MeV) for four values of α and selected values of θ_0.