Experimental Demonstration of Wake-Field Effects in Dielectric Structures

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We have measured the wake fields induced by short, intense relativistic electron bunches in a slow-wave structure consisting of a dielectric-lined tube, as a test of the dielectric wake-field acceleration mechanism. These fields were used to accelerate a second electron bunch which followed the driving bunch at a variable distance. Results are presented for different dielectrics and beam intensities, and are compared with theoretical predictions.

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Recently, several wake-field acceleration methods have been proposed[1-3] to increase the accelerating gradient of future linear colliders for high-energy particle-physics research. One of these schemes is the dielectric wake-field accelerator,[4] in which an intense, low-energy relativistic charged bunch excites electromagnetic wake fields (Čerenkov radiation) in a dielectric-loaded structure, which are then used to accelerate a second, less intense bunch to high energies. This method can be alternatively described as high-gradient rf acceleration with a Čerenkov maser[5-7] as the microwave power source. One notable advantage of the dielectric wake-field accelerator is that the radial wake fields, which are potentially deleterious in all wake-field schemes, can in principle be made quite small.[4] It is also worth noting that ferrite-loaded wake-field devices have been proposed.[8,9] In this Letter we report on experimental studies of acceleration by the dielectric wake-field acceleration mechanism.

The experimental technique uses the Argonne Advanced Accelerator Test Facility[10] to generate two electron bunches, a 21-MeV "driver" and a 15-MeV "witness." These bunches travel along the axis of the structure under study, and into a momentum-analyzing magnetic spectrometer. The distance between the two bunches is varied by extending the path length traversed in the Advanced Accelerator Test Facility by the witness beam, and the change in the energy of the witness bunch as a function of the separation between the two bunches is measured. The witness-beam energy change is proportional to the longitudinal wake field induced by the driver beam.

The geometry of a dielectric cavity is shown in Fig. 1. It consists of a cylindrical metallic tube partially filled with a dielectric material with dielectric constant ϵ. There is a hole in the center of the dielectric through which the driver and witness bunches pass. As the driving bunch travels through the center hole it excites modes in the cavity through the Čerenkov radiation mechanism. All the excited modes have a phase velocity equal to the velocity of the bunch, in our case $\sim c$. The amplitudes of these modes depend upon the pulse length and a profile of the driving bunch. For a driving pulse of N particles, whose longitudinal profile is a Gaussian with rms bunch length σ_z, the excited longitudinal electric field E_z at a given delay distance z_0 in the hole can be expressed as follows[11]:

$$E_z = \frac{2Ne}{\epsilon b} \sum_{\lambda} \left[\frac{J_0(s_\lambda b) N_0(s_\lambda a) - N_0(s_\lambda b) J_0(s_\lambda a)}{(d/ds)[J_1(sb)N_0(sa) - J_0(sa)N_1(sb)]\,|_{s=s_\lambda}} \right] \cos\left(\frac{\omega_\lambda}{v} z_0\right) \exp\left(-\frac{(\omega_\lambda \sigma_z)^2}{2c^2}\right). \qquad (1)$$

The wave numbers s_λ are the roots of

$$J_1(s_\lambda b)N_0(s_\lambda a) - J_0(s_\lambda a)N_1(s_\lambda b) = 0, \qquad (2)$$

where J_n and N_n are the nth orders of the Bessel functions of the first and second kinds, respectively. The resonant frequencies are thus

$$\omega_\lambda = s_\lambda c/(\epsilon - 1)^{1/2} \qquad (3)$$

and the wake potential, the most important experimentally measured quantity in this experiment, is simply defined as the energy change of the witness bunch,

$$W_z = \Delta E = -e\int_0^L E_z\,dz, \qquad (4)$$

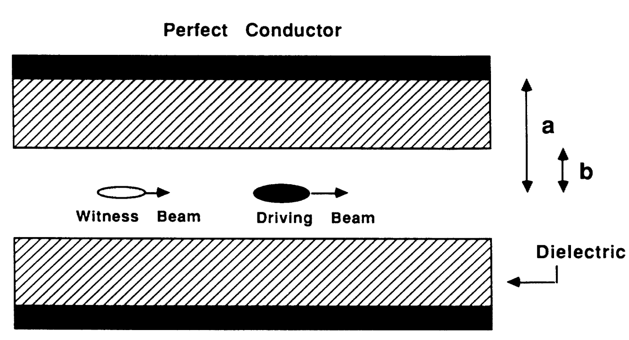

FIG. 1. Sketch of the dielectric cavity.

TABLE I. Experimental cavities and beam conditions.

Material	Length (cm)	a (cm)	b (cm)	Driver charge (nC)	Driver length FWHM (ps)
Polystyrene	51	1.27	0.63	~2.6	~23
Steatite	51	1.27	0.63	~2.0	~23
Nylon	51	1.27	0.63	~2.6	~30

where L is the structure length, equal to 51 cm for the present experiments.

In order to systematically study the wake-field effects in the dielectric-loaded slow-wave structures, we constructed several such structures whose dimensions, along with the experimental driving-bunch conditions, are shown in Table I. The measured longitudinal wake potentials for them are plotted in Figs. 2(a), 3(a), and 4, where the wake field is measured by the shift in the average energy of the witness bunch as a function of delay for each structure. The error on each point reflects both the statistical uncertainty in the determination of the energy shift and the pulse-to-pulse driver charge fluctuation.

At negative delay values, the witness bunch passes through the cavity in front of the driver and by casuality is unaffected by the wake fields of the driver. As the delay is increased, the witness bunch overlaps the driver, and begins to be affected by the retarding and deflecting fields induced by the driver bunch. At still larger delays, the witness bunch probes the wake field left behind by the driver bunch.

We have calculated the wake field using Eqs. (1) and (4) for comparison with the experimental results. Our analysis assumes that ϵ is constant over the frequency range of interest. Since the exact value of ϵ is not known, we fit the calculations to the experimental curves using ϵ as the fitting parameter. We note that our values for ϵ are within the accepted ranges for these materials.[12] Since the driver and witness bunches have a finite length, we have smoothed the calculated result by an appropriate Gaussian resolution function.

The wake potential for the polystyrene scan is plotted in Fig. 2(a), and shows that for an approximately 2.6-nC driving bunch, the wake-field amplitude averaged over the witness pulse is 120 keV with a period of 110 ps. Higher-order modes with small amplitudes are also excited and are superimposed on the fundamental. A Fourier transform of the wake-field scan clearly shows the fundamental mode at 10 GHz and also a second mode at 23 GHz with a relatively small amplitude. The calculated result, shown in Fig. 2(b), agrees well with the data when ϵ is chosen to be 3.1.

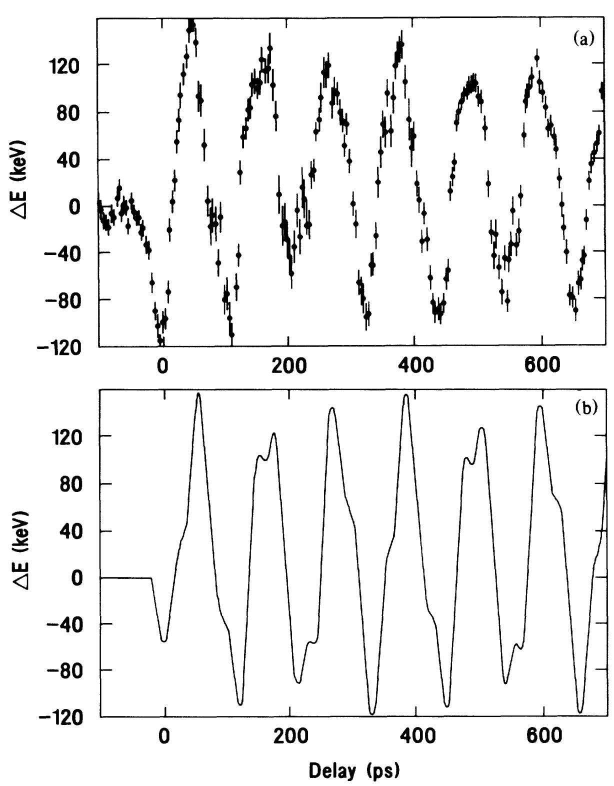

FIG. 2. Polystyrene scan: (a) measured and (b) calculated wake potential.

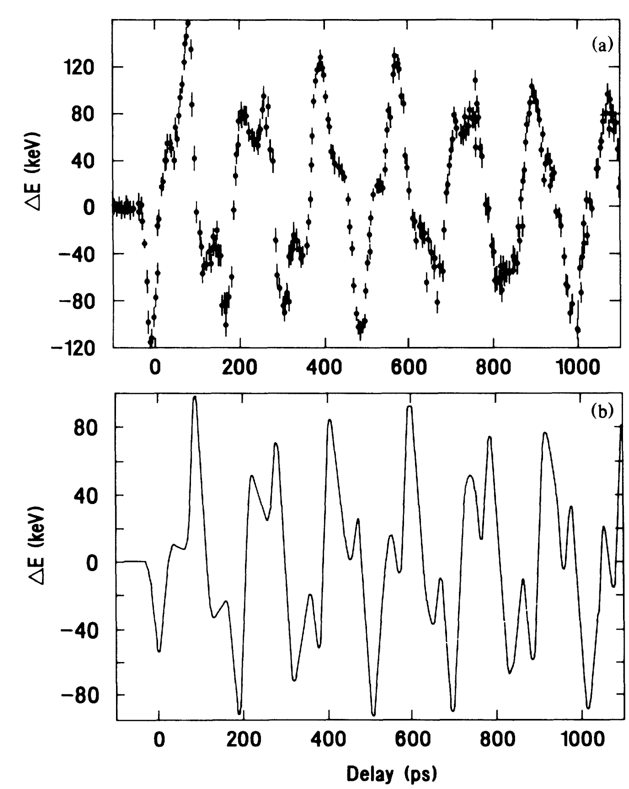

FIG. 3. Steatite scan: (a) measured and (b) calculated wake potential.

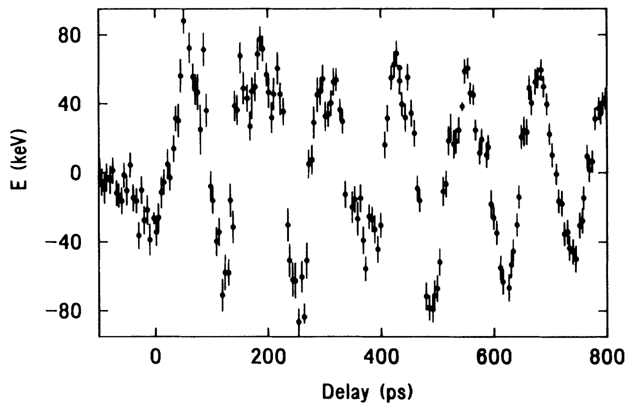

FIG. 4. Nylon scan: Wake potential measured as a function of witness-bunch delay.

The data for the steatite scan is shown in Fig. 3(a), and shows the period to be ≃160 ps, with an amplitude of 100 keV. Because of the larger dielectric constant, one would expect that the wake field would have a longer wavelength in steatite than in polystyrene, as is shown in the data. The Fourier transform of the data indicates that the fundamental wake field is excited at 6 GHz and a strong second mode at 17 GHz, as theoretically expected. Figure 3(b) shows the calculated wake field, which shows very good agreement with the experimental data when $\epsilon = 5.9$.

A third scan, with nylon for the dielectric, is shown in Fig. 4. The wake field had a period of 130 ps and an amplitude of 80 keV. In this experiment, the measured driver pulse length (FWHM) was 30 ps, longer than in the previous experiments. When this was included in the calculations, the experimental results agreed well with the theoretical predictions, both in wake amplitude and period, for $\epsilon = 3.9$. It should be noted that transverse deflections were small for all dielectrics tested, in contrast to the large transverse wake fields measured in structures[10] and plasmas.[13]

Because of limited driving-beam current and rather large transverse emittance of the beam, the observed accelerating gradients were modest, with maximum observed amplitudes of 0.3–0.5 MeV/m. In fact, accelerating devices based on this technique may achieve gradients useful for future high-energy machines. An example is given in Ref. 4, where by use of a linearly ramped driver bunch with a peak current of 5 kA in a 20-GHz dielectric structure, an accelerating gradient of 100 MeV/m is predicted.

In summary, we have experimentally demonstrated the principle of dielectric wake-field acceleration. We have accelerated a low-intensity electron bunch using the wake field induced by an intense driving electron bunch in several different dielectric-loaded structures. We have found that the experimental results agree reasonably well with theoretical predictions. In our experiments, no apparent nonlinear effects were expected or observed. We plan to do further studies of nonlinear effects in different materials, such as ferrites, using this type of structure. We hope to experimentally address the questions of shock wave formation[14] and the potential of nonlinear dielectric properties to compress wake-field pulses in time, thus raising the amplitude of the fields available for accelerating particles.

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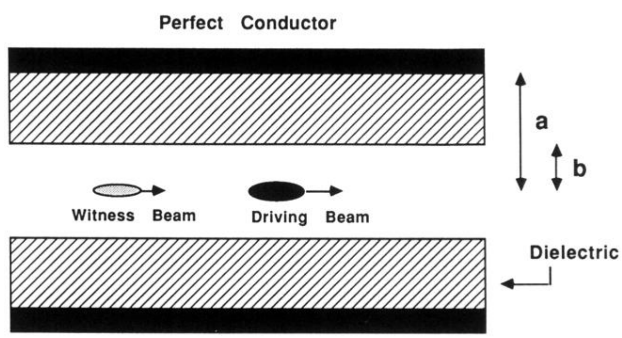

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