AN EXPERIMENTAL TEST OF THE THEORY OF THE STIMULATED DIELECTRIC WAKE-FIELD ACCELERATOR*

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Abstract

We have installed a dielectric-lined wakefield accelerator at the Accelerator Test Facility (ATF), Brookhaven National Laboratory. The first experiment, reported here, uses a single 0.2 nC, 10 psec bunch of 40 MeV electrons to excite the multi-mode $\mathrm{TM}_{0\mathrm{m}}$ wakefields which trail the bunch. The device is configured as a cylindrical waveguide containing an annular alumina liner; the electrons move along the axis of symmetry inside a 3 mm diameter bore hole. The spectrum of modes set up by the electron bunch is picked up by a radial probe and detected by a spectrum analyzer; this is compared with theory. This spectrum can be used to construct the axial wakefield pattern.

1 INTRODUCTION

In a dielectric wakefield accelerator, a dielectric loaded waveguide supports wakefields radiated by the passage of an electron bunch which travels at the speed of light in the structure (Cerenkov Radiation). Our studies here relate to a cylindrical structure, consisting of a thick cylindrical shell of alumina ($\kappa \sim 9.6$) having a small bore hole (3 mm dia.) which permits the electron beam to pass down the axis, and a comparatively large outer radius (R = 2.064 cm), all contained within a close-fitting conducting cylinder which serves as a vacuum wall. In this paper, we describe experimental results including portions of the spectrum of microwave modes excited by the passage of a single 0.2 nC, 10 psec, 40 MeV (ATF diagnostics) bunch of charge provided by the ATF rf linac at Brookhaven National Laboratory. This spectrum compares favorably with the computed spectrum, obtained by solving the dispersion relation of the structure[1].

The particular waveguide used here has two novel properties: First, the dimensions and large κ will favor the coherent superposition of many waveguide modes, travelling with the electron speed, which cause a narrow, highly-defined pulse of axial electric field $\mathrm{E_z}$ to repeat periodically along the axis of the device. Factors which favor a sharply-defined high amplitude wakefield pulse are: (1) a small bore hole; (2) a dispersion-free dielectric; (3) a very short bunch containing as much charge as possible. However, these agreeable features do not by themselves advance in a significant way the prospects for using wakefields to achieve high accelerating gradients in future accelerators. Second, we can exploit the nearly-periodic characteristic of these wakefields by locating additional drive bunches in the decelerating field of the previous bunches such that the constructive interference of the fields will build up a truly large accelerating gradient. The strategy of the multiple bunch wakefield accelerator is to use a train of very short (perhaps $\sim$ 1 psec in the future) bunches to build up a larger wakefield than could be obtained from a single bunch of proportionally higher charge. This can occur because shorter bunches are much more effective in setting up strong wakefields than are longer bunches.

The principles of such an accelerator have been set forth[2] in a simplified geometry. The first bunch radiates coherent spontaneous Cerenkov radiation. The next drive bunch in addition radiates stimulated radiation, because it is located in the decelerating field of the first bunches, and so on. This permits a rapid buildup of the wakefields at the position where a test bunch follows in the accelerating phase. The lack of dispersion in alumina[3] means that the waveguide modes can have nearly-constant frequency differences. Thus dispersion does not smear out the pulses of high wakefield intensity. Wakefield devices such as this one are subject to the following problems: (1) dielectric breakdown, at some field; (2) instability (caused principally by the dipole mode); (3) slippage. However, temporarily setting aside these issues (which may be helped by separating the drive beam line from the accelerated beam line and staging), in this paper we are preparing to study the multibunch wakefield acceleration in an experiment which will be run at ATF, starting with a single bunch.

In order to do the multibunch experiment, careful measurements must be made to prepare the device so that the wakefields will have the correct periodicity for the chosen accelerator system. Since the ATF uses a 2.85 GHz power source and a laser rf photocathode gun, the drive bunches are to be separated by 21 cm, and the test bunch will follow at 10.5 cm. These bunches will be obtained by taking one laser pulse and splitting it into three drive bunch pulses and one weak test bunch pulse: the structure is about 54 cm in length. We report our first measurements of the rf spectrum from the passage of a single bunch; this not only permits a check of the accuracy of our calculations, but also a measurement of the wakefield periodicity. Having done this, one can then obtain a very accurate value for the dimensions of the wakefield device which will support a multibunch train that will build up wakefields.

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2 APPARATUS

Oversize alumina castings were obtained from LSP Industrial Ceramics (Lambertville, NJ). Since no sample 60 cm in length had the straightness of bore hole that was required, it was decided to use two selected shorter alumina sections smoothly butted together. These samples were placed into a metal-walled cylindrical cavity resonator, and the sequence of $\mathrm{TM_{01n}}$ mode frequencies was measured[4]: this yielded a $\kappa = 9.57$. However, this measurement had only so much accuracy — not adequate to get the wakefield period accurate for four bunches (i.e. within 1 mm) — and so it was decided to grind the outer diameter of the alumina slightly oversize, and then determine the correct diameter using the theory from the experimental spectrum of wakefields excited by a single bunch.

The apparatus (Figure 1) is installed on the beamline 3 of the ATF rf linac facility, which is operated so as to produce a single pulse of beam electrons from the irradiation of a rf gun photocathode with a near-UV laser pulse (the fourth harmonic of the Nd:YAG laser). Halo electrons are removed at the input by scrape-off into a tungsten plug. The alumina OD and the stainless steel jacket ID are machined so that a sliding fit is obtained. No problems with pump-

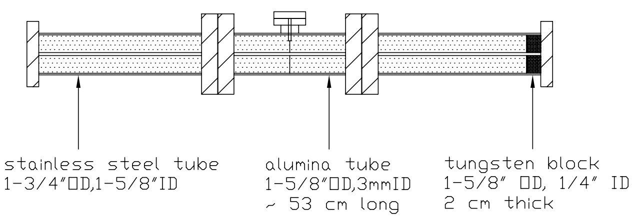

Figure 1: The wakefield device

down were encountered. Halfway along the device, a radial wire probe is inserted into a hole milled along the interface between the two adjacent alumina cylinders. A 3.5 m piece of EZ Flex 402 rf coax (comparable to $MIL-C-17$ semi-rigid) joins the probe terminal to a terminated crystal detector and the spectrum analyzer (Tektronix 492P); the rf waveform envelope is monitored using a 1 GHz bandwidth oscilloscope. The Cerenkov radiation trails the charge, and is directed downstream; however, it should be reflected by the end walls and contained within the structure. A typical pulse, Fig. 2, shows the radiation set up by the electron bunch lasts $\sim$ 20 nsec, several bounce times; it would appear that cavity modes are not excited, since radiation in these modes should persist much longer ($\sim$ 1 μsec, related to the resonator Q for microwaves).

3 RESULTS

We present two cases of the spectrum scan here. In Fig. 3 which covers 1.7–5.5 GHz band, $\mathrm{TM_{01}}$ and $\mathrm{TM_{02}}$ modes were detected at near 1.9 and 4.4 GHz respectively. In Fig. 4, $\mathrm{TM_{04}}$ and $\mathrm{TM_{05}}$ modes were detected near 9.5 and 12.1 GHz. The spectrum analyzer sweep was calibrated us-

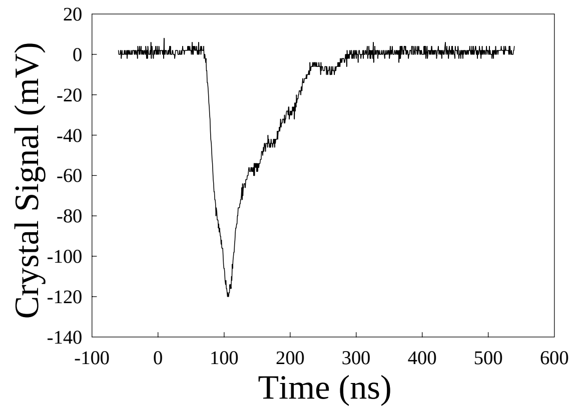

Figure 2: The rectified crystal signal

ing a frequency source and a wavemeter, as it was found to vary somewhat from band-to-band. For these data, a single bunch of charge ($\sim$ 0.2 nC) was passed through the apparatus at 1.5 Hz, while the spectrum analyzer was allowed to accumulate data over many minutes. The spectrum analyzer operates by stepping a fixed bandwidth of frequency along a band, thereby catching radiation which has the correct frequency when that channel is open. There are 1000 frequency bins in a band and it takes 50 seconds to step through the band. We usually accumulate the data over 30–45 minutes. The ordinate is in the logarithmic scale to allow for larger dynamic range.

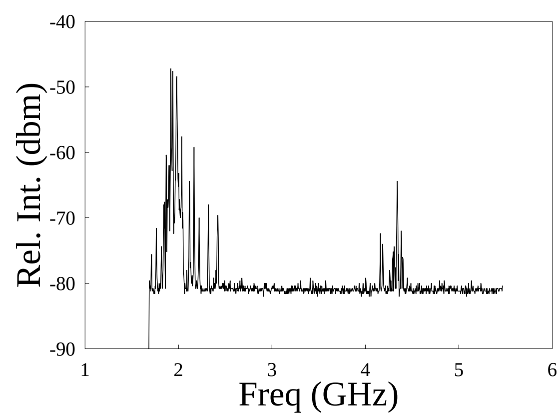

Figure 3: Spectrum between 1.7–5.5 GHz, $\mathrm{TM_{01}}$ and $\mathrm{TM_{02}}$ are shown.

Table I is a summary of the six frequencies observed. The lowest frequency predicted and observed was 1.9 GHz; the highest frequency detected by the apparatus was about 15 GHz, on the highest band available to us using this spectrum analyzer. Frequencies above 15 GHz would suffer more attenuation from the coaxial cable. Because of the frequency-dependent experimental parameters (e. g, the couplings between the radial wire probe and various modes), the amplitude of the various modes are not known, and so $\mathrm{E_z(t)}$ cannot be obtained from the data.

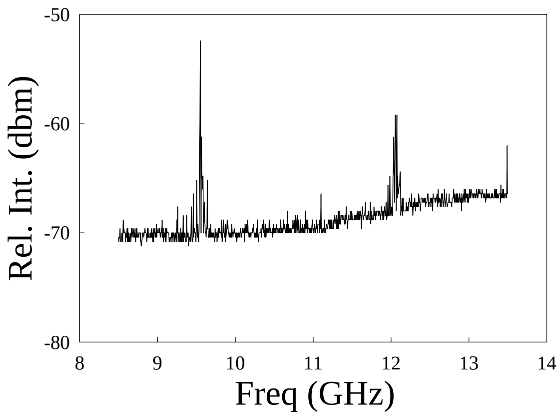

Figure 4: Spectrum between 8.5–13.5 GHz, TM_{04} and TM_{05} are shown.

Table 1: $\mathrm{TM}_{0\mathrm{m}}$ mode frequency table (GHz)

mode	$\mathrm{Freq}_{\mathrm{ex}}$	$\mathrm{Freq}_{\mathrm{th}}$
1	1.920	1.907
2	4.376	4.420
3	6.956	6.983
4	9.545	9.574
5	12.12	12.18
6	14.84	14.80

Column 3 of Table I gives the theoretical prediction of the mode frequencies, using the actual inner and outer radii of the alumina cylinder (with $\kappa = 9.65$ providing the best fit). To analyze this data, we use the dispersion relation[1] for the $\mathrm{TM}_{0\mathrm{m}}$ modes:

$$\frac{I_1(k_1 a)}{I_0(k_1 a)} = \frac{\kappa k_1}{k_2} \frac{J_0(k_2 R) N_1(k_2 a) - J_1(k_2 a) N_0(k_2 R)}{J_0(k_2 R) N_0(k_2 a) - J_0(k_2 a) N_0(k_2 R)} \tag{1}$$

where a and R are the inner and outer radii of the cylinder, and the mode frequencies are related to the k_1 and k_2 (the transverse wavenumbers in the vacuum and dielectric regions respectively) by

$$k_{1m} = \omega_m / c\beta\gamma = k_{2m}\gamma_\kappa/\gamma \tag{2}$$

where m is the mode index number, γ is the relativistic factor (corresponding to 40 MeV here), and

$$\gamma_\kappa = (\kappa\beta^2 - 1)^{-1/2}. \tag{3}$$

The fit of the dispersion theory for the $\mathrm{TM}_{0\mathrm{m}}$ series and the data is excellent. Certain spectra also reveal the appearance of additional modes having smaller amplitude. Several of these frequencies correlate well with predicted modes of the $\mathrm{HEM}_{1\mathrm{n}}$ and $\mathrm{HEM}_{2\mathrm{n}}$ (“dipole” and “quadrupole”) class, which are unstable for finite beam offset from the axis (for example, in Fig. 3, the small peak to the left of TM_{02} is related to HEM_{13}). Indeed, further experimentation has found that the appearance of these modes is favored by deliberate beam misalignment.

4 REFERENCES

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