BEAM TEST OF A TUNABLE DIELECTRIC WAKEFIELD ACCELERATOR*

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Abstract

We report on a collinear wakefield experiment using the first tunable dielectric loaded accelerating structure. Dielectric-based accelerators are generally lacking in approaches to tune the frequency after fabrication. However, by introducing an extra layer of nonlinear ferroelectric which has a dielectric constant sensitive to temperature and DC voltage, the frequency of a DLA structure can be tuned on the fly by controlling the temperature or DC bias. The experiment demonstrated that by varying the temperature of the structure over a 50°C temperature range, the energy of a witness bunch at a fixed delay with respect to the drive beam could be changed by an amount corresponding to more than half of the nominal structure wavelength.

INTRODUCTION

The need for frequency tuning of any accelerating structure arises from the fact that the frequency of the assembled accelerating structure will, in general, differ from the design due to various sources of error. In a metallic disk-loaded accelerating structure, the frequency and field balance are generally tuned through the slightly geometrical perturbations (e.g. push-pull button or plunger) for each cell. Dielectric Loaded Accelerating (DLA) structures are typically constructed from the circular or rectangular dielectric-lined waveguides [1]. Volume of the dielectric material inside the metal waveguide and its dielectric constant determine the dispersion relation of the accelerating mode. Frequency errors in a DLA structure are dominantly caused by machining tolerance of the dielectric dimensions and dielectric constant heterogeneity. For example, for an 11.424 GHz circular DLA structure made of a ceramic tube having the inner radius of 3mm, the outer radius of 4.567mm, and dielectric constant of 20, 1μm of the machine error in the outer radius can cause a 6MHz frequency shift. On the other hand, DLA structures generally cannot be geometrically deformed so that without tuning a high machine tolerance is required in the dielectric fabrication that in turn raises the cost.

One approach to vary the frequency of a DLA structure was originated in [2], in which a thin layer of a ferroelectric material was applied outside the layer of conventional ceramic (see Fig. 1a). A temperature change or DC bias voltage can vary the dielectric constant of the ferroelectric layer so that the effective dielectric constant inside the metal waveguide changes. So does the frequency of the DLA structure. Two types of dielectric materials have variable electromagnetic properties that can be controlled by external fields: ferrites by magnetic fields and ferroelectrics by electric fields. Ferrite material is impractical to use in high frequency, high gradient accelerators because of its extremely high loss factor, and also the magnetic field will interfere with the electron beam optics. A ferroelectric crystal or ceramic is a material with a spontaneous dielectric polarization below some Cure temperature. The response time of ferroelectrics to the external DC electric field is in the order of ~10ps for the crystalline and ~100ps for ceramic compounds. However, one fact limiting the application of this nonlinear material in high energy accelerators in the past is that the ferroelectrics are very lossy in the > 10 GHz frequency range. The typical loss factor for BST ($BaTiO_3$–$SrTiO_3$) ferroelectric ceramics, which are commonly used at room temperature, is (1~3)×10^{-2} near 10 GHz frequency range. Recently, the new ferroelectric material made of BST-MgO-$MgTiO_3$ (BSTM) composites has been developed to reduce the loss tangent to the low 10^{-3} while the wide tunability maintained [2]. The progress makes it possible to demonstrate the first tunable DLA structure and leap forward the dielectric-based accelerator technologies for the future high energy machine.

A TUNABLE DLA STRUCTURE

Using the concept shown in Fig. 1a, a 14GHz tunable DLA structure, was constructed lately to perform a tunable wakefield acceleration experiment. Its major parameters are summarized in Table I. The structure consists of four segments of 1-inch long double-layer dielectric tubes and two copper end plugs housed in a copper tube. The inner layer is forsterite with a dielectric constant of 6.8, and the outer layer is a BSTM based ferroelectric layer with dielectric constant of 310 at room temperature. An E-field probe is built in to the structure to monitor the rf signal for future beam experiments. The entire structure is wrapped with cooling channels driven by a chiller operating a temperature from 10 to 60°C. A bench test has been performed using a simple coaxial mode launcher, which was connected to a network analyzer, to excite the accelerating mode in the structure. Two thermocouples were used to monitor the structure temperature. The resonant frequency of one dominant wakefield mode, TM_{02} mode at ~14GHz, was recorded while changing the temperature. The results are plotted in Fig.1b, where a significant positive temperature tunability, 15MHz/°C, has been observed. As a comparison, we also measured the temperature tunability of a conventional DLA structure, which was constructed with a single layer dielectric tube (it has the dielectric

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constant of 4.7, inner radius of 4.79 mm and outer radius of 7.49 mm to match the same operating frequency as the tunable DLA structure). The result is also plotted in Fig.1b. A slightly negative frequency response slope (-200kHz/°C) of the conventional DLA structure is due to the thermal expansion of the copper tube.

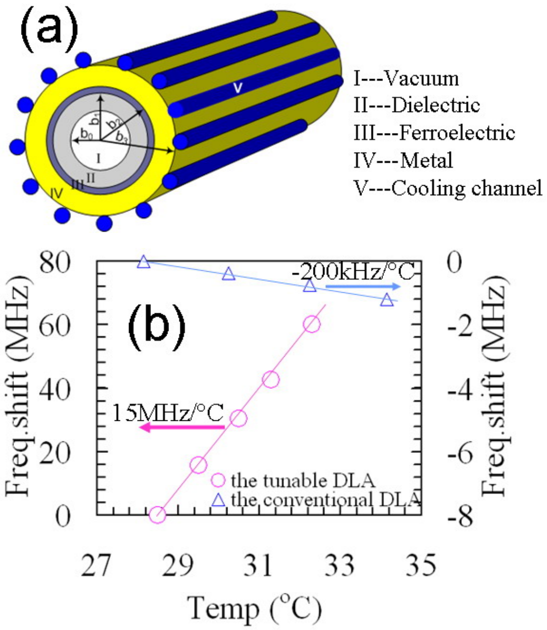

Figure 1: (a) The tunable DLA structure; (b) Comparison of the temperature dependence of the 14 GHz tunable and a conventional DLA structures as measured using the network analyzer.

Table 1: Parameters of the 14GHz tunable DLA structure

Geometric and accelerating parameters	**Value**
Radius(refer to Fig.1): b_0, b_1, b_2	4.79 mm, 6.99 mm, 7.49 mm,
Effective Length	101.6 mm
Dielectric constant: dielectric, ferroelectric	6.8, 310 (at room Temp.)
Loss tangent: dielectric, ferroelectric	2×10^{-4}, 2×10^{-3}
Freq. of two dominant wakefield modes	7.8 GHz, 14.1 GHz (at room Temp.)
Q of two dominant wakefield modes	385, 1250
Peak wakefield by 50 nC drive bunch (σz=2.3 mm)	16 MeV/m

TUNABLE WAKEFIELD EXPERIMENT

The wakefield experiment was performed at Argonne Wakefield Accelerator (AWA) facility located at Argonne National Laboratory (ANL). A 1.3 GHz photocathode rf gun can provide ~100 nC charge in single bunch operation or several tens of nC per bunch in bunch train operation [3]. The energy of the electron drive bunch at the end of the linac is approximately 15 MeV. Major diagnostics used during the experiment included: 1) two Inductive Current Transformers (ICTs) on both sides of the tunable DLA structure to record the charge entering and exiting the structure; 2) phosphor screens on each side of the structure to monitor the transverse beam profile; 3) a magnetic spectrometer on the downstream end to measure the beam energy; and 4) a 6 GHz digital oscilloscope to record the down-converted wakefield signal from the field probe in the tunable DLA structure.

The collinear wakefield acceleration experiment required both a high charge drive bunch and a trailing low charge witness bunch. The bunches were generated by splitting a laser pulse in two, delaying the low intensity fraction, and injecting both pulses at normal incidence into the same rf gun. When the drive bunch was placed at the optimal gun phase of approximately 50° (sine convention), without consideration of generating a witness bunch, a charge of 50 nC and rms bunch length ~2.3 mm was transported through the structure. This corresponds to 16 MV/m accelerating gradient based on both theory and numerical simulations. During the wakefield experiment, where both the drive and witness bunch were produced, neither bunch could be launched from the optimal phase and a compromise was chosen with the drive phase at ~20° and the witness at ~70°. The separation in phase is required so that the energies of the bunches differ and hence they can be separated in the energy spectrometer. This non-optimum launch phase for the drive bunch decreased the charge from 50 nC to about 20 nC. Even so this charge was adequate to provide a detectable energy change of the trailing witness bunch in the experiment.

In order to observe a significant energy variation, the witness bunch has to be launched far behind the drive bunch so that the accumulated frequency shift is large enough to cover at least a half cycle of the wakefield signal. This means that the drive and witness bunch were not in the same rf bucket of the gun although they were launched at their respective phases (20^0 and 70^0) as described above. The witness bunch energy was monitored while the temperature of the structure was varied. Because the frequencies of each mode of the wakefield signal have a strong temperature dependence, the energy of the witness bunch will change accordingly when the temperature changes. The principle of the experiment is shown in Fig. 2 which shows the calculated longitudinal wakefields of the tunable DWA structure for three different temperatures:15°C, 35°C, and 65°C, corresponding to three different dielectric constants of the ferroelectric material: 328, 296, and 248, respectively. (Note that a higher temperature corresponds to a lower dielectric constant). While the delay of the witness bunch is constant (26.2 cm) the phase of the witness bunch relative to the drive bunch varies over half a cycle of the wakefield as the temperature of the structure is swept over 50° C.

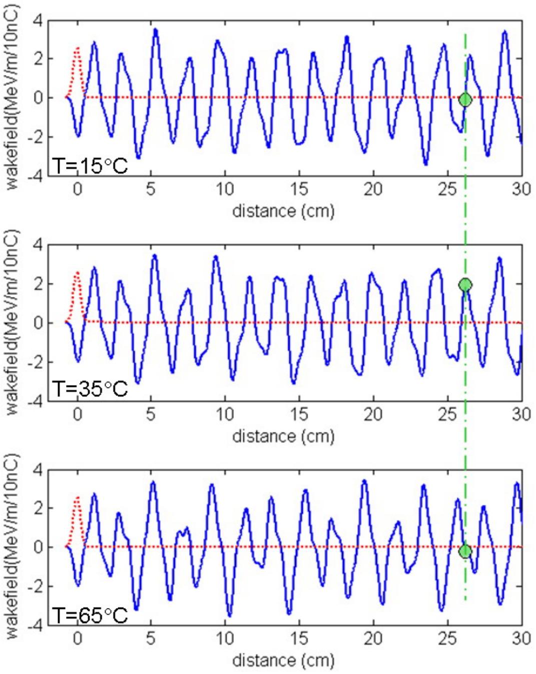

Figure 2. The calculated wakefield of the tunable DWA structure for three different temperatures which correspond to three different permittivities of the loaded ferroelectric material. A witness bunch is trailing 26.2 cm behind the drive bunch for all cases. The solid line is the wakefield; dashed line is the drive bunch; and the large dot represents the position of the centroid of the witness bunch.

The wakefield of the DLA structure was measured as the temperature was swept over 50°C which resulted in a maximum frequency shift of~0.7 GHz. The measurements were taken with the witness bunch at a fixed delay of 26.2 cm behind the drive bunch. The witness bunch experienced the entire range of wakefield phases during the 50°C temperature sweep. The wakefield of the DWA structure at each temperature was obtained by taking the difference between the energy of the witness bunch with and without the drive bunch present. The total number of measurements at each temperature was 40 and each measurement point was acquired after the temperature of the DWA structure had stabilized. It took about 30 minutes for the temperature to stabilize during the experiment as monitored by observing the frequency spectrum of the signal from the E-probe on the DWA structure.

The comparison between theory and measurement is shown in Fig. 3. The longitudinal wakefield of the tunable DWA structure was calculated by using the analytical solution for the wakefields in a multilayer dielectric-lined circular waveguide. Only the first five modes were used in the calculation since this is the number of modes excited by the 2.3 mm bunch. To calculate the centroid energy variation of the short Gaussian witness bunch (*rms* length 1.5 mm for the 1 nC bunch from AWA gun) we integrated of the longitudinal wake potential over the charge distribution of the witness bunch. Then we repeat the first two steps with a continuously varying dielectric constant of the ferroelectric material to simulate the temperature change in the experiment. The range of the dielectric constant change is indicated by comparing the measured signal frequencies from the probe and the calculation. The calculated results plotted in Fig. 3 cover a permittivity range of the ferroelectric layer from 336 to 240 that represents the temperature change from 10°C to 70°C. It is estimated that dielectric constant of the ferroelectric material used in the DWA structure can change by 1.6 units (or ~0.5%) /°C.

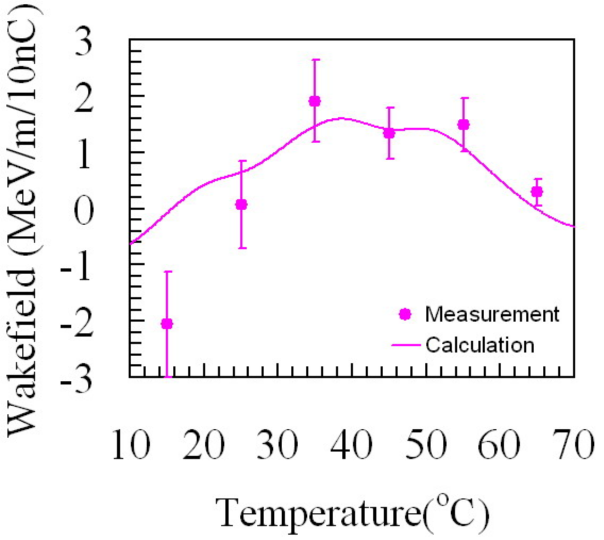

Figure 3. Comparison of the measured and calculated wakefield (normalized to 10 nC drive bunch) excited in the DWA structure as a function of temperature.

CONCLUSION

In conclusion, a novel low loss BSTM ferroelectric material has been used in dielectric based accelerators as a method of frequency tuning. A wakefield experiment using an accelerated witness beam successfully demonstrated this technique using the first tunable dielectric accelerator.

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