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Experimental Demonstration of Wakefield Acceleration in a Tunable Dielectric Loaded Accelerating Structure

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Abstract: We report on a collinear wakefield experiment using the first tunable dielectric loaded accelerating (DLA) structure. By introducing an extra layer of nonlinear ferroelectric, which has a dielectric constant sensitive to temperature and DC bias, the frequency of a DLA structure can be tuned. During the experiment, the energy of a witness bunch at a fixed delay with respect to the drive beam was measured while the temperature of the structure was scanned over a 50°C range. The energy change corresponded to a change of more than half of the nominal structure wavelength.

Recently, significant progress has been made in the development of dielectric wakefield accelerators. Sustainability of dielectric materials at high gradient has been demonstrated: 100 MV/m at microwave frequency [1] and GV/m at THz [2]. While the quest for high gradient has been the primary focus of the field, synchronization between the electron beam velocity and the phase velocity of the accelerating field is also necessary since it is required for the bunch to continuously gain energy. Achieving precise synchronization requires a method of frequency tuning the accelerating structure since the frequency of the assembled accelerating structure will, in general, differ from the design due to various sources of error. Until now, a viable method to tune the frequency of a dielectric based accelerator has not been demonstrated.

We are using a nonlinear dielectric to tune the DLA structure. Traditionally, metallic disk-loaded accelerating structures, are tuned by making small geometrical perturbations to each cell [3] and/or by varying the temperature of the entire structure to change the volume (and hence the frequency) of the structure. Dielectric Loaded Accelerating (DLA) structures are typically constructed from circular or rectangular dielectric-lined metallic waveguides [4]. The operating frequency of a DLA structure is determined by the volume of the dielectric material inside the metallic waveguide and its dielectric constant. However, unlike metallic structures, DLA structures are not readily deformed geometrically due to their lack of malleability. Therefore, we have developed an alternate method based on the use of a nonlinear material as a part of the DLA structure.

The approach we take to tune the frequency of the DLA structure, which was originally suggested in Ref. [5], is to add a thin layer of nonlinear ferroelectric material between the layer of conventional ceramic and the conducting outer sleeve (see Fig. 1a). The dielectric constant of the ferroelectric layer can be varied with either temperature or DC voltage. Therefore, the effective dielectric constant inside the metal waveguide changes and hence so does the frequency of the DLA structure. However, one issue limiting the application of nonlinear materials of this kind in high energy accelerators in the past is that ferroelectrics tend to be lossy in the > 10 GHz frequency range. The typical loss factor for BST ($Ba_xSr_{1-x}TiO_3$) ferroelectric ceramics, which are commonly used at room temperature, is $(1\sim3)\times10^{-2}$ near 10 GHz [6, 7]. Recently, new ferroelectric materials made of BST-MgO-Mg_2TiO_4 (BSTM) composites have been developed to reduce the loss tangent to the low 10^{-3} range while maintaining a large tunability [8, 9].

In this Letter, we demonstrate tuning by performing a wakefield acceleration experiment in which the phase of the accelerating wake from the drive bunch was tuned over a wide range. Using the concept shown in Fig. 1a, a 14 GHz tunable DLA structure was constructed for the dielectric wakefield acceleration experiment. The parameters of this device are given 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 generated by the beam. The entire structure is wrapped with cooling channels driven by a chiller operating over a temperature range from 15 to 65°C.

Initial characterization of the DLA structure was done via a bench test using a simple coaxial mode launcher, 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, the TM_{02} mode at ~14 GHz, was recorded while changing the temperature. The results are plotted in Fig.1b, where a significant positive temperature tunability coefficient of 15 MHz/°C has been observed for the structure incorporating the ferroelectric layer. For comparison, we also measured the temperature tunability of a conventional DLA structure, which was constructed with a single layer dielectric tube (dielectric constant of 4.7, inner radius of 4.79 mm and outer radius of 7.49 mm to obtain the same operating frequency as the tunable DLA structure). The result is also plotted in Fig.1b.

The slightly negative frequency response coefficient (-200 kHz/°C) of the conventional DLA structure is caused by the thermal expansion of the copper tube.

The wakefield experiment was performed at Argonne Wakefield Accelerator (AWA) facility located at Argonne National Laboratory (ANL). A diagram of the beamline is shown in Fig. 2. 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 [10]. 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 [11].

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 [11]. 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 (20º and 70º) 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. 3 which shows the calculated longitudinal wakefields of the tunable DLA 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. Due to the temperature variation of the ferroelectric material properties, the RF properties of the DLA structure will change as well. For example, the quality factor of the 14 GHz mode will drop by approximately 16% from the peak due to the 50° C change in temperature.

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 DLA 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 DLA 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 DLA structure.

The comparison between theory and measurement is shown in Fig. 4. The longitudinal wakefield of the tunable DLA structure was calculated by using the analytical solution for the wakefields in a multilayer dielectric-lined circular waveguide [12] and the method presented in [13]. 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. 4 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 DLA structure can change by 1.6 units (or ~0.5%) /°C. The larger discrepancy between the measured and calculated wakefields observed at lower temperatures likely arises from a combination of two effects: a strong nonlinear behavior of the ferroelectric material loss and beam jitter present during the experiment.

For future reference we note that, in addition to the temperature control, a DC bias voltage will also change the dielectric constant of the ferroelectric material. A 0.5 ns per degree response in a ferroelectric based phase shifter was reported recently [14]. While introduction of a high DC voltage to a tunable DLA structure in the vacuum requires specific designs (some possible technologies have been suggested [5]), this approach is still attractive due to its short response time compared to the temperature control. In order to evaluate this concept, we bench tested another tunable DLA structure under a high voltage DC bias. The configuration and parameters are shown in Fig. 5a. The length of the dielectric tube is two thirds of the ferroelectric tube. The inner surface of the rest one third of ferroelectric tube was metalized (coated with silver ink) and connected to positive DC voltage. The silver layer thickness was much less that one skin depth at the relevant frequencies. The outer surface of the ferroelectric tube was coated with the silver ink as well to allow a good electric contact with the grounded copper jacket. A 5000 V, 2 mA dc power supply was used to apply high voltage biasing at the inner surface of the ferroelectric skirt. Similarly, a TM mode launcher was used at one side of the device to excite the longitudinal modes of the tunable DLA structure. The measurement results are plotted in Fig. 5b. A maximum 6 MHz frequency shift was measured for the lowest resonance frequency with a 2.5 kV DC applied bias voltage. A tuning coefficient of ~0.1 MHz/ (kV/cm) is estimated for this particular case. Note that the tuning range in this device will depend on the size of the ferroelectric surface area to which the high voltage DC is applied.

In conclusion, a novel low loss BSTM ferroelectric material has been used in dielectric based accelerators as a method of frequency tuning. Measurements show an excellent tuning capability through control of either temperature or DC bias voltage. A wakefield experiment using an accelerated witness beam successfully demonstrated this technique using the first tunable DLA structure. One can conclude that the best solution for the future tunable DLA structures would be a combination of ”coarse” but slow temperature tuning by 100s of MHz and rapid fine tuning with high voltage dc biasing applied. The new nonlinear ferroelectric material is also good candidate for other high vacuum, high gradient applications.

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TABLE I. Design 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 (σ_z=2.3 mm)	16 MeV/m

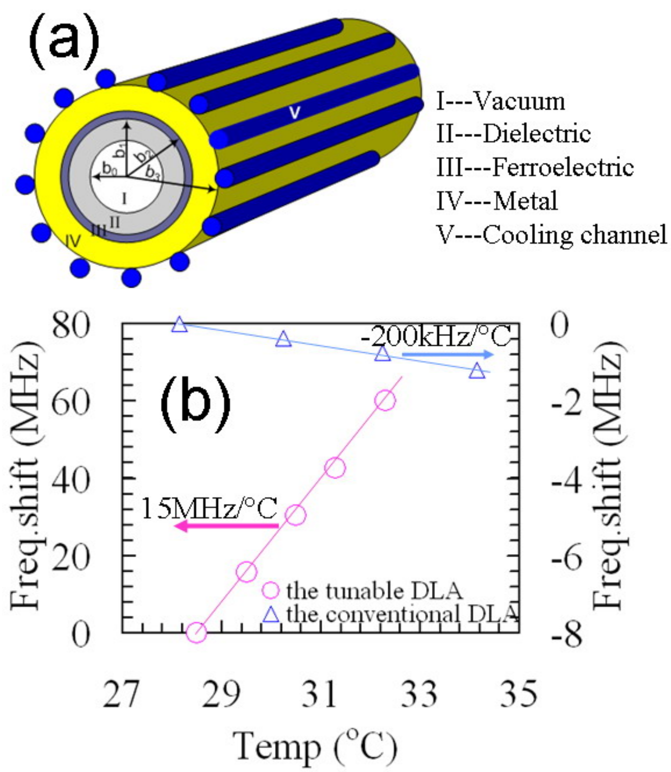

FIG.1: (a) The tunable DLA structure; (b) Comparison of the temperature dependence of the 14 GHz tunable and a conventional DLA structures as measured using the network analyzer.

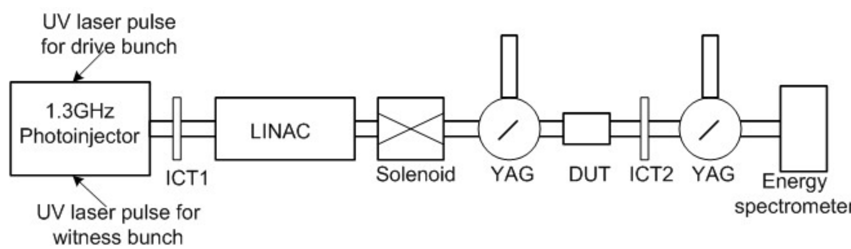

FIG.2. Simplified diagram of the AWA 15 MeV beamline used to perform the wakefield acceleration experiment.

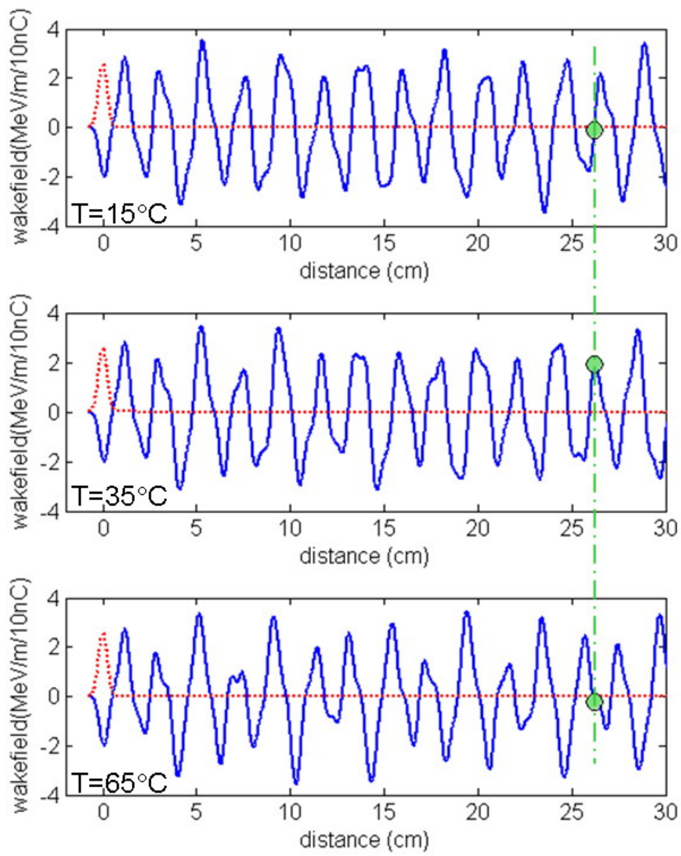

FIG.3. The calculated wakefield of the tunable DLA structure for three different temperatures which correspond to three different permittivities of the loaded ferroelectric material. A witness bunch is trailing 26.2 cm behind the drive bunch for all cases. The solid line is the wakefield; dashed line is the drive bunch; and the large dot represents the position of the centroid of the witness bunch.

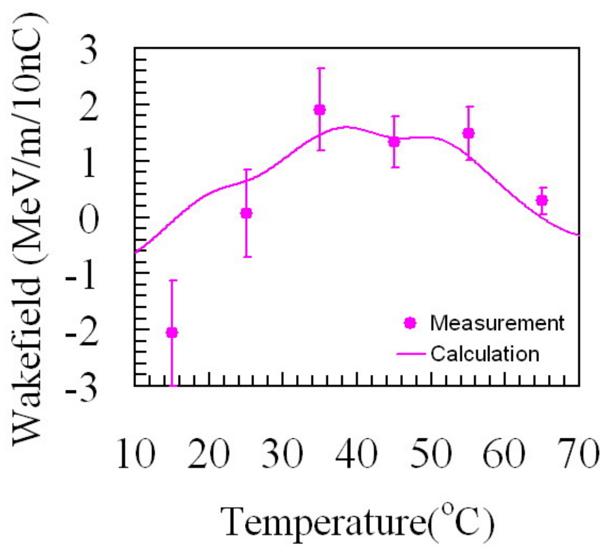

FIG.4. Comparison of the measured and calculated wakefield (normalized to 10 nC drive bunch) excited in the DLA structure as a function of temperature.

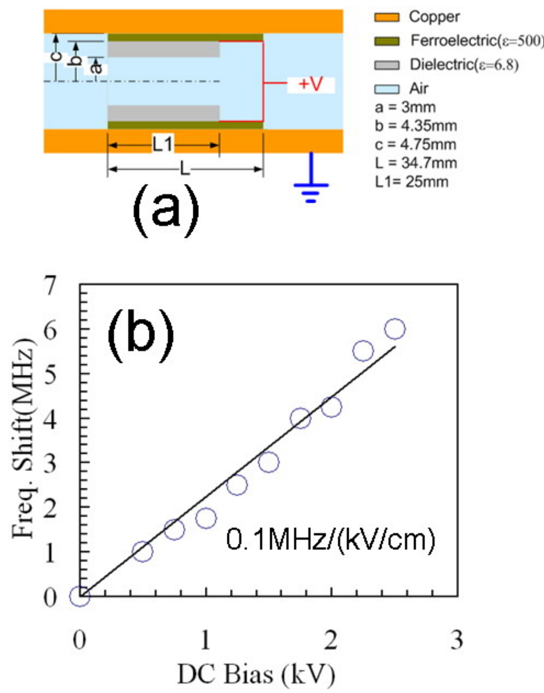

FIG.5. (a) Bench test configuration of a DC voltage tunable DLA structure; (b) Bench measurement result (frequency change vs applied DC voltage).