NONLINEAR DIELECTRIC WAKEFIELD EXPERIMENT FOR FACET*

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Abstract

Recent advances in ferroelectric ceramics have resulted in new possibilities for nonlinear devices for particle accelerator and rf applications. The new FACET (Facility for Advanced Accelerator Experimental Tests) [1] at SLAC provides an opportunity to use the GV/m fields from its intense short pulse electron beams to perform experiments using the nonlinear properties of ferroelectric DLAs (dielectric loaded accelerators). Simulations of Cherenkov radiation in THz nonlinear structures to be used in FACET experiments will be presented. Signatures of nonlinearity are clearly present in the simulations: superlinear scaling of field strength with beam intensity, frequency upshift, and development of higher frequency spectral components.

FERROELECTRIC MATERIALS

Recent developments in the manufacture of nonlinear ferroelectric ceramics have opened up new possibilities for advanced nonlinear devices for accelerator and rf applications. Frequency agile wakefield structures have been demonstrated [2]. Beam diagnostics based on nonlinear waveguides are another possibility, since the frequency spectrum is a function of both beam intensity and pulse shape. Nonlinear structures may also find applications in rf sources for frequencies (such as sub-mm waves) not easily accessible by conventional technologies. Electromagnetic shock formation can be used to produce intense short broadband rf bursts. Finally, a major focus of this paper is the application of wave steepening/pulse compression effects in nonlinear waveguides to enhance the performance (gradient and efficiency (transformer ratio)) of wakefield accelerators.

A ferroelectric ceramic is a material with an electric field dependent dielectric permittivity that can be very rapidly altered by either an external bias voltage pulse or strong transient fields in the material. Typical representative ferroelectric materials are $(Ba,Sr)TiO_3$ or a $BaTiO_3 – SrTiO_3$ solid solution (BST). The BST material can be synthesized in polycrystalline, ceramic layer and bulk forms. BST(M) ferroelectrics (BST material with Mg-based additives) exhibits some very favorable properties for wakefield accelerator applications. The relative dielectric constant ε can be tuned over a wide range. Furthermore very small values of the loss tangent can be achieved even at high frequencies, e.g. in the (3-4)$\times 10^{-3}$ range at 11.4 GHz.

Response times of $\sim 10^{-11}$ sec for the crystalline form and $\sim 10^{-10}$ sec for ceramic compounds have been measured. Unlike semiconductors and plasma devices, ferroelectrics allow control of their dielectric properties in two directions using a single external control pulse.

Technologies based on nonlinear optical phenomena have had a significant impact in the laser field, where harmonic generation and other effects are routinely and productively used. Similar effects have been employed at rf frequencies where the nonlinear properties of ferrite loaded transmission lines have been used to produce short rf pulses at MHz frequencies [3]. Substantial progress in the area of ferroelectric-based ceramic materials offers the possibility of extending the frequency range of nonlinear rf devices to X-band and above.

Serious interest and progress in microwave dielectric materials has arisen in part from studies of dielectric loaded accelerating structures and beam driven microwave sources [4]. Also, early in the development of quantum electronics nonlinear dielectrics were already being studied as harmonic generating devices [5]. The properties of wakefields in a nonlinear dielectric waveguide were initially studied a number of years ago [6]. Numerical experiments showed that some nonlinear wave sharpening did occur and resulted in enhancement of the acceleration gradient.

Euclid has been involved in the development of ferroelectric compositions for electronic applications. These materials have been synthesized for use in advanced technology components for X-band and Ka-band RF systems in high gradient accelerators, and offer significant advantages for high power RF manipulation. These low loss ferroelectric materials have so far been used as key elements of both tuning and phase shifting components [2, 7].

When ferroelectrics are used for tuning accelerating structures [2, 8], the permittivity of a slab or cylindrical shell of the material is adjusted with an applied DC bias voltage. Typical values of the tunability (change in relative permittivity with a change in the electric field) are roughly 30% and can be up to 80% at 4-5 MV/m [9] with a reasonable loss tangent of $\sim 5\times 10^{-3}$ at X-band.

The high dielectric constant of ferroelectrics (~500) is not desirable for many applications. For example, the use of high permittivity materials leads to enhanced wall losses in cylindrical geometries. Lowering the permittivity (and the loss tangent) through the use of ferroelectric-low loss tangent dielectric composites is the approach we plan to follow. Theoretical work [10] has shown that ferroelectric composites can be designed that also preserve or even enhance the tunability of the material, and DC permittivities ~100 in nonlinear ferroelectric ceramics are feasible.

In the tunable devices studied so far by Euclid [2], the electric field of the rf signal is much smaller than the strength of the dc bias field used of to modify the average permittivity of the loading material. In these cases the rf

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field has a negligible additional effect on the permittivity. We consider here the large signal case where the permittivity of the ferroelectric loading of a dielectric wakefield structure or resonator is significantly affected by the strength of the rf field.

NONLINEAR DLA EXPERIMENTS

We have the opportunity to use the GV/m fields available at FACET to perform experiments using nonlinear DLAs. Ultimately the goals of this research are to show that nonlinear effects can be used to enhance the accelerating field in dielectric wakefield accelerators and to investigate the application of rf frequency multiplication to high frequency rf sources.

The nonlinear materials considered here are commonly characterized by the tunability $n \equiv \varepsilon(E=0)/\varepsilon(E)$. For a composite of a low permittivity linear dielectric and a ferroelectric, Tagantsev [10, 11] showed that the relationship between the electric field and the tunability is of the form

$$E(n)=\xi(n+2)\sqrt{(n-1)} \qquad (1)$$

Besides the constant of proportionality ξ the other free parameter in this expression is $\varepsilon(E=0)$, the zero field permittivity. Based on dynamic and static tunability measurements [13], we can obtain approximate values for the two free constants. A plot of the displacement as a function of electric field obtained by inverting this expression is shown in Fig. 1.

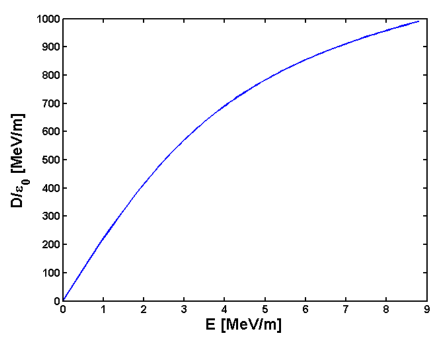

Figure 1: Approximate constitutive relation based on dynamic tunability measurements for BST(M).

Eq. 1 provides a good starting point for the analysis of the full nonlinear problem although there are several questions concerning ferroelectric properties that will need to be settled by this experiment. One is the issue of the frequency response of the nonlinear medium. Another issue is the electric field strength at which the medium saturates, i.e. where the response becomes linear again. Wave breaking, which may not be well modeled by the simulation code, can be studied in this experiment. Analysis of the data will provide the opportunity to determine these properties of ferroelectrics at field strengths and frequencies unavailable in bench tests.

There are a number of commercial and in-house software packages available to model wakefields and electromagnetic wave propagation. The capability of treating nonlinear effects in electrodynamics codes is not widely available. The common Yee algorithm for time and space discretization does not handle nonlinear effects well; the tendency towards formation of shocks (singularities in the fields) leads to the development of large unphysical oscillations unless the algorithm is modified.

The Arrakis code [12, 13] was developed to model electromagnetic wave propagation in nonlinear and dispersive dielectrics in a coaxial geometry. The code is capable of treating electromagnetic shock formation and propagation.

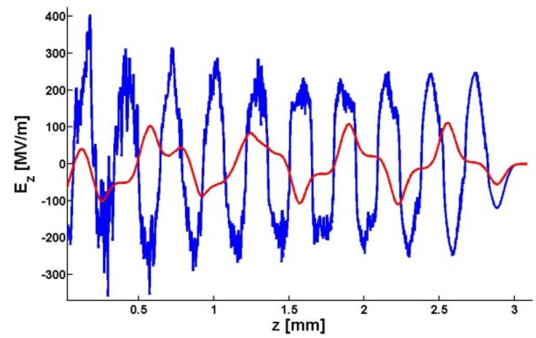

Figure 2: Computed wakefield (snapshot of the axial electric field) in a 300 GHz nonlinear dielectric structure, $\varepsilon(E=0)=225$, a=50 μm, b=61 μm, with beam parameters σ_z=50 μm. Red: Q=0.003 nC (scaled to 0.3 nC); Blue: Q=0.3 nC. The center of the beam is at approximately 2.9 mm.

We expect that the nonlinear regime can be attained easily for structures made from composite ferroelectrics and using the FACET beam. We consider a 300 GHz structure loaded with the composite dielectric with field-dependent permittivity as shown in Fig. 1. Arrakis simulations were run for beam intensities of 0.003 and 0.3 nC, corresponding to linear and weakly nonlinear cases respectively. No other beam or dielectric parameters were changed.

Fig. 2 shows a comparison of the axial electric fields for different beam intensities. (For clarity, the Q=0.003 nC data is multiplied by a factor of 100; thus for the case of a linear medium the curves would be identical.) Signatures of nonlinearity are clearly present: superlinear scaling with bunch charge, frequency upshift, and development of higher frequency spectral components (Fig. 3).

The possibility of identifying the existence of an electromagnetic shock wave in the simulations is of interest. The Arrakis code can handle weak shocks because of the numerical viscosity built into the algorithm. The presence of stronger shocks requires more sophisticated techniques such as shock capturing or fitting. A possible hint of the need for an expanded approach is the presence of very high frequency oscillations (Gibbs phenomenon) on the crests and troughs of the nonlinear case in Fig. 2. Nevertheless, it is apparent that the FACET experiment will have a good shot at observing and diagnosing nonlinear wakefield effects in ferroelectric structures.

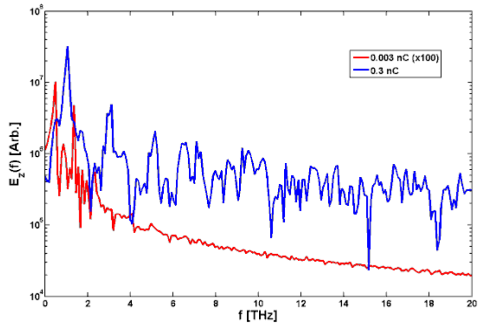

Figure 3: Spectra of the wakefields from Fig. 2. The effects of nonlinearity are apparent from the frequency upshift of the fundamental mode and the increased high frequency spectral content in the high charge data.

The dielectric that will be used for the nonlinear wakefield structures is based on a heterogeneous mixture of ferroelectric and magnesia. The ferroelectric is a $(Ba,Sr)TiO_3$ (BST) solid solution with the optimum ratio of barium and strontium. The barium/strontium correlation in the compound with the perovskite structure determines the Curie temperature of the ferroelectric. The value of the Curie temperature shifts towards lower temperatures with the increase of strontium concentration in the solid solution. Meanwhile, the increase of the strontium titanate content leads to the sharp decrease of both the dielectric constant of the BSTO (BST-Oxide) solid solution (~several thousand close to the ferroelectric phase transition) and the electric field tunability.

Addition of magnesia (a linear dielectric with $\varepsilon \approx 9.8$ and $\tan \delta \approx 10^{-4}$ at microwave frequencies) to the solid solution within a wide concentration range leads to the formation of a mechanical mixture of initial phases that weakly interact with each other at the sintering temperatures of ceramics. It makes it possible to use these compositions as the source to produce ferroelectrics with a given ε while maintaining both the high tunability from the BST and low dielectric losses in the microwave range.

The electrical properties of the samples can also be influenced by shaping methods like hydraulic pressing, isostatic pressing, and extrusion, as well as the technology of the thermal treatment of the initial powders and the sintering of ceramic preforms on the base of these powders. We intend to perform investigations of the physical and chemical properties and the structure of the ferroelectric samples of the composition $(Ba_x,Sr_{1-x})TiO_3$ ($x = 0.4 – 0.6$) with complex additives of magnesium compounds.

SUMMARY

BST(M) ceramics have been developed that possess simultaneously large tunability factors, small zero-field dielectric constants, and small loss tangents. The effects of dynamic dielectric nonlinearity have been studied in numerical simulations and have led to designs for nonlinear wakefield devices. Measurements of wakefields in these structures are planned for the new FACET facility at SLAC.

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