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)TiO₃ or a BaTiO₃ – SrTiO₃ solid solution (BST). The BST material can be synthesized in polycrystalline, ceramic layer and bulk forms. BST(M) ferrolectrics (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)\times10^{13} range at 11.4 GHz.

Response times of \(-10^{-11}\) sec for the crystalline form and \(-10^{-10}\) 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 \(\approx5\times10^{-3}\) 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 to modify the average permittivity of the loading material. In these cases the rf
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 \( n = c(E=0)/c(E) \). 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

\[
E(n) = \xi (n+2) \sqrt{(n-1)} \quad (1)
\]

Besides the constant of proportionality \( \xi \) the other free parameter in this expression is \( c(E=0) \), 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.

\[
\varepsilon(E=0) = 225, a = 50 \mu m, b = 61 \mu m, with beam parameters \sigma_0 = 50 \mu m. Red: Q = 0.003 nC (scaled to 0.3 nC); Blue: Q = 0.3 nC. The center of the beam is at approximately 2.9 mm.
\]

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.
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.

REFERENCES