A TUNABLE DIELECTRIC LOADED STRUCTURE WITH BUILT IN TRANSVERSE MODE SUPPRESSION

A. Kanareykin, Euclid Concepts LLC, Solon, OH 44139, USA
A. Altmark, I. Sheinman, Electrical Engineering University, St. Petersburg, 197376, Russia

Abstract

Recently, a method for tuning dielectric-loaded accelerating (DLA) structures has been proposed [1,2]. In these structures, a ferroelectric layer backs a conventional ceramic layer, thus allowing the effective dielectric constant of the waveguide to be varied by applying a DC electric field to the ferroelectric layer. In this paper, we present a design for a cylindrical version of this multilayered, tunable DLA structure that has the additional benefit of suppression of transverse deflecting modes [3,4] due to the axially segmented conducting wall. This structure consist of a layer of conventional ceramic, surrounded by a thin layer of a ferroelectric, that is in turn surrounded by axially-oriented, insulated microstrip electrodes and a layer of absorbing material (ferrite). The axial orientation of the microstrips means that transverse deflection modes are suppressed, since they require an azimuthal current, while longitudinal accelerating modes are allowed, since they only require axial currents. We will present calculations of the relevant accelerator parameters for a cylindrical DLA structure.

INTRODUCTION

A new method of wakefield acceleration of the charged particles, using wakefields generated by the short high charge electron bunches passing through dielectric loaded accelerating structure, now is the object of intensive experimental and theoretical study. Commonly a dielectric loaded accelerating structure (DLA) is the single-layered dielectric (ceramic) tube with an inner vacuum channel for the passing electron beams. A dielectric cylinder is inserted into a conductive copper jacket.

Wakefield acceleration assumes the energy transfer from a high-current low-energy electron beam (driver) to a low-current high-energy accelerating beam of charged particles (witness). While passing the ceramic waveguide the driver beam generates Cherenkov electromagnetic waves (wakefields) with the longitudinal fields up to 100 MV magnitudes to be used for the witness beam acceleration.

Large amplitude longitudinal wakefields also imply that strong transverse deflecting forces will be generated if the drive beam in the structure is misaligned. This deflection field can have serious detrimental effects on the accelerated beam from the head - tail single bunch break up instability of the accelerated beam, resulting from the leading particles in an offset bunch driving HEM modes that in turn deflect the electrons in the tail of the bunch. The deflected tail electrons will eventually be driven so far off axis that all or most of the particles will be lost by scraping on the inner walls of the dielectric waveguide. On the other hand, synchronization between the electron beam velocity and the phase velocity of the accelerating field must be maintained in order for the bunch to gain energy. For some applications DLA structure requires an unachievably tight machining tolerance of the waveguide geometry and extremely expensive ceramic material manufacturing process. Recently, a method for tuning DLA structures has been proposed [1,2]. A combination of ferroelectric and ceramic layers have been used to permit tuning of a composite ceramic–ferroelectric waveguide while keeping the overall material loss factor in the $(4\div5)\times10^{-4}$ range. It was shown that the losses in the composite structure are comparable to the losses in conventional DLA structures that consist of a single dielectric cylinder inserted into a conductive copper jacket. Dielectric permeability variation allows adjusting of the phase-beam matching between the longitudinal wakefield and the witness beam position for acceleration mechanism efficiency. [6].

Tunable DLA Structure

The DLA structure with ferroelectric layer tuned by an external DC electric field is shown in Fig. 1. The inner layer is ceramic, with permittivity typically in the range of 4÷36. The outer layer is a film made of BST ferroelectric, dielectric constant of 200÷500, placed between the ceramic layer and the copper sleeve. The DLA structure tuning is achieved by varying the permittivity, ε_2, of the ferroelectric film by applying an external DC electric field across the ferroelectric. One can use the well-developed technology based on photolithography and microstrip contact deposition to supply a DC field to the ferroelectric film. This technology has been widely used in the field of high frequency phase-shifters and tunable filters design based on thin ferroelectric films. The main problems to be addressed in order to apply this technology for our particular design are:

- The configuration has to match the desired set of guiding modes
- DC field penetration into the ferroelectric layer with the field magnitude for the maximum tuning range (10 V/μm for the material to be used)
- Satisfy conditions of minimum insertion losses.

Fig. 1 shows our current preferred geometry for the configuration of the bias field microstrips for the ferroelectric-ceramic tunable DLA structure. Figure 2 shows the particular dimensions of the microstrips structure for (10÷13) GHz accelerating waveguide. One has to find an appropriate microstrip width for the particular layer. Our simulations showed that for the (180÷220) μm layer that corresponds to 11 GHz average frequency the optimal ratio is $h = 3\times d$, where h is the layer thickness and d is the strip width.

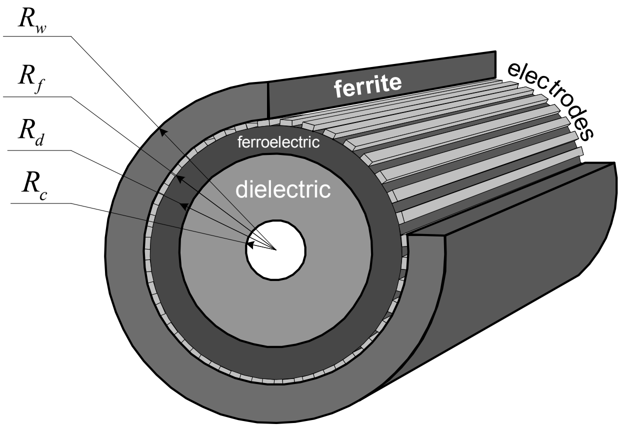

Figure 1. Tunable dielectric loaded accelerating structure with transverse deflecting modes suppression.

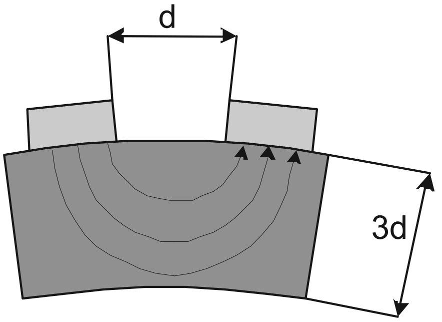

Figure 2. Microstrip profile. The ferroelectric layer thickness is within 3d, where d is a microstrips gap.

The microstrip separation is approximately d as well. For the (10÷13) GHz frequency range d = (50÷60) μ. A DC bias of (0.5÷1) KV is applied across this gap to provide the (5÷10) V/μ biasing field.

Transverse Biasing

It should be mentioned that the biasing field is transverse relative to the accelerating field for the microstrip configuration in Fig. 1. The ferroelectric material we plan to use is to be formed in a polycrystalline paraelectric phase [5] and does not show any significant anisotropy. One can refer here to the measurements of the 106 MHz shift of the TM_{01} fundamental frequency of the 11.42 GHz planar ceramic loaded waveguide with BST ferroelectric layer with the dielectric constant of 500 supplied with the *transverse biasing* field [5]. Microstrip configuration gap was 300 μ for the bias DC field of 2.8 V/μ.

Transverse Modes Suppression

The deflection modes cause BBU effects resulting in particle loss and consequently in acceleration distance limitation. An rf slow wave structure that supports accelerating modes while having damped the deflecting modes then be desirable. Such a device was proposed and experimentally tested in [3,4], where the uniform outer copper sleeve was replaced by axial, closely spaced, insulated wires that allow only axial wall currents of the system. This anisotropic copper metallization provides very low Q factor selectively for the deflecting transverse modes while maintaining high Q for the accelerating mode. The axial orientation of the microstrips means that transverse deflection modes are suppressed, since they require an azimuthal current, while longitudinal accelerating modes are allowed, since they only require axial currents. The direct wakefield measurements showed the attenuation was consistent with the 246 pcs e-folding time bench test and therefore the BBU effects can be greatly reduced in the DLA structures [3].

One can see in Fig. 1 and Fig. 2 that the microstrip configuration completely satisfies the transverse mode suppression design discussed above. It is fortunate we have all-in-one transverse mode suppressor and tunable accelerating structure providing with the same microstrip configuration.

Fig. 3 presents HEM11 and HEM12 transverse mode magnitude vs. the distance behind the bunch of 100 nC charge, $\sigma_z = 0.4$ cm, the offset of $r_0 = 0.03$ cm. The three various thickness of absorbing ferrite Δ is shown. Parameters of the waveguide, Fig. 1, are: $R_c = 0.5$ cm, $R_d = 0.6$ cm, $R_f = 0.623$ cm, $R_w = R_f + \Delta$, dielectric constant of the ceramic layer $\varepsilon_d = 16$, dielectric constant of the ferroelectric layer $\varepsilon_f = 200$, ferrite conductivity $\sigma_{ferro} = 0.1$ $(\text{ohm}\times\text{m})^{-1}$, $\mu_{ferro} = 5$, $\varepsilon_{ferro} = 1$. One can see the deflecting field magnitude is almost flat for the relatively thin ferrite layer of 0.4 cm and it is damping dramatically for the ferrite layer of 0.8 cm thickness. The transverse field suppressor parameters are extremely sensitive to the right choice of the absorbing sleeve geometry due to the redistribution of the wakefields power over the waveguide boundaries.

Fig. 4 shows the transverse field superposition of HEM_{11} and HEM_{12} modes for the offset of 0.25 cm, the beam is deflected significantly. The repetitive rate frequency of the AWA photoinjector is 1.3 GHz that corresponds to 22÷23 cm available spacing between the bunches. One can see that the transverse field magnitude will be damped down by that distance.

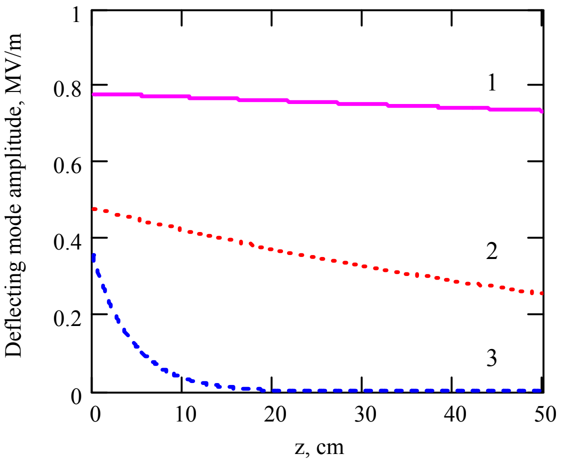

Figure 3. Magnitude of a radial deflecting field of the first transverse mode vs. the distance z behind the bunch for the 13.625 GHz accelerating structure. Three thickness of ferrite have been studied, 1 – Δ = 0.4 cm, 2 – Δ = 0.5 cm, 3 – Δ = 0.8 cm. 100 nC beam offset is 0.03 cm.

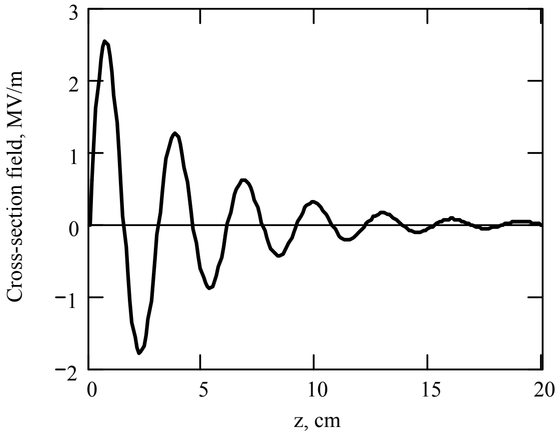

Figure 4. Deflecting field magnitude vs. the distance *z* behind the bunch, offset is of 0.25 cm, the beam is deflected off the half of the vacuum channel radius.

The beam misalignment will cause the azimuthal field between the microstrips embedded into the ferroelectric layer [7]. Figure 5 shows that the magnitude of this field is in the range of 0.5÷0.6 MV/m for the critically deflected beam with the offset is 0.25 cm and almost negligible for the initial offset of 0.03 cm. The DC bias field that we have used for the ferroelectric layer tuning [5] was in the range of 2.8 MV/m for the 300÷500 µm gap between the microstrips in comparison with 0.5 V/µm rf field at the same point.

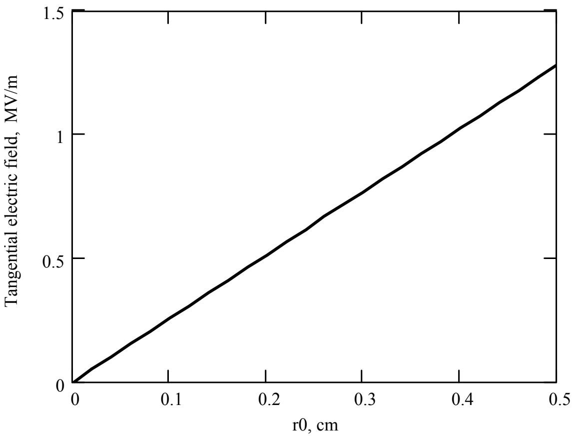

Figure 5. Azimuthal field magnitude between the microstrips vs. offset of the 100 nC electron beam passing through the 13.625 GHz accelerating structure. The beam rms length is 0.4 cm.

SUMMARY

The microstrip configuration for the tunable dielectric loaded accelerating structure fabricated with the double-layer ferroelectric technology will support the accelerating modes of the waveguide while the transverse deflecting modes can be damped. It should be noticed that the frequency tuning during the experiment favorably distinguishes the dielectric loaded accelerating structures from the conventional accelerators and opens a variety of applications for the systems with the “wave-beam” precise matching requirements.

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