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Electromagnetic simulation study of dielectric wall accelerator structures*

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Abstract: Two types of dielectric wall accelerator (DWA) structures, a bi-polar Blumlein line and zero integral pulse line (ZIP) structures were investigated. The high gradient insulator simulated by the particle in cell code confirms that it has little influence on the axial electric field. The results of simulations using CST microwave studio indicate how the axial electric field is formed, and the electric field waveforms agree with the theoretical one very well. The influence of layer-to-layer coupling in a ZIP structure is much smaller and the electric field waveform is much better. The axial of the Blumlein structure's electric field has better axial stability. From both of the above, it found that for a shorter pulse width, the axial electric field is much higher and the pulse stability and fidelity are much better. The CST simulation is very helpful for designing DWA structures.

Key words: DWA, electromagnetic simulation, DWA structures

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1 Introduction

Dielectric wall accelerator (DWA) [1, 2] technology incorporates an energy storage mechanism, a switching mechanism, and an acceleration mechanism. Electromagnetic simulation of DWA structures includes these effects and also details of the switch configuration and how that switch time affects the electric field pulse which accelerates the particle beam. DWA structures include both the Blumlein line and the zero integral pulse (ZIP) line configurations and the simulations include the effects of the beam pipe, the beam pipe walls, and the high gradient insulator (HGI) insulating stack. Design content includes the transmission line impedance (typically a few ohms), the driving switch inductances, and the layer-to-layer coupling effects and the associated effect on the acceleration pulse's peak value.

Figure 1 shows a sketch map of the DWA [3], which consists of stacks of Blumeins, HGI, the SiC photoconductive switches, the proton source, and the laser systems. The switches are controlled by the laser system. The axial accelerating electric fields are excited by the switches formed by the Blumleins. The proton source provides the protons for acceleration. The beam pipe consists of a dielectric cylinder (outer) and an HGI (inner), because of its high vacuum surface flashover breakdown strength. The structure of the HGI [4] is different from a traditional dielectric. It is formed by many alternating layers of metal and insulated dielectric.

In CST microwave studio, no switch element can be used directly, but from Ref. [5], a step-pulse approach was used instead. In this simulation work, the switching time was expressed by the step pulse with about 500 ps rising time. The voltage amplitude of the step pulse is 1 V. The simulated pulse waveforms agree with the experiments results very well [6], thus confirming that this method works well and is adaptive to simulate the DWA structures. The

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HGI stack is too complex to model and the computing time is very long, so before simulating the DWA structures, the high frequency (HF) character of the HGI was studied first. In a DWA design, the collapsing field from the pulse forming lines will penetrate to the inner wall of the beam pipe, to produce a high gradient field in which the ion beam will be rapidly accelerated.

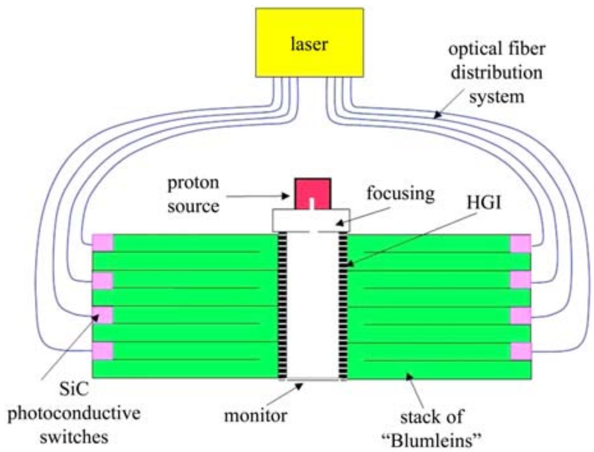

Fig. 1. Sketch map of the DWA.

2 High frequency character of the HGI

The HGI [7] involves the use of alternating layers of conductors and insulators with periods of order 1 mm or less. This structure performs many times better (about 1.5 to 4 times higher breakdown electric field) than conventional insulators in long-pulse, short-pulse, and alternating polarity applications. In a DWA, the wall of the accelerating tube is formed by an HGI. So the pulses collapsing from the pulse forming lines must be incident to the HGI and form the accelerating field in the tube. The PIC (particle in cell) method was used to simulate the dielectric wall tube without or with an HGI structure, to find the difference of HF characters between them.

The inner radius and height of the dielectric cylinder are 12 mm and 40 mm, respectively, and the ratio of insulator and metal thickness of the HGI is 3/1. The dielectric permittivity is 10. The eigenmode is calculated by using the PIC method. The results are shown in Fig. 2. Fig. 2(a) and (b) show the dielectric cylinder without an HGI, and (c) and (d) are the dielectric cylinder with an HGI.

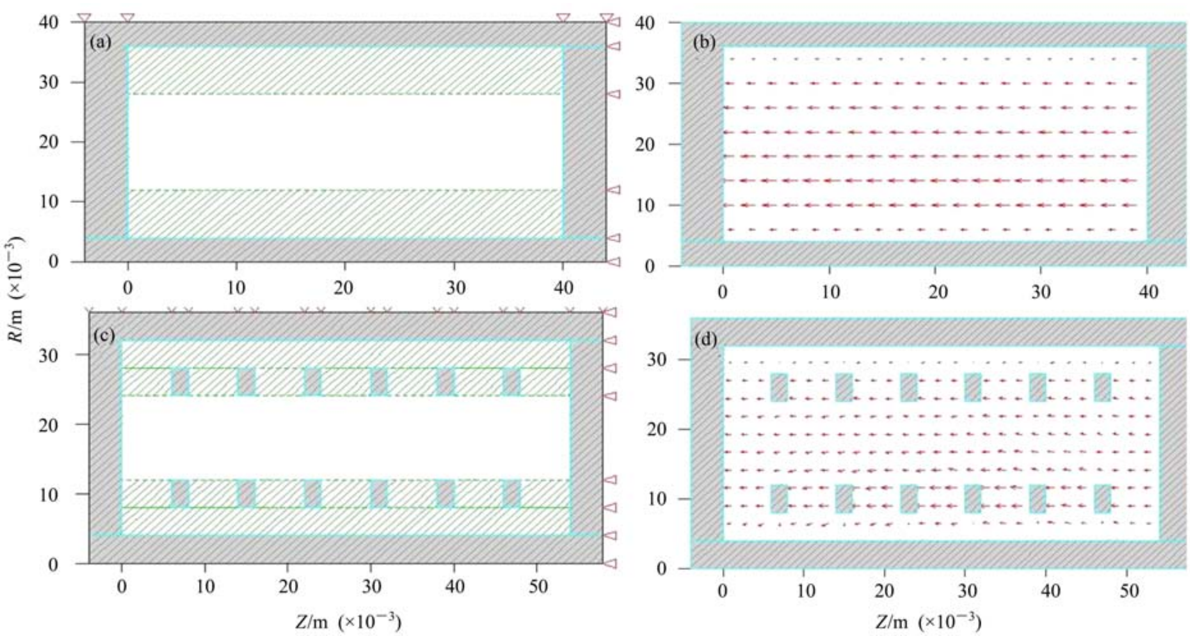

Fig. 2. The eigenmode simulation results of the dielectric cylinder without an HGI ((a) and (b)) and with an HGI ((c) and (d)).

The results of (b) and (d) confirm that with and without an HGI, the dielectric cylinder resonator is in the same modes; the eigenfrequency is slightly different. The inner electric fields have no differences between them. So the HGI does not change the field in the tube. The main use of an HGI is to enhance the surface flashover breakdown strength. Therefore in the DWA simulation, in order to simplify the model and to save simulating time, the HGI is not considered.

3 Two DWA structures

The DWA is designed with bi-line symmetrical structures. Double-ended feeds cancel the dipole magnetic fields in the beam pipe. The geometry parameters are the same for both Blumlein and ZIP structures. The line length is 75 cm, the width of the conductor is 12 cm, the thickness of the dielectric is 2 cm, and the thickness of the conductor is 0.5 cm. The permittivity of the dielectric is 10 and 2.2. Then the pulse width and the character impedance, are 15.8 ns and 20 Ω ($\varepsilon_r = 10$) and 7.6 ns and 42.4 Ω ($\varepsilon_r = 2.2$). The material of beam tube is the same as the line, of which the inner and the outer radius are 3.0 cm and 5.5 cm, respectively. The two DWA geometries are shown in Fig. 3(a) and (b), with four layers stacked together. The DWA can be operated by a single-pulse line one by one or a cell one by one. Here, one cell, composed of only four layers, was simulated to investigate the behavior of the electric field in the beam pipe.

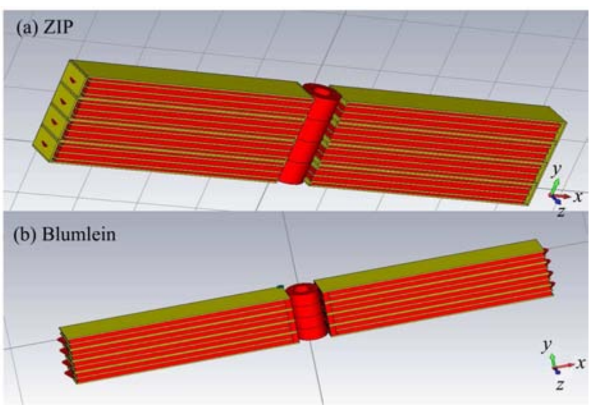

Fig. 3. (color noline) Two structures of (a) the DWA ZIP and (b) the Blumlein.

4 Simulation

The simulation was carried out using CST code with different permittivities of 10 and 2.2 for the same geometric parameters of both structures. The change of permittivity influences the pulse width and line character impedance. From Ref. [8], it confirms that the three-layer cylindrical electromagnetic scattering width will be different according to different permittivity and radius. Furthermore, the permittivity will influence the wave frequency propagating in the lines. The beam tube, which can be considered as a dielectric resonator, will work in different modes with different frequencies of excited signals.

4.1 Simulation of the Blumlein structure

The electric field in the middle of the beam tube is computed according to the above description. The beam direction is along y, and the transverse directions are x and z because the space of the beam tube is full of an electric field, and the transverse character of the beam must be affected. Thus, the distribution of the transverse electric field of x and z directions have to be considered. The electric fields at all three directions E_x, E_y and E_z are shown in Fig. 4(a) at $\varepsilon_r = 10$, and (b) at $\varepsilon_r = 2.2$. It is easy to know that the maximum of accelerating field E_y occurs in the middle of the tube. E_z gets the amplitude of about 1/4 of E_y for the high permittivity material and nearly zero for the low permittivity one. E_x is always nearly zero for both materials. It is obvious that a lower permittivity material (for the same geometric parameters) is a better candidate for designing and constructing a DWA to eliminate the influence of transverse aberration when an ion beam is accelerated. The waveforms of accelerating electric field pulses (E_y) at different points along the beam pipe central line are shown in Fig. 5. It also tells us that the electric field reaches

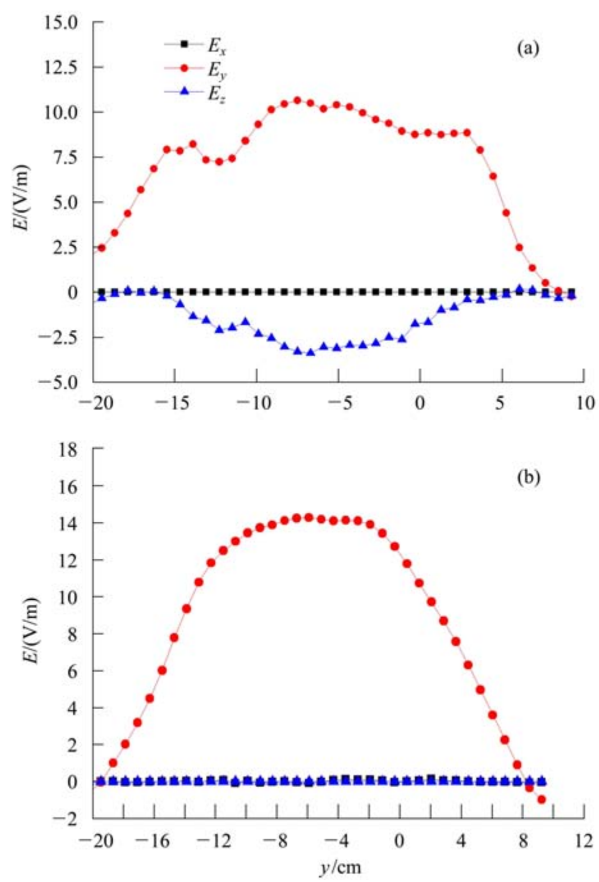

Fig. 4. Three directions of fields along the central line of the beam tube for the Blumlein structure at $\varepsilon_r = 10$ (a) and $\varepsilon_r = 2.2$ (b).

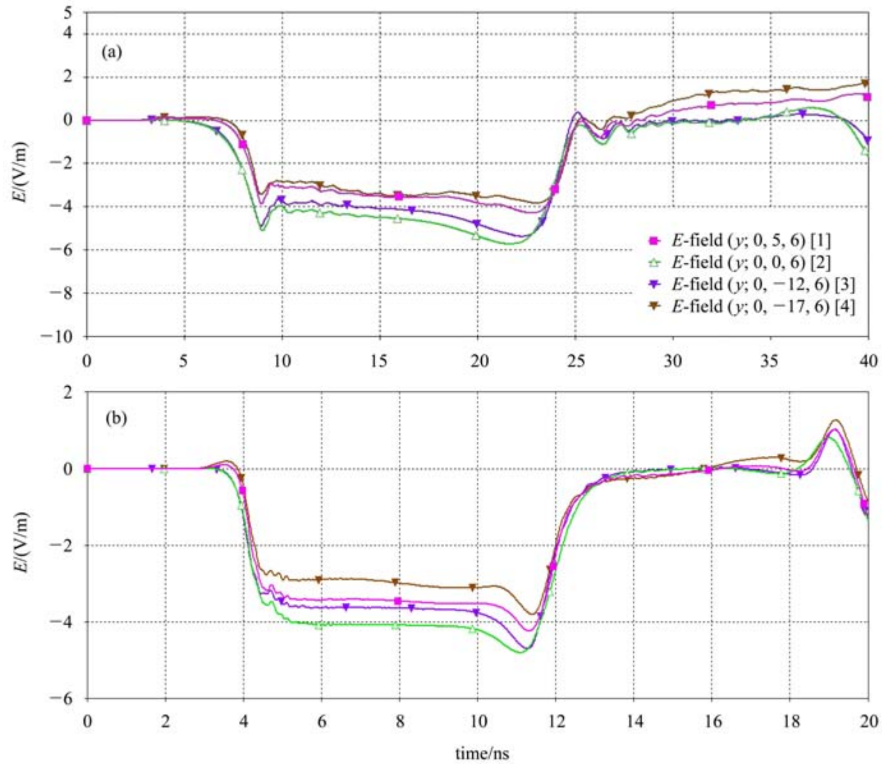

Fig. 5. (color online) The electric field waveforms E_y along the y axial at four points $\varepsilon_r = 10$ (a) and $\varepsilon_r = 2.2$ (b).

the maximum in the middle position and the waveforms are nearly consistent. The waveform is distorted compared with that of the single Blumlein's, because of the electromagnetic coupling of the layers. Furthermore, the length of the match line is difficult to determine, because it is affected by many factors, such as beam impedance and line impedance. The waveform for the low dielectric permittivity shown in Fig. 5(b) is better than the high one shown in Fig. 5(a).

4.2 Simulation of the ZIP structure

The ZIP simulation adopts the same method as the Blumlein one, and the considered plane is also the same, by which the results can be compared with each other. The main electric field direction is the same as the beam direction, here it is the y direction. But the other two directions are also considered, which affect the beam transverse character. The electric field amplitudes of three directions on the central line along the beam tube are shown in Fig. 6 at $\varepsilon_r = 10$ (a) and $\varepsilon_r = 2.2$ (b). In the middle of the beam tube, E_y gets the peak value. However, along the beam tube, the electric field E_y is not smooth, and has steps, mainly because of its structure. For a single ZIP line, at the output port, the up and down parts are shorted conductors, so there is no electric wave getting across.

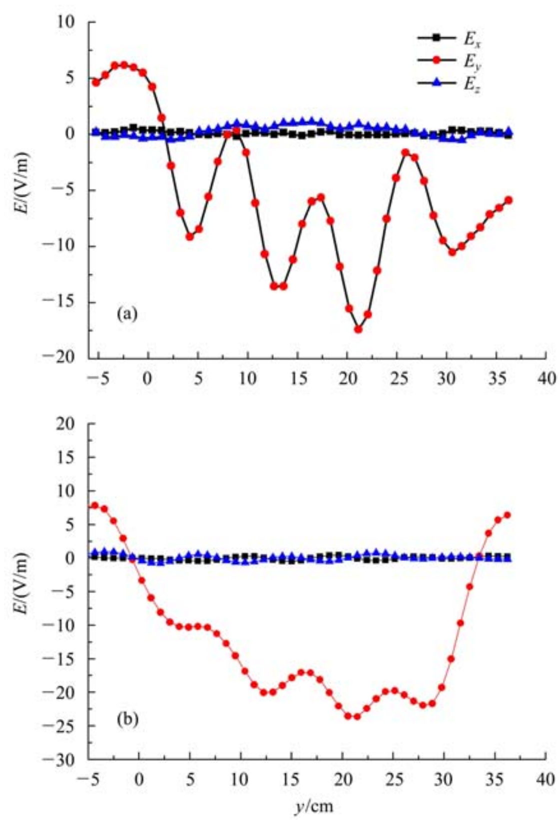

Fig. 6. Three directions of electric field on the central line along the beam tube for a ZIP structure at $\varepsilon_r = 10$ (a) and $\varepsilon_r = 2.2$ (b).

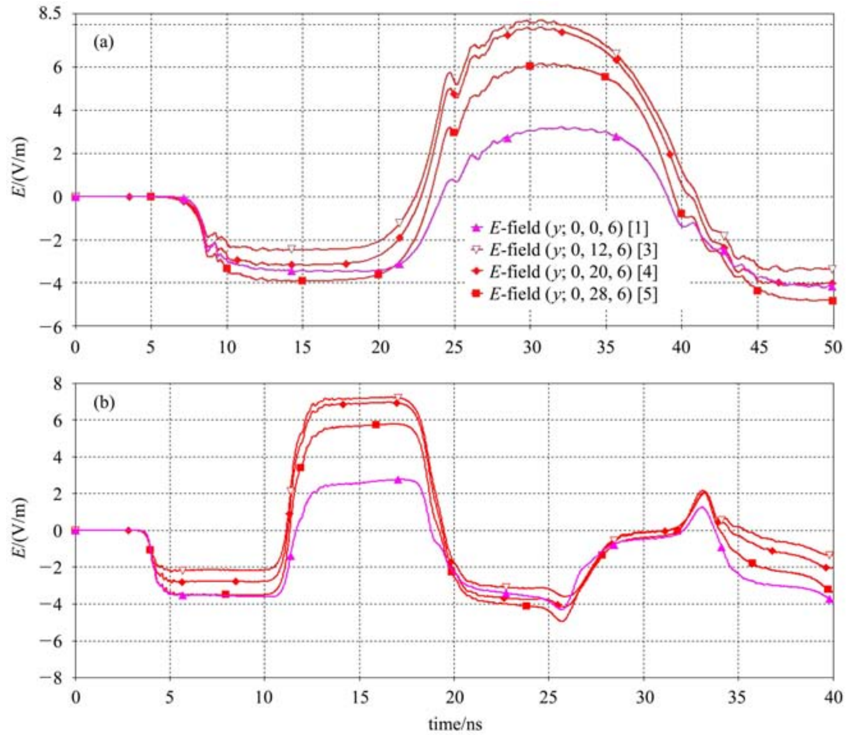

Fig. 7. (color online) The electric field waveforms E_y at different points $\varepsilon_r = 10$ (a) and $\varepsilon_r = 2.2$ (b).

Also, the E_y of low permittivity along the beam tube in Fig. 6(b) is smoother and larger than the one of high permittivity in Fig. 6(a). At both lower and high permittivity, E_z and E_x are nearly zero.

Figure 7 shows the electric field waveforms E_y along the y axial at four points (y=0, 12, 20, 28 cm). E_y at four different points shows excellent pulse stability and fidelity along the beam pipe. The waveform is well consistent with the single ZIP line's. It confirms that there is little coupling influence among each layer. The peak value of electric field is also in the middle of the beam pipe. However, in Fig. 7(a), the waveform is distorted more in the high permittivity one.

5 Conclusion

From the simulation results, although the ZIP structure is more complex, it has little coupling influence layer to layer according to the single ZIP line. The transverse character of the ZIP structure is better than that of the Blumlein one. Both the E_z and the E_x of ZIP are nearly zero, but the E_z of Blumlein is much larger. The ZIP structure can deliver storage energy absolutely to the load (beam), and it works more efficiently. The E_y of the Blumlein structure along the beam tube is smoother than the ZIP's, so it has better axial stability. Except the different structures, the dielectric permittivity is also considered. The dielectric permittivity affects the pulse width and line's impedance. For both structures, the axial electric field is much higher and the pulse stability and fidelity are much better with lower permittivity (shorter pulse width). However, the simulation results are consistent with Ref. [9]. The simulation by CST can be used to design DWA structures.

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