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LONGITUDINAL AND TRANSVERSE WAKEFIELDS SIMULATIONS AND STUDIES IN DIELECTRIC-COATED CIRCULAR WAVEGUIDES

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Abstract

In recent years, there has been a growing interest and rapid experimental progress on the use of e.m. fields produced by electron beams passing through dielectric-lined structures and on the effects they might have on the drive and witness bunches. Short ultra-relativistic electron bunches can excite very intense wakefields, which provide an efficient acceleration through the dielectric wakefield accelerators (DWA) scheme with higher gradient than that in the conventional RF LINAC. These beams can also generate high power narrow band THz coherent Cherenkov radiation. These high gradient fields may create strong instabilities on the beam itself causing issues in plasma acceleration experiments (PWFA), plasma lensing experiments and in recent beam diagnostic applications. In this work we report the results of the simulations and studies of the wakefields generated by electron beams at different lengths and charges passing on and off axis in dielectric-coated circular waveguides. We also propose a semi-analytical method to calculate these high gradient fields without resorting to time consuming simulations.

INTRODUCTION

The dielectric accelerator is one of the most advanced accelerator concept, in which the ultra high accelerating field can be excited by either optical to infrared laser or ultrashort relativistic electron bunches [1–3]. The beam driven dielectric wakefield accelerators (DWFA) make use of the electromagnetic Cherenkov radiation (wakefield) [4] from the electron bunches that pass through the dielectric-lined waveguides (DLW). In this paper we report the electromagnetic simulations performed by CST Microwave Studio [5] and HFSS [6] codes of an ultra-relativistic electron bunch that goes through a circular waveguide coated with a dielectric material.

THEORETICAL CONSIDERATION

Inside a circular waveguide filled with only one dielectric or completely empty, pure TM_{mn} and pure TE_{mn} electromagnetic (e.m.) modes can be excited. If the waveguide is filled with different dielectric materials, as in our case, pure modes becomes hybrid [7–9]. A generic hybrid TM mode could have a longitudinal component of the magnetic field and hybrid TE modes could have a longitudinal component of the electric field.

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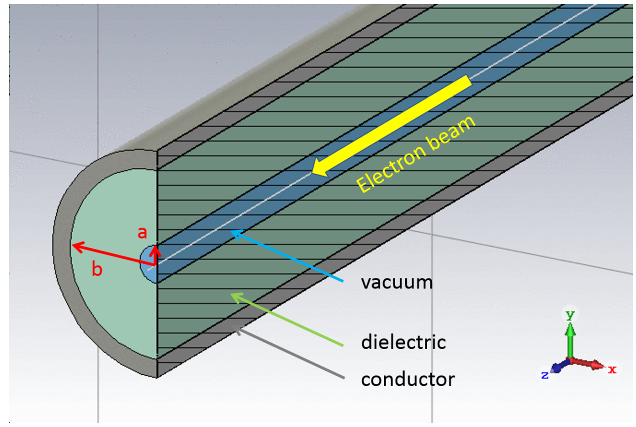

Figure 1: DLW geometry.

An electron beam traveling inside the hybrid waveguide having zero transverse component of the velocity can couple exclusively with those e.m. modes that have a non zero component of the longitudinal electric field.

If the beam travels on-axis, it can couple only with monopolar modes having the first index $m = 0$, the hybrid TE modes have not longitudinal electric field on-axis but only off-axis, so in this case, the beam can couple only with TM_{0n} modes. If the beam travels off-axis, it can couple even with the other multi-polar modes both transverse magnetic and, in theory, transverse electric hybrid modes that could have a little longitudinal component off-axis.

When a relativistic electron bunch passes near a material boundaries, e.m. fields generated by the head of the bunch affect the tail of the bunch through the short range wakefield or those of the following bunches through the long range wakefields. In the case of metallic boundaries, both the electrical resistance of the metal and the geometric variation of the boundary contribute to the wakefields. In the case of a dielectric boundary, the Cherenkov radiation condition will be satisfied when the particle velocity $\beta = v/c > \epsilon_r^{-0.5}$, in which case the beam generate wakefields.

PARTICLE IN CELL SIMULATION RESULTS

Here we report the result of Particle In Cell (PIC) simulations performed with CST Microwave Studio package [5]. The reference geometry is that of Figure 1. The outer radius is $b = 2.5$ mm, the circular waveguide is filled, from the radius $a = 0.5$ mm to the outer radius, with a perfect dielectric material of dielectric constant $\epsilon_r = 4.82$, the external

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conductor is loss free. The length of the structure is about 100 mm. We considered gaussian electron beams of different lengths and different charges, we explored longitudinal dimensions that goes from σ_z = 1 mm to σ_z = 0.1 mm and charges from 50 pC to 200 pC. The electron beam energy is E = 126 MeV, the transverse dimension of the beam is that of the metal cathode which must be defined in the PIC simulations. We have chosen a beam transverse dimension of σ_t = 0.15 mm. Figure 2 shows the absolute value of the electric field inside the dielectric guide when the electron beam has almost reached the exit of the structure, after t = 0.29 ns from the cathode emission (left part).

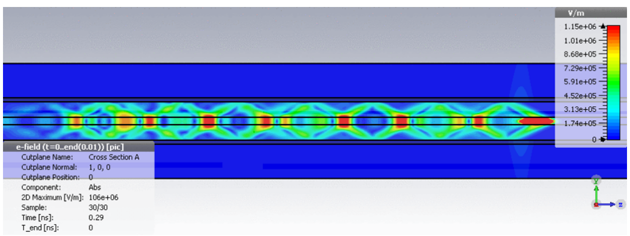
Figure 2: |**E**| behind the electron beam, inside the DLW, at time 0.29 ns, when the beam is at z = 80 mm.

Simulations were performed with on-axis electron beam for different charges and longitudinal dimensions, and with the electron beams passing off-axis.

Electron Beam On-Axis

Electron Beam Charge Variation Figure 3 shows the longitudinal electric field (E_z) on the axis behind the electron beam for different values of the total charge (50 pC, 100 pC and 200 pC), keeping the longitudinal dimension of the beam fixed at σ_z = 1 mm. There is a direct proportionality between the electric field amplitude and the total charge, as reported in [10–12].

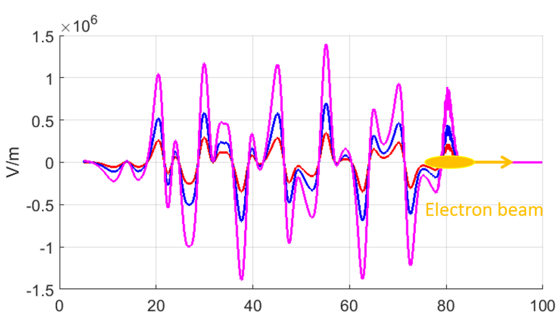

Figure 3: E_z behind the electron beam, after t = 0.29 ns from the cathode emission, for different beam total charges: 50 pC (red); 100 pC (blue); 200 pC (magenta).

Electron Beam Length Variation Figure 4 shows the longitudinal electric field (E_z) for 50 pC charged beam for different longitudinal dimensions σ_z (1 mm, 0.5 mm, 0.3 mm and 0.1 mm). The effects of the beam shortening are substantially two: the field amplitude is inversely proportional respect the beam length [10] and the field on axis tends to concentrate at a distance determined by the thickness of the dielectric ($b - a$ of Figure 1). For shorter electron beams the longitudinal electric field assume a spike shape, presenting zones with a high accelerating gradient. For these structures (Figure 1), using 0.1 mm long beams, electric fields of the order of some MV/m are reached.

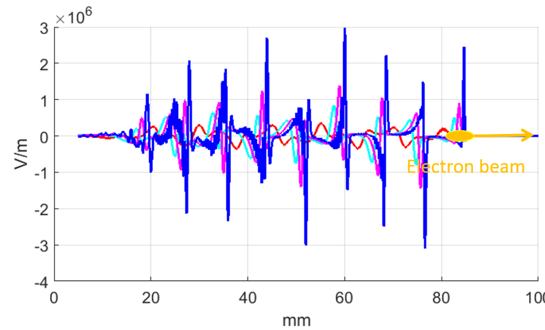

Figure 4: E_z behind the electron beam, at t = 0.29 ns, for different σ_z: 1 mm (red) line; 0.5 mm (cyan); 0.3 mm (magenta) and 0.1 mm (blue).

Electron Beam Off-Axis

For the simulations with the off-axis beam we focused on the lower sigma, σ_z = 0.1 mm. We have used a shorter structure, 30 mm long, (see Figure 5) to save simulation time, since billions of meshes are needed. Furthermore, a structure with the same traversal dimensions was simulated but without the external cylindrical conductor to align the simulations results with the measurements at SPARC_LAB [13,14] at LNF (107 MeV, σ_z = 0.105 mm). The difference in the absence of an external conductor is that the field generated behind the beam has a decreasing amplitude. The e.m. field emitted is transmitted through the dielectric-vacuum discontinuity and thus its on-axis component is damped.

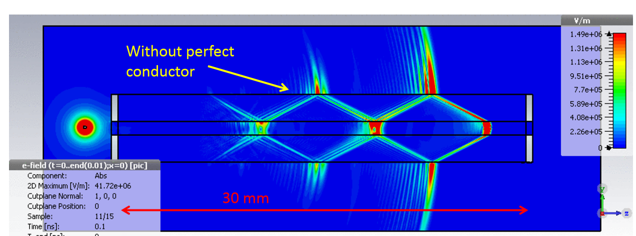

Figure 5: |**E**| behind the electron beam, inside the DLW, at time 0.10 ns, when the beam is at the longitudinal coordinate z = 27 mm, 0.1 mm off-axis of the 30 mm long structure.

Longitudinal Electric Field The on-axis longitudinal electric field (E_z) for the off-axis electron beam is reported in Figure 6. Even without the external conductor the field preserves its spike shape, the amplitude is around 3 MV/m but it is evidently damped behind the beam position. The longitudinal field does not show variation as the transverse position of the beam varies. This is due to the fact that

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the E_z field of the monopolar modes (TM_{0n}) in a rather extended area around the axis has an approximately constant behaviour.

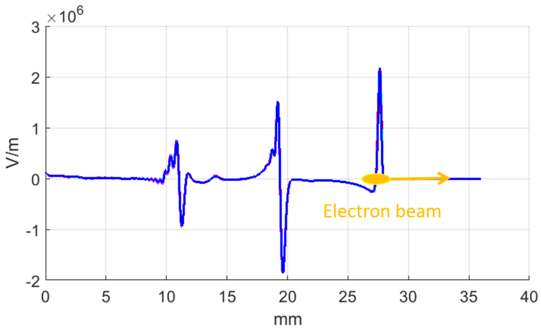

Figure 6: E_z behind the electron beam, after $t = 0.1$ ns from the cathode emission, for different transverse position of the cathode: on-axis; 0.1 mm; 0.2 mm and 0.3 mm.

Transverse Electric Field The on-axis traverse electric field (E_y) for the off-axis electron beam, under the same condition as the Figure 5, is reported in Figure 7 where it is possible to see a zoom of the region around the beam.

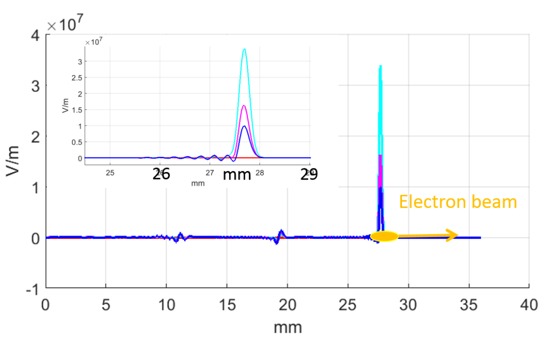

Figure 7: E_y behind the electron beam, after $t = 0.1$ ns from the cathode emission, for different transverse position of the cathode: on-axis (red); 0.1 mm (cyan); 0.2 mm (magenta) and 0.3 mm (blue).

When the electron beam passes off-axis, it also excites multipolar modes. The modes that mainly contribute to the generation of the transverse field are the dipolar modes (hybrid TM_{1n}). These dipolar modes have a zero longitudinal electric field on axis, but the field is not zero off axis.

Off-axis beams traveling longitudinally through a dielectric capillary or a dielectric coated waveguide are subjected to intense transverse electrical forces. For electron beams with the characteristics investigated in this work it is possible to generate transverse e.m. fields of the order of tens of MV/m (Figure 7). Such very high fields could cause beam breakup instability (BBU) that could lead to the loss of the beam itself or at least to an unwanted deflection of the beam.

WAKEPOTENTIAL COMPUTATION

It is necessary to calculate the longitudinal and transverse wake potentials [15], to estimate the integrated effects of the electric fields, shown in the previous sections, on the drive and witness beams. Figure 8 shows the longitudinal and transverse wake potentials for a gaussian beam of a length $\sigma_z = 0.3$ mm, with a charge of 50 pC, passing through 0.1 mm off-axis the structure. The figure shows the integrated field (potential) that a charge feels at a certain distance from the drive beam (long range wakefields). In addition, the drive beam also feels the effects of such crossing (short range wakefields), as can be seen in more detail in the enlargement of the first ten centimeters. The entire drive beam is slowed down by the effect of the emission of the wake fields (through the Cherenkov radiation), it also undergoes a strong transverse wake field that acts on the tail of the beam.

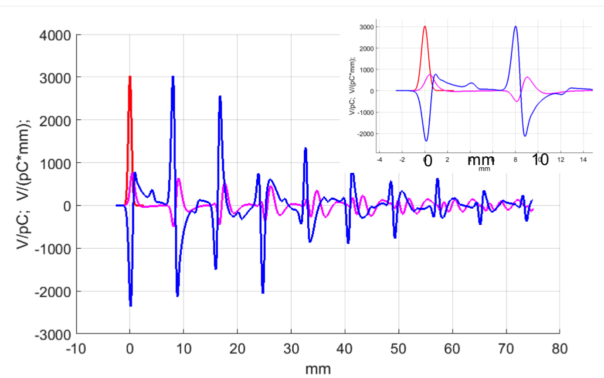

Figure 8: Wake potentials of a $\sigma_z = 0.3$ mm gaussian electron beam, 50 pC of charge, 0.1 mm off-axis. Reference beam current pulse (red); Longitudinal wake potential (blue); Transverse wake potentials (magenta).

SEMI-ANALYTICAL METHOD

Gaussian beams with $\sigma_z = 1$ mm and $\sigma_z = 0.5$ mm can respectively excite frequency up to 100 GHz and 200 GHz. Ultra-relativistic bunches traveling on-axis of the circular structure can interact only with TM_{0n} modes that travel themselves at the speed of light. Any e.m. disturbance can be written as the sum of harmonics that are potentially excitable, with amplitudes dictated by the shape of the power spectrum of the beam, at different frequencies and appropriately in phase. By executing 2D simulations on a generic section of the structure it is possible to calculate the dispersion diagram of the modes very quickly. By intersecting these curves with the line relative to a phase velocity equal to c, we estimate the frequencies at which these modes can be excited. Finally, with these frequencies it is possible to calculate the coefficients (weights) with which to multiply the amplitudes of the corresponding harmonics. We report the result of this development in Figure 9 relative to the case of a 1 mm long beam that can excite the first three monopolar modes in the guide, and in Figure 10 for a 0.5 mm long beam and the sum of the first five monopolar modes.

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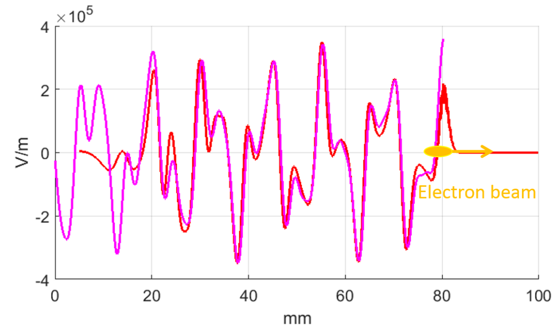

Figure 9: E_z behind the electron beam with a σ_z = 1 mm, after t = 0.29 ns from the cathode emission: PIC results (red), sum of the first three TM_{0n} modes (magenta).

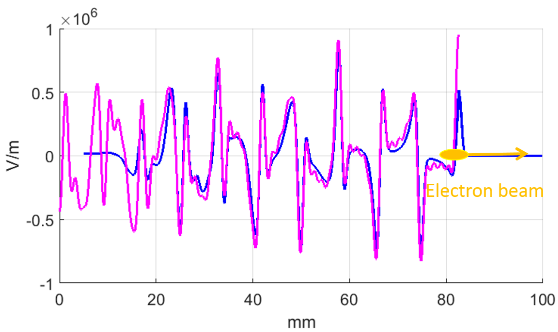

Figure 10: E_z behind the electron beam with a σ_z = 0.5 mm, after t = 0.29 ns from the cathode emission: PIC results (blue), sum of the first five TM_{0n} mode (magenta).

CONCLUSION

In this paper the effects of the passage of an ultra-relativistic electron beam through a partially filled dielectric waveguide were analyzed. Electrical fields of tens of MV/m can be produced by the passage of such electron beams through structures of transverse dimensions of the order of a few mm. These intense fields can be used to produce electromagnetic radiation in the THz range ([16, 17]), they can be also used for new generation accelerators [18] and for various applications in the field of longitudinal diagnostics [19] or for plasma lensing applications [20]. To produce increasingly higher gradients, further studies and simulations are needed, using beams shorter than 50 μm and dielectric guides of smaller dimensions than have been analyzed up to now. For this reason a fast and effective method [21] has been proposed to estimate these fields in a short time compared to the conventional wakefield and particle in cell simulations.

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