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COUPLER DESIGN FOR THz DLW LINACS*

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Abstract

A promising approach for compact linear accelerators in the THz frequency range is based on dielectric-loaded waveguides (DLWs). Higher breakdown fields expected at THz frequencies should enable higher acceleration gradients. However, the accelerating mode of a cylindrical DLW (TM_{01}) is not the fundamental and only mode inside the waveguide at the operating frequency. Therefore, a method is required to ensure excitation of the proper mode only. Here we present a coupler design to convert the guided electromagnetic TE_{01} mode in a rectangular waveguide to the TM_{01} mode of a cylindrical DLW. The symmetry of the structure and its feeding waveguides allows us to suppress all undesired modes and consequently increase the coupling efficiency to the desired mode. Moreover, this configuration shows an extremely wide bandwidth suggesting that the coupler is also suitable for short THz pulses.

INTRODUCTION

Most of the multi-cycle THz driven accelerators are based on traveling waves inside a waveguide. Phase velocity inside a metallic waveguide is higher than the speed of light. But the phase velocity can be reduced to the speed of the electrons by partial loading with a dielectric. Therefore, dielectric lined waveguides (DLWs) are considered the most promising components for THz acceleration during the last decades [1-3]. In this work, we study cylindrical DLWs. The most effective mode of a cylindrical DLW as a LINAC is the TM_{01}-mode, which has its maximum electric field component in the acceleration direction. This mode is not the fundamental mode of the DLW since two degenerated HE_{11} (hybrid) modes have a lower cut-off frequency and would potentially be excited simultaneously with the desired mode. Considering that the TM_{01} mode is used at frequencies far away from its cut-off to reduce the phase velocity below the speed of light, we most likely have higher-order modes such as HE_{21} (hybrid) propagating, depending on the dimensions of the DLW. Hence, the coupler part must be designed with the utmost caution to suppress all the parasitic modes. Excitation of the parasitic modes not only decreases the power of the TM_{01} mode, but also affects the electron bunches while being accelerated (especially nonrelativistic electrons). So far, segmented waveplates (SWP) have been used to generate a radially polarized beam for exciting the TM_{01} mode effectively [1,2]. Reflection from the SWP and coupling issues at the end of the horn structure near the waveguide reduce the efficiency of this coupling method. Designing an integrated mode convertor and coupler can improve the efficiency and provide more control over the parasitic modes. In addition, the integrated design is appropriate for two or more separate THz pulses.

PARASITIC AND DESIRED DLW MODES

On the one hand, increasing the generated THz power is always beneficial in terms of acceleration gradient, but on the other hand, we have a higher level of parasitic modes which have deleterious effects on the acceleration process. Therefore, quantifying the negative effects of the parasitic modes would be helpful prior to the design and fabrication of the coupler structure.

In this study, a dielectric material with a permittivity of 4.8 has been chosen to load a cylindrical metallic waveguide at a frequency of 300GHz. Figure1 shows the phase velocity of different propagating modes of the DLW for different vacuum radii. Note that the dielectric thickness is optimized to keep the phase velocity of the TM_{01} mode fixed.

For selecting the vacuum radius, we need to consider the bunch size as well as the acceleration gradient. On the one hand, larger vacuum radii are preferred for larger electron bunches and higher bunch charges, but on the other hand, the electric field decreases by increasing the vacuum radius for a given THz energy. Therefore, there should be a tradeoff in selecting a proper vacuum radius [4]. Here we consider a vacuum radius of 200µm for all the following simulations. In the AXSIS project, the LINAC is designed to accelerate electrons from 430 keV to close to 20 MeV [5].

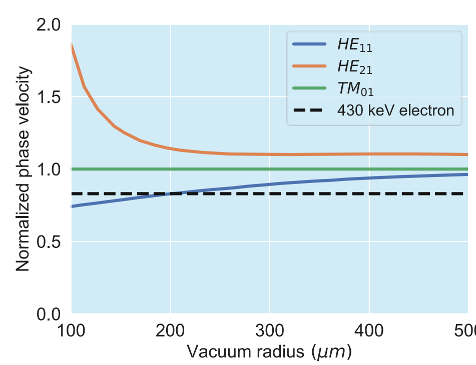

Figure 1: Normalized phase velocity of first three propagating modes inside the DLW.

Figure 2 shows the cross-sectional electric field distribution for the first four modes and Table 1 specifies the characteristics of these modes.

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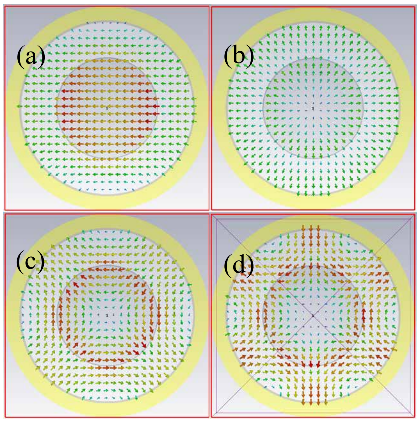

Figure 2: Electric field distribution of (a) HE_{11} (b) TM_{01} (c) HE_{21} (d) HE_{31} modes of the DLW.

Table 1: Modes Characteristics of the DLW

Mode	HE_{11}	TM_{01}	HE_{21}	HE_{31}
Cut-off frequency (GHz)	210	239	285	327
phase velocity at 300 GHz	0.82c	1c	1.1c	-

As can be seen in Fig. 2, the fundamental HE_{11} mode can deflect the electrons (even those on the axis) transversely. This effect might be negligible for relativistic electrons based on the Panofsky-Wenzel theorem [6], but it has a strong effect on nonrelativistic electrons, especially at the first stage of acceleration. Since the energy of the multi-cycle THz pulse (~23mJ with ~550ps duration) used in the AXSIS machine [5] is relatively high, even coupling of a small fraction of the energy to the parasitic modes (especially HE_{11}) affect the electron bunch. Figure 3 (a) depicts an electron bunch of ~10mrad divergence and ~40µm size in different time frames inside the DLW during the acceleration. HE_{11} and TM_{01} modes are excited together with a 45-degree phase shift. The power of the HE_{11} mode is assumed to be 20dB lower than that of the TM_{01} mode.

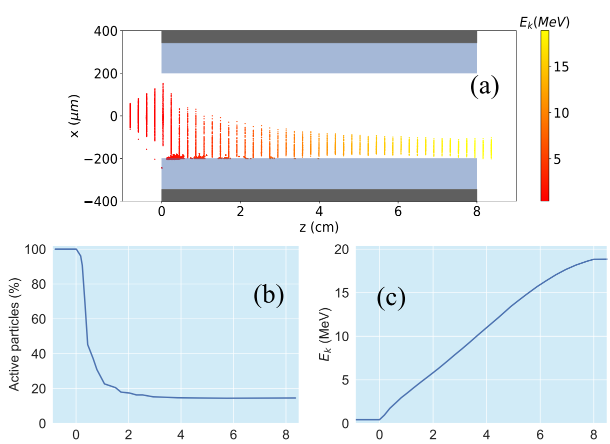

Figure 3: (a) Electron bunch in different time frames inside the DLW (b) number of active particles and (c) average kinetic energy of the active particles while being accelerated.

The number of active particles coming out of the DLW depends on the injection phase of the parasitic HE_{11} mode. Since this mode is excited due to imperfections in the structure, its initial phase may vary. Figure 4 show the final active particles as a function of HE_{11} mode power (solid lines show the maximum and minimum number of active particles while sweeping the injection phase of HE_{11} mode).

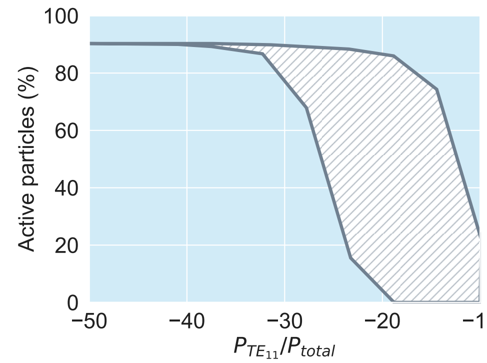

Figure 4: Active particles to total particles ratio as a function of HE_{11} mode power (injection phase of the HE_{11} mode is swept).

As evidenced by Fig. 4, one needs to suppress the parasitic modes considerably especially when the power of the desired mode is higher.

As a consequence, our coupler structure must have significantly low coupling to unwanted modes. In the next section, we proposed a coupler structure to fulfill this target.

COUPLER DESIGN

As explained in the previous section, we have three propagating modes at the operating frequency. One can take advantage of the symmetries in order to restrain both HE_{11} and HE_{21} from being excited in the tube. Here we select rectangular waveguides as coupler feeds which makes it feasible to test the coupler independently with a Vector Network Analyzer (VNA). Then the design procedure would be straightforward only by matching the TM_{01} mode of the cylindrical DLW to a four-sided feed with rectangular TE_{01} modes. Figure 5 shows the transmission from the input ports of the coupler to the TM_{01} mode of the tube (clearly, other modes are not excited when all feeds are in phase) while the inlet depicts the four-sided feed coupler design.

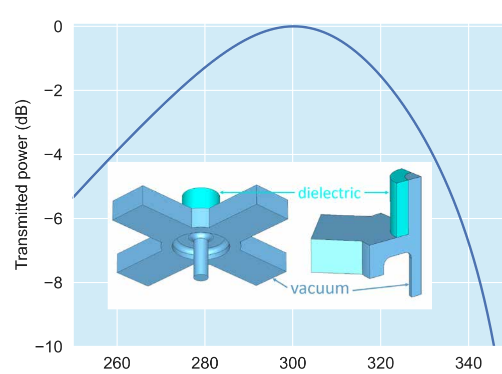

Figure 5: Transmitted power of the designed coupler.

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Having a broad bandwidth makes the coupler suitable even for short multi-cycle THz pulses. One can make it even broader by changing the feed dimensions elaborately. Since this coupler needs to be connected to the VNA for measuring its characteristics, we simply use standard rectangular waveguides for the feeding network.

The LINAC of the AXSIS machine is powered by two separate THz multi-cycle pulses which are quite similar and generated ideally out of one source. However, the designed coupler as shown in Fig. 5 has four feeds. Thus, we need to add a pair of power dividers to the structure to feed the four waveguides. Figure 6 illustrates the transmission power to the TM_{01} mode and the inlet shows the entire design for the two-sided pumped coupler.

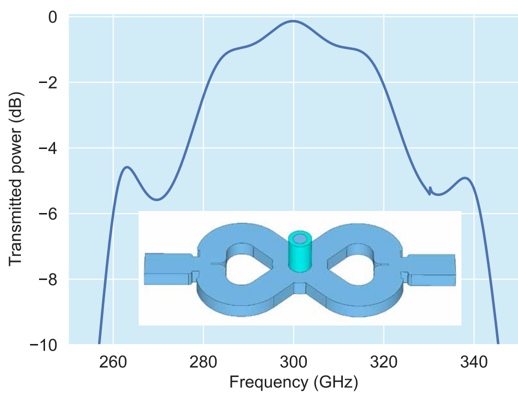
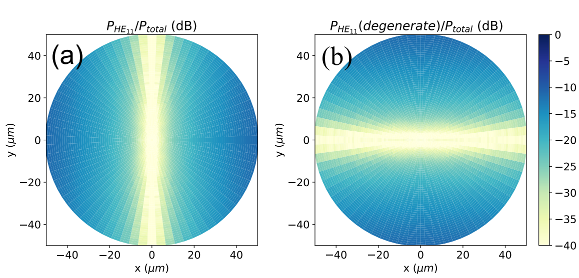


Figure 6: Coupler design with two feeds.

The feeding network can be connected either to VNA for testing or to a pair of horn antennae in order to couple free space Gaussian THz beams to the waveguides.

MISSALIGNMENS AND PARASITIC MODES

The symmetry of the structure is employed to suppress unwanted parasitic modes. However, the way the structure is assembled can break the symmetry and excite these modes. The structure is presumed to be fabricated out of two pieces (the bottom part containing the waveguides and the top one surrounding the dielectric tube). The misalignment of these two parts may excite parasitic modes. Figure 7 shows the coupled power to unwanted modes as a function of misalignment of the tube.



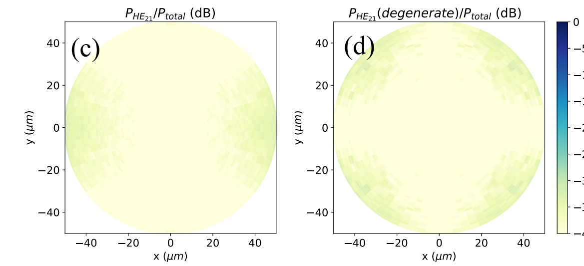


Figure 7: Coupled power to (a) HE_{11} mode and its (b) degenerate HE_{11} mode (c) HE_{21} mode and its (b) degenerate HE_{21} mode.

As seen in Fig. 7, excitation of the two degenerated HE_{11} modes is more sensitive to the misaligned layers while HE_{21} modes still have reasonably low power. As a consequence, in order to keep the power of HE_{11} modes below -25 dB, the misalignment of the layers must be less than 10 µm.

CONCLUSION

We proposed a coupler structure for DLW LINACs. This coupler is capable of combining and converting two TE_{01} modes of rectangular waveguides to TM_{01} mode of a DLW. Other propagating parasitic modes inside the DLW may affect the acceleration process. Therefore, a symmetrical structure has been designed and proposed to suppress the parasitic modes and couple the maximum power to the desired mode. Coupling to parasitic modes due to the misalignment of the layers and the effect of the parasitic modes on the electron bunch have also been studied.

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