BEAM–DRIVEN WAKEFIELD IN LAYERED PLASMA WAVEGUIDE

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Plasma wakefield accelerators (PWFA) represent one of the promising new accelerator concepts that are now being developed intensively for future applications in high-energy physics and industry. Among the unresolved problems of practical implementation of PWFA there are maintaining the required quality (emittance, size, energy spread) and stable transportation of drive and accelerated bunches over long acceleration distances. For improving the bunch transport, we propose that the plasma channel method should be modified through filling the bunch transport channel with the background plasma, the density of which is lower than the main plasma density building up an accelerating wake wave. We call this waveguide structure with a non-uniform transverse plasma profile a layered plasma waveguide (LPW). The layered plasma has been modeled as a combination of a tubular plasma and a plasma column of significantly different densities (Fig. 1). The plasma column has a lower density. In the linear approximation of plasma dynamics, and sharp interface between the plasma layers analytical expressions for the excited longitudinal and transverse wakefields were obtained [1].

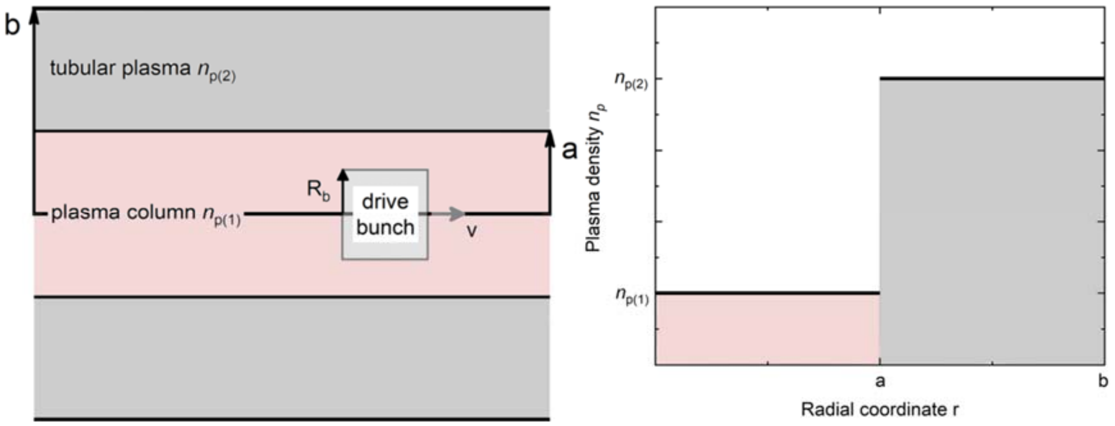

Fig. 1. (left) Sectional view of the cylindrical plasma waveguide. Metal coating, layered plasma, and drive bunch are shown schematically. The drive bunch moves along to the waveguide axis without an offset. (right) The layered plasma comprises two layers adjacent one to another: the inner plasma (the plasma column of radius a) has the density $n_{p(1)}$, the density of the outer (tubular) plasma is equal to $n_{p(2)}$. The outer radius of the tubular plasma equals the radius of the waveguide.

For numerical analysis, it was chosen the following parameters: waveguide radius of 600 um, plasma column radius of 300 um, plasma column density of $4.93 \mathrm{x} 10^{14}$ cm^{-3}, tubular plasma density of $1.53 \mathrm{x} 10^{16}$ cm^{-3}, energy of electron drive bunch of 5 GeV, charge of the drive bunch of 2.0 nC, length of the drive bunch of 250 um, radius of the drive bunch of 250 um. The dispersion dependencies of the TM-modes of the LPW was obtained and analyzed, and it was found that there was a single TM wave resonant with the electron bunch. It is shown that for certain density ratios of the outer and inner plasmas, it is possible both to accelerate and focus simultaneously the drive and witness bunches. Based on the obtained analytical expressions, the structures of the axial and radial wakefield amplitudes have been numerically investigated. Figure 2 shows the 2D distributions of axial E_z and radial $W_r = E_r - \beta H_\varphi$ wakefields excited by a single drive electron bunch. The most essential qualitative differences between the wakefields distributions, namely, in their longitudinal structure, are observed in the region of the plasma column of the layered plasma waveguide. In this region, the transverse wakefield W_r has a clearly defined longitudinal period equal to ≈ 1.5 mm, which corresponds to the Langmuir wave frequency ≈ 200 GHz. In the distribution of the longitudinal wakefield E_z in the region of the plasma column two periods can be seen, viz., ≈ 1.5 mm and ≈ 0.5 mm. The second period is due to the excitation of the TM_{01} wave of the layered plasma waveguide, having the frequency ≈ 600 GHz (Cherenkov resonant frequency).

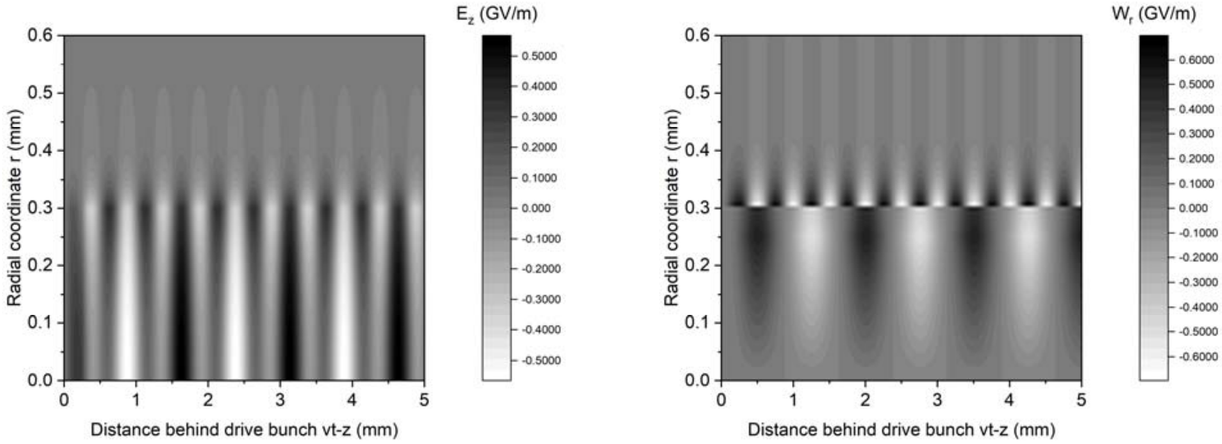

Fig. 2. Two-dimensional distributions of the longitudinal (left) E_z and transverse (right) W_r wakefields excited by a single drive electron bunch. The drive bunch propagates from right to left along the waveguide axis with constant velocity. Drive bunch head is located at $vt - z = 0$.

In the tubular plasma region, the distributions of the longitudinal and transverse wakefields have a similar longitudinal structure with the period equal to the period of the TM$_{01}$ wave. Their amplitudes decline rapidly from the interface inward the tubular plasma in consequence of the surface character of the TM$_{01}$ wave. A spectral amplitude-frequency analysis of the excited wakefields has been carried out as well. Figure 3 shows the spectra of the excited wakefield. In the plasma column region, the wakefield spectra demonstrate two maxima, which correspond to the Langmuir frequency of the plasma column ≈ 200 GHz, and the resonant eigenfrequency of the waveguide ≈ 600 GHz. The frequency that gives the main contribution to the longitudinal wakefield is the resonant frequency.

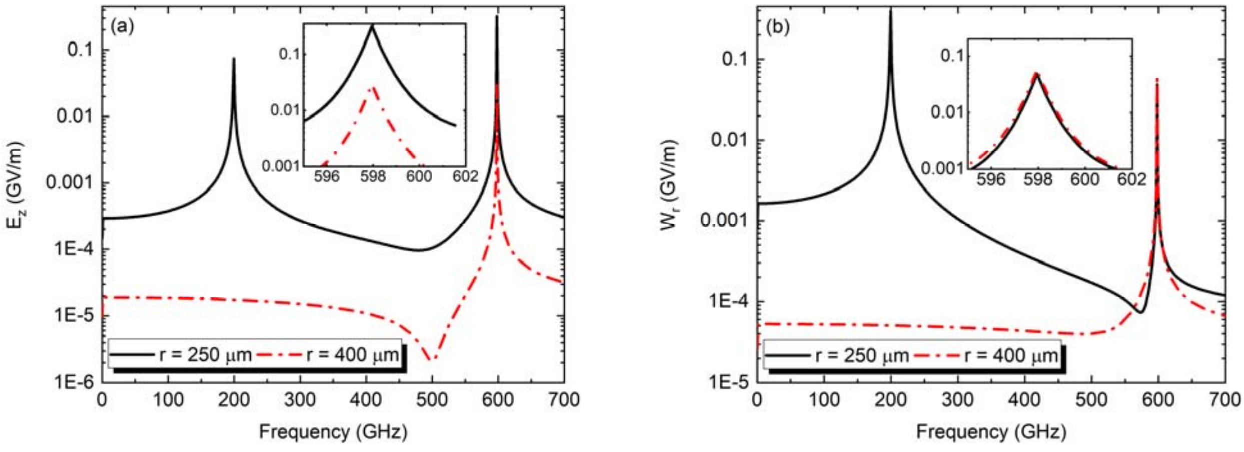

Fig. 3. Amplitude-frequency spectra of the longitudinal (a) and transverse (b) wakefields excited by a single drive electron bunch calculated in the plasma column region at r = 250 um (solid black line), and in the tubular plasma region at r = 450 um (dash-dotted red line).

The transverse wakefield spectrum shows that in the plasma column region the main contribution corresponds to the Langmuir frequency, and the contribution to its total amplitude at the resonant frequency is negligibly small. In the tubular plasma region, the spectra of both the longitudinal and transverse wakefields have a single maximum corresponding to the resonant frequency.

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1. K.V. Galaydych, P.I. Markov, G.V. Sontikov Wakefield acceleration in a layered plasma waveguide. arXiv:2601.04903 [physics.acc-ph].