Accelerating Field Step-Up Transformer in Wake-Field Accelerators

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I. Introduction

In the wake-field scheme of particle acceleration, a short, intense drive bunch of electrons passes through a slow-wave structure, leaving behind high rf power in its wake field. The axial accelerating electric field associated with the rf can be quite large, > 100 MeV/m, and is used to accelerate a much less intense "witness" beam to eventual energies > 1 TeV. The rf power is deposited predominantly in the fundamental mode of the structure, which, for dielectric-lined waveguide as used at Argonne, is the TM_{01} mode. In all likelihood the field amplitude will be limited only by rf breakdown of the dielectric material, the limit of which is currently unknown in the short time duration, high frequency regime of wake-field acceleration operation (~ns, 20GHz).

To obtain such strong electric fields with the given wake-field rf power, the dimensions of the dielectric-lined waveguide have to be fairly small, OD of the order of a cm and ID of a few mm, and this gives rise to the generation of strong deflection modes with beam misalignment. While a scheme exists to damp such deflection modes on a bunch-to-bunch time scale,[1] head-tail beam deflection could still be a problem and BNS damping as well as FODO focusing are incomplete cures.[2]

Presented here are details of a scheme by which the rf power is generated in a large-diameter wake-field tube (stage I), where deflection mode generation by the intense drive beam is tolerable, and then fed into a small-diameter acceleration tube (stage II) where the less intense witness beam is accelerated by the greatly enhanced axial electric field. The witness beam generates little deflection-mode power itself, even in the small acceleration tube, thus a final high-quality, high-energy electron beam is produced.

The wake-field transformer is illustrated in Fig. 1, where one of several possible rf transfer schemes is shown. Other transfer schemes are the use of multiple rectangular waveguides or having the beam entry/exit apertures in hollow waveguide rather than dielectric-lined. Computer simulation and bench measurements have shown that the quarter-wave section illustrated in Fig. 1 yields successful transfer of TM_{01}-mode rf power between dissimilar-impedance sections as well as acting as a filter of undesired modes. Bench measurements have also shown that the beam entry/exit wall apertures have little effect on rf phase and power transfer if the aperture is small compared to the rf wavelength.

As a final comment in this introduction, it should be pointed out that the rf gymnastics illustrated in Fig. 1 result in nominally a factor of two enhancement of the ultimate accelerating electric field as compared to the case where the drive beam is sent directly into the small-diameter structure. The principle advantage of the step-up transformer is the large reduction of deflection-mode worries and allowance of larger diameter (weaker focused) drive beams.

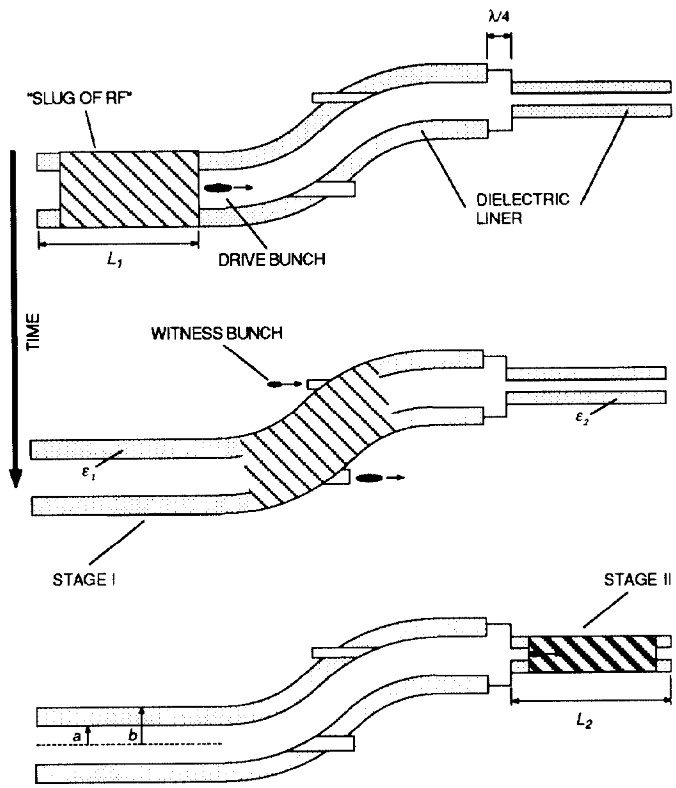

Figure 1: The wake-field step-up transformer using dielectric-lined waveguide with a hollow waveguide quarter-wave matching section.

II. Acceleration Parameters

Before describing the matching of rf from stage I to stage II and the optimization of ultimate accelerating gradient, it is necessary to define the parameters to be optimized or used in the optimization.

As the drive beam passes through stage I with energy $U_d = q_1 V_1$, where q_1 is the drive-bunch charge and V_1 is its voltage, its loss of energy to the fundamental mode is given by

$$\Delta U_1 = q_1^2 \, F_1 \, W_1 \, L_1 / 2 \ , \qquad (1)$$

where F_1 is a form factor reducing the wake amplitude due to the finite bunch length, W_1 is the TM_{01}-mode point-

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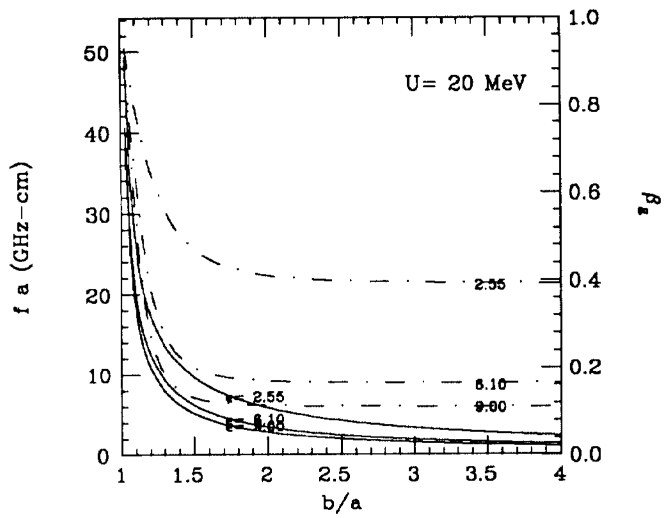

Figure 2: Plot of frequency (solid) and group velocity (dashed) of TM_{01} mode in dielectric-lined waveguide vs ratio of outer to inner wall radii for various relative permittivities.

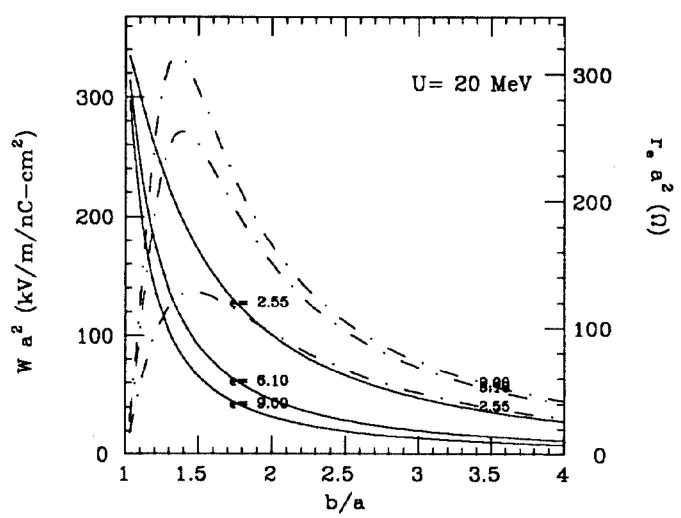

Figure 3: Plot of longitudinal wake function (solid) and an impedance parameter (dashed) of TM_{01} mode in dielectric-lined waveguide vs ratio of outer to inner wall radii for various relative permittivities.

source wake function in stage I, L_1 is the axial length of the stage I, and the factor of two comes from the fundamental theorem of beam loading. For a Gaussian longitudinal beam profile,

$$F_1 = \exp\left(-\omega^2 \sigma_1^2 / 2\right) , \tag{2}$$

where ω is the angular frequency of the mode and σ_1 is the drive-bunch temporal standard deviation. The accelerating gradient in stage I, if the witness were to simply follow the drive beam, is $E_1 = q_1 F_1 W_1$.

The energy change of the witness beam passing through stage II due to the TM_{01} mode is given by

$$\Delta U_2 = q_2 (E_2 - q_2 F_2 W_2 / 2) L_2 , \tag{3}$$

where $E_2 = R E_1$ is the accelerating gradient in stage II due to the rf generated in stage I, R is the electric field step-up ratio given by

$$R = \sqrt{\frac{\beta_{g1}(1-\beta_{g2}) W_2}{\beta_{g2}(1-\beta_{g1}) W_1}} \tag{4}$$

with β_{gi} the group velocity in the respective stage, L_2 is the physical length of stage II, and all other quantities are as defined previously but applied to stage II. The useful length of stage II is determined by the length of stage I, compression of the "slug of rf" generated in stage I due to group velocity effects in the two stages, and transit time of the witness bunch passing through the rf slug in stage II. This length is given by

$$L_2 = \frac{\beta_{g2}(1-\beta_{g1})}{\beta_{g1}(1-\beta_{g2})} L_1 . \tag{5}$$

Given the ratio of drive to witness-bunch charge, $N = q_1/q_2$, a voltage transformer ratio can then be defined as the energy transferred *per particle* from the drive bunch to the witness bunch,

$$T = \frac{\Delta U_2/q_2}{\Delta U_1/q_1} = \left(2R - \frac{F_2 W_2}{N F_1 W_1}\right) \frac{\beta_{g2}(1-\beta_{g1})}{\beta_{g1}(1-\beta_{g2})} \cdot \tag{6}$$

Since T is defined on a per particle basis, it can be less than zero or greater than one without being unphysical. The first case implies the witness loses energy and the second that multiple drive particles are needed per witness particle. The efficiency of energy transfer from the drive to witness bunch is just $\eta = T/N$. A value of N can always be found such that $\eta = 1$ with $T = N$, corresponding to the first bunch transferring all its wake energy to the second. However, operating a wake-field accelerator near $\eta = 1$ would yield a poor quality witness beam due to its finite bunch length; the head-tail energy spread would be nominally twice the average energy gained in the stage.

Lastly, a set of generalized curves containing dielectric-lined waveguide properties can be generated for use in the optimization of acceleration gradient E_2 or efficiency η. Such a set of curves are shown in Figs. 2 and 3 for a TM_{01}-wave phase velocity synchronous with a 20 MeV electron, which will be the energy available from phase I of the Argonne Wake-Field Accelerator (AWA).[3] Variation with phase velocity is negligible for $\beta \sim 1$. Plotted as a function of b/a , where b is the outer radius of the dielectric-lined waveguide and a is the inner radius, are: product of operating frequency and inner radius, fa ; normalized wave group velocity, β_g ; product of point-source wake function and inner radius squared, $W a^2$; and product of a shunt-like impedance and inner radius squared, $r_e a^2$. The impedance is defined here as $r_e = E^2/P$, where E is the acceleration field on axis and P is the rf power in the mode. This differs from the standard shunt impedance by the lack of an attenuation factor in the denominator. The electric field step-up ratio is then $R = \sqrt{r_{e2}/r_{e1}}$.

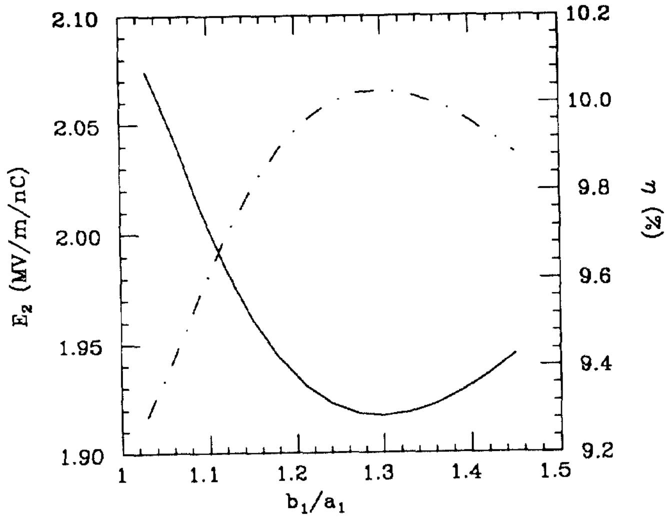

Figure 4: Plot of accelerating field in stage II normalized to 1 nC of drive-bunch charge (solid) and transformer efficiency (dashed) for the TM_{01} mode vs ratio of stage I outer to inner wall radii. Other parameters of the transformer are as listed in Table 1.

III. Transformer Matching And Optimization

There are lower limits on the inner radii of the dielectric-lined waveguide in stages I and II determined by allowable deflection-mode generation for typical beam misalignment. This limits the maximum field in stage II, E_2, which increases with decreasing inner radius of stage II, a_2. Also, there is an upper limit on operating frequency which is determined by the finite witness or drive bunch length and fabrication technology. Thus, to start the matching procedure, the parameter fa_2 is determined from the respective limits of the individual quantities. This yields b_2/a_2 from Fig. 2 and subsequently β_{g2}, W_2, and r_{e2} from Figs. 2 and 3.

Knowing all the parameters of stage II, the quantity b_1/a_1 can then be scanned over a reasonable range, such as that in Fig. 2, discarding cases requiring a_1 to be less than the allowable minimum. For each value of b_1/a_1, the parameters a_1, β_{g1}, W_1, and r_{e1} are determined from Figs. 2 and 3, and the equations in section II can then be used to calculate the final field gradient E_2 and efficiency of energy transfer η.

IV. Discussion

A result of the procedure outlined in section III is plotted in Fig. 4 for typical parameters to be used in phase I of the AWA, as listed in Table 1. The accelerating gradient is normalized to 1 nC of drive-bunch charge and the radius a_2 is fixed at a minimum value to yield maximum E_2, but a_1 varies with each value of b_1/a_1. If the drive bunch were sent directly into stage II for this case, the axial wake-field gradient would be $W_2 \sim 1.0\,\mathrm{MV/m/nC}$ as compared to $E_2 \sim 2.0\,\mathrm{MV/m/nC}$ for the transformer.

Electron energy	20	MeV
Drive bunch charge q_1	100	nC
Witness bunch charge q_2	10	nC
Bunch length σ	5.0	ps
Transformer frequency	20	GHz
Inner radius a_1	> 5.0	mm
Permittivity ϵ_1	2.55	
Inner radius a_2	2.00	mm
Outer radius b_2	3.37	mm
Permittivity ϵ_2	9.00	
Stage II group velocity β_{g2}	0.120	

Table 1: Beam parameters and sample transformer parameters for phase I of the AWA.

The typical drive-bunch charge to be produced in the AWA will be 100 nC.

When searching for maximum efficiency, the procedure is similar except that a_2 may be larger than its minimum allowable value. After a minimum acceptable accelerating gradient E_2 is specified, the efficiency of energy transfer η varies slowly with changing dimensions and requires thorough optimization only if it is a critical parameter in a particular design.

The computer simulation mentioned in section I of a wake-field transformer was performed with ARCHON,[4] a parallel time-domain finite-difference code developed at Argonne. It demonstrated successful passage of an rf slug through the quarter-wave matching section and agreed with analytic calculations of electric field step-up. Further details and figures can not be presented here due to page constraints.

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