Power Generation and Extraction Using a Rectangular Dielectric Loaded Waveguide

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Abstract

Power extraction with a drive particle beam is a promising approach for high power RF source development. Compared to applications based on circular structures, the use of a rectangular dielectric loaded waveguide can potentially lead to higher output power, where a flat drive beam with higher charge can be used. We report on the design of a 7.8GHz power extractor using a rectangular dielectric loaded waveguide, including mode analysis and numerical simulation. Calculation shows 160MW of power can be generated by a bunch train with 100nC of charge per bunch.

1. Introduction

Dielectric loaded accelerating structures have been studied for many years [1，2，3]. Recently, for future high gradient linear accelerators, there have been some interests in rectangular dielectric loaded waveguides [4]. As shown in Fig. 1, such a waveguide consists of a metallic rectangular waveguide (inner dimensions: $w\times 2b$), and two dielectric slabs (dimensions: $w\times(b-a)$) at the top and bottom sides to reduce the phase velocity of electromagnetic waves for synchronization with charged particles to reach efficient acceleration. The region between the two slabs provide a rectangular vacuum channel for the particle beam. This waveguide is attractive in the following aspects:

- Tuning: the operating frequency of the waveguide can be easily adjusted by moving the metallic side walls inwards/outwards, if clearance is provided between each dielectric slab and the adjacent side wall;
- Stored energy: at a certain frequency for a given accelerating gradient the rectangular waveguide can store more energy than a cylindrical one, thus beam loading can be reduced;
- Focusing: in the beam channel, the accelerating field is not uniform transversely, so transverse forces on a relativistic beam exist, which is able to provide a focusing force that acts on the beam like an RF quadruple while the beam is being accelerated.

In this paper, we report on design for a 7.8GHz power extractor using a rectangular dielectric loaded waveguide, which is the first stage of the two beam acceleration (TBA) scheme. In this scheme power generated by a drive beam, either a single particle bunch or a bunch train, in the first stage (decelerating stage) is transmitted through an output coupler to accelerate another beam in the second stage (accelerating stage). The design for the decelerating stage using the rectangular dielectric loaded waveguide is shown in Section 2, while the output coupler is still being investigated.

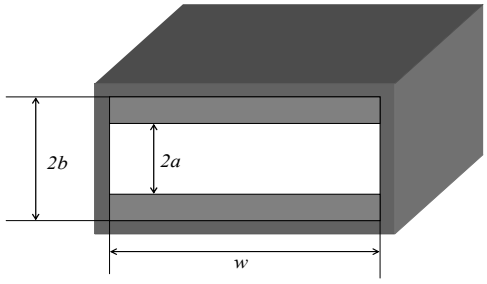

Fig. 1 Dielectric-loaded rectangular waveguide

2. Decelerating Waveguide Design

In a waveguide shown in Fig. 1, the LSM_{11} mode has the strongest interaction with an on-axis beam, therefore this it is chosen as the deceleration mode, whose complete solution is given by [4]. The frequency of the mode at which it can be synchronous with the beam, is chosen to be 7.8GHz, the 6th harmonic of the linac frequency (1.3GHz) at the AWA facility. The beam channel dimensions are set according to the typical transverse size of the flat driving beam, and other parameters are adjusted to move the synchronous frequency to 7.8GHz, where the calculation is performed with MathCAD. The length is chosen for the desired number of stacked RF pulses in bunch train excitation. The final design is a tradeoff between various constraints and the parameters are listed in Table I.

Table I: Parameters for the dielectric loaded waveguide

f	7.8 GHz	frequency
a	3.0 mm	marked in Fig. 1
b	6.0 mm	marked in Fig. 1
w	28.4 mm	marked in Fig. 1
L	800 mm	waveguide length
ε_r	10	relative permittivity of the dielectric
δ_d	5×10^{-4}	loss tangent
β_g	0.11	relativistic group velocity
Q_w	4135	wall quality factor
Q	1348	total quality factor
r/Q	5.043 KΩ/m	R over Q per unit length

First we calculate the excited wakefield gradient and power with basic wakefield formulization, then we verify it with MAFIA simulation. The wakefield can be expressed as a sum over the waveguide parameter r/Q, a function only of the structure geometry for each mode [5]. The summation is an infinite series and it can be truncated by taking the integral over the finite bunch length of the drive beam. The amplitude of the longitudinal wakefield excited by a charged particle beam traveling on axis can be easily obtained as following [6]:

$$E_{0i} = 2k_{li}q = \frac{q\omega_i}{2}\left(\frac{r}{Q}\right)_{(x_0,y_0)_i} \tag{1}$$

where, the subscript i indicates the ith mode; k_l is a normalized loss factor, $(r/Q)_{(x_0,y_0)}$ is calculated at the beam particle's instantaneous position (x_0, y_0) for each mode, and q is the charge. The mode selection for longitudinal wakefield calculation is based on the relation between the system response and signal excitation, and in this paper the LSM_{11} mode is selected. We assume a Gaussian longitudinal beam shape (with bunch length σ_z and charge q). The longitudinal wake field $E_z(z)$ at distance z behind the drive electron beam is then given by

$$E_z(z) = \frac{1}{\sqrt{2\pi}\cdot\sigma_z}\int_{-\infty}^{z}\sum_{i=1}^{\infty}E_{0i}\cos[\beta_i(z-z')] \times \exp\left(-\frac{z'^2}{2\sigma_z^2}\right)dz' \tag{2}$$

In Fig. 2, the longitudinal wakefield of LSM_{11} mode using Eq. (2) is shown. For this example, a bunch with $\sigma_z = 2mm$ and q = 1nC located at $x_0 = 0$ and $y_0 = 0$ is traversing along the axis at the speed of light in dielectric loaded rectangular waveguide. We can easily find the amplitude of the wake field is 0.117MV/m per nC. In order to confirm the analytical result here, a commercial EM simulation tool MAFIA is used for the same structure, and the result is shown in Fig. 3, where the amplitude is 0.119MV/m per nC, close to the value calculated with Eq. 2.

The excited power at the downstream end of the tube can be calculated from the gradient for a certain mode pattern. The MAFIA simulation in last paragraph shows that with 100nC single bunch excitation, the induced gradient will be 11.9MV/m, corresponding to 18.3MW of power generated. If a bunch train with a bunch frequency 1.3GHz and 100nC charge per bunch is used as the driving beam, the excited gradient will be 33.14MV/m, corresponding to 160MW of power generated. In the bunch train excitation, at least four bunches are needed for the gradient and power to reach the above values.

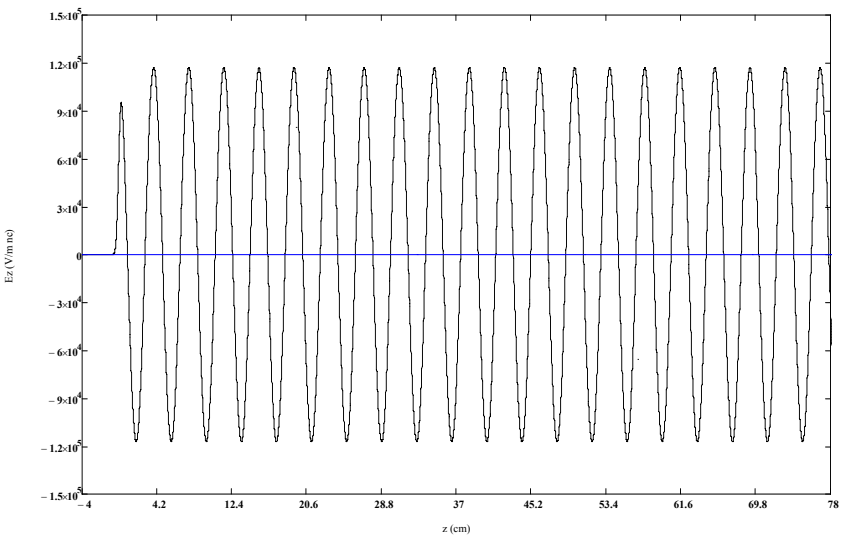

Fig. 2 Calculated longitudinal wakefield using the field analysis method (a=3mm, b=6mm, w=28.4mm, $\varepsilon_r = 10$, and $\sigma_z = 2mm$, q=1 nC)

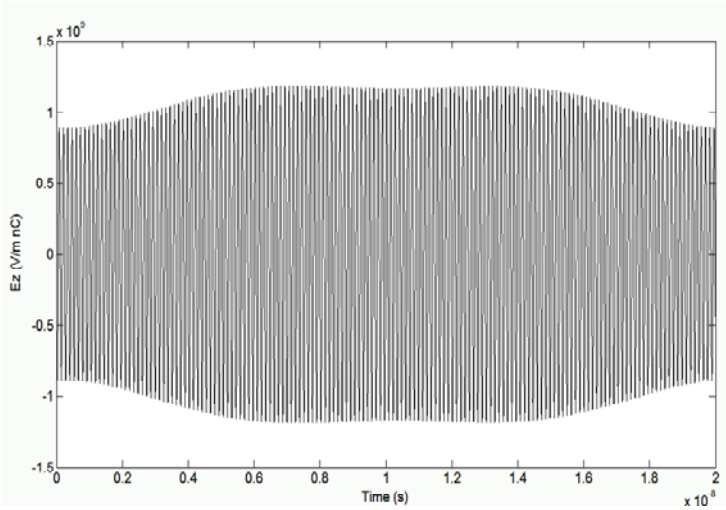

Fig. 3 Simulated longitudinal wakefield using the MAFIA code.

3. Summary

In this paper, we presented the design for a power extractor using a rectangular dielectric loaded waveguide, whose output power level is on the order of 100MW. This waveguide can allow more charge to pass compared to a circular one, thus higher power can be potentially excited. A wide band output coupler is still being investigated. This power extractor shows potentials for the use of a high charge rectangular beam with large transverse beam size.

4. Acknowledgement

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5. References

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