Construction and testing of an 11.4 GHz dielectric structure based traveling wave accelerator

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We report on the design, numerical modeling, and experimental testing of a cylindrical dielectric loaded traveling wave structure for charged particle beam acceleration. This type of structure has similar accelerating properties to disk-loaded metal slow wave structures but with some distinct advantages in terms of simplicity of fabrication and suppression of parasitic wakefield effects. Efficient coupling of external rf power to the cylindrical dielectric waveguide is a technical challenge, particularly with structures of very high dielectric constant ϵ. We have designed and constructed an *X*-band structure loaded with a permittivity $\epsilon = 20$ dielectric to be powered by an external rf power source. We have attained high efficiency broadband rf coupling by using a combination of a tapered dielectric end section and a carefully adjusted coupling slot. Bench testing using a network analyzer has demonstrated a power coupling efficiency in excess of 95% with bandwidth of 30 MHz, thus providing a necessary basis for construction of an accelerator using this device. We have also simulated the parameters of this structure using a finite difference time domain electromagnetic solver. Within the limits of the approximations used, the results are in reasonable agreement with the bench measurements.
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I. INTRODUCTION

The proposed use of rf driven dielectric based structures for particle acceleration can be traced to the early 1950's.[1] Since then, numerous studies have examined the use of dielectric materials in accelerating structure.[2,3] The advantages and potential problems of using dielectric material are discussed in the above references and are summarized here:

(1) Simplicity of fabrication: The device is little more than a tube of dielectric surrounded by a conducting cylinder. This is a great advantage for high frequency (10 GHz) structures compared to conventional structures where extremely tight fabrication tolerances are required. The relatively small diameter of these devices also facilitates placement of quadrupole lenses around the structures.

(2) Reduced sensitivity to the single bunch beam break-up (BBU) instability: The frequency of the lowest lying HEM_{11} deflecting mode is almost always lower than that of the TM_{01} accelerating mode.

(3) Simple reduction of coupled bunch effects: It has been demonstrated experimentally that it is relatively straightforward to build deflection damping into dielectric structure so that very large attenuation ($\approx$250 dB/m) of all but TM_{0n} modes can be obtained.[4]

Potential challenges of using dielectric materials in a high power rf environment are breakdown and thermal heating. Dielectric breakdown limits under high power of tens of MW and with pulse lengths of nanoseconds need to be determined through careful experiments and appropriate selection of material. The recent development of high dielectric constant ($\epsilon \sim 20-40$), low loss dielectric materials ($Q \sim 10\,000-40\,000$) warrants serious consideration of dielectric structures as accelerating devices.[5]

Another practical problem to be addressed when building a dielectric accelerator occurs because the outer diameter of the dielectric is much smaller than the rectangular waveguide which couples the external rf power to the device. Therefore, impedance matching becomes a difficult task. There is also no previous work in this area to provide guidance on coupling design. We found that by using a combination of side coupled slots and tapering the dielectric near the coupling slots, one can efficiently couple the rf power from a rectangular waveguide to the circular dielectric waveguide. We have designed and constructed a prototype 11.4 GHz dielectric loaded accelerator (Fig. 1) to study the rf coupling scheme and electrical properties of the dielectric under high vacuum and high power rf fields. We found that by careful tuning of the rf coupling slots and more importantly by tapering the inner radius of the dielectric tube near the coupling slot, one can obtain a coupling coefficient greater than 95%. We have also verified this coupling scheme using a numerical simulation and report the results in Sec. IV.

II. TRAVELING WAVE DIELECTRIC LOADED ACCELERATING STRUCTURE BASICS

The dielectric traveling wave accelerator has a simple geometry. Consider a cylindrical structure partially filled

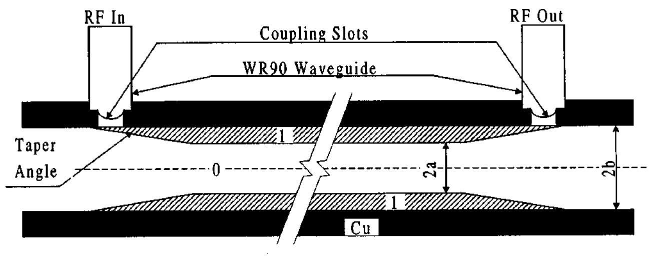

FIG. 1. Dielectric loaded traveling wave accelerator prototype used for the network analyzer measurements. The length of the dielectric is 25 cm and consists of 1 in. long segments. Regions 0: vacuum; 1: dielectric.

with dielectric material (ϵ) with inner radius a and outer radius b, made by fitting a dielectric tube into a conducting cylinder. There are two ports on the side for rf coupling purposes, as shown in Fig. 1. The axial electric fields inside the structure can be determined analytically

$$E_z^{(0)}=E_0 I_0(kr)e^{i(k_z z-wt)},$$
$$E_z^{(1)}=[B_1 J_0(sr)+D_1 N_0(sr)]e^{i(k_z z-wt)}. \tag{1}$$

Here, E_0, B_1, and D_1 are the field amplitudes in region 0 (vacuum) and 1 (dielectric), respectively, and are related by boundary conditions at the radial dielectric-vacuum interface. The wave numbers k and s are given by the relations:

$$k^2=\frac{\omega^2}{v^2}(1-\beta^2),$$
$$s^2=\frac{\omega^2}{v^2}(\beta^2\epsilon-1), \tag{2}$$

where $\beta c=v=\omega/k_z$ is the phase velocity of the wave traveling inside the tube; β determines the synchronism of the wave and the accelerated particles. By proper choice of a, b, and ϵ, one can adjust the phase velocity accordingly. (This proposed scheme works not only for acceleration of electrons which typically have velocity $\sim c$, but also for low phase velocity particle acceleration, such as heavy ions.) The transverse electric field can be written as

$$E_r=\frac{i}{(\omega/v)(\beta^2\epsilon-1)}\frac{\partial E_z}{\partial r} \tag{3}$$

and the magnetic field $H_\phi=\epsilon E_r$ everywhere inside the tube. By matching the boundary conditions at a and b (E_z and D_r continuous), all the field components can be calculated accordingly.

The stored energy per unit length U in the tube is the sum of contributions from both vacuum and dielectric regions, and can be expressed as

$$U=\frac{1}{4}\sum_{0,1}\int(\epsilon E^2+H^2)r\,dr=E_0^2 u, \tag{4}$$

where u is a geometric factor which depends solely on the structure geometry and dielectric constant ϵ. For a given rf power, the axial electric field E_0 in the vacuum channel $(r\langle a)$ can be expressed as

$$E_0=\left(\frac{P}{u\beta_g c}\right)^{1/2}, \tag{5}$$

TABLE I. Dimensions and physical properties of the 11.43 GHz dielectric tube.

Coefficient	Value
Material	MgCaTi
Dielectric constant ϵ	20
Taper angle	8°
Loss tangent δ	10^{-4}
Inner radius a	0.3 cm
Outer radius b	0.456 cm
Frequency of TM_{01} mode	11.42 GHz
Frequency of HEM_{11} mode	9.96 GHz
Group velocity v_g	0.057c
Attenuation	4 dB/m
Power required (10 MV/m gradient)	2.6 MW

where $c\beta_g$ is the group velocity and P is the rf power passing through a cross section perpendicular to the axis of the structure. The dielectric loss plus wall loss per unit length is then found from

$$\eta=\frac{2\pi f\delta U_{\text{out}}}{v_g(U_{\text{in}}+U_{\text{out}})}+\frac{R_s\oint_{\text{wall}}dl\langle H^2\rangle}{v_g(U_{\text{in}}+U_{\text{out}})}, \tag{6}$$

where U_{in} and U_{out} are the stored energy per unit length in the vacuum and dielectric, respectively, δ is the loss tangent of the dielectric, f is the frequency of the rf, and R_s is the surface resistance of the conductor.

The electric fields in the vacuum region described by Eqs. (1) and (3) have very interesting characteristics. When $k\rightarrow 0$ in Eq. (2), i.e., the phase velocity of the wave is c, E_Z is independent of r. This implies that there are no focusing and defocusing forces for a relativistic particle traveling inside the vacuum channel. This is critical for emittance preservation in the linac, particularly for high brightness photoinjector structures.

III. CONSTRUCTION AND BENCH TESTING OF THE 11.4 GHZ STRUCTURE

We have developed a design for an X-band structure (11.4 GHz) using the parameters given in Table I. The choice of X band for the test dielectric structure permits comparison with the expected performance of rf structures designed for the next linear collider (NLC),[6] since this technology represents the current state of the art in conventional metallic accelerating structures. High power X-band klystron rf sources are presently available at SLAC;[6] high power tests of these prototype devices will eventually be carried out there.

The dielectric material is a MgCaTi compound that has a relative permittivity of 20 and can be readily obtained from commercial vendors. The desired group velocity for the NLC structure design is in the $0.03c$–$0.05c$ range.[6] The dielectric loaded structure has a comparable shunt impedance and group velocity to the conventional X-band structure. The rectangular waveguide used for rf coupling to the device is WR 90. A complete solution for the dispersion curve of the dielectric structure has been derived elsewhere;[7,8] the dispersion curves of our device are shown in Fig. 2 for the TM_{01} and HEM_{11} modes. We would like to point out that one of

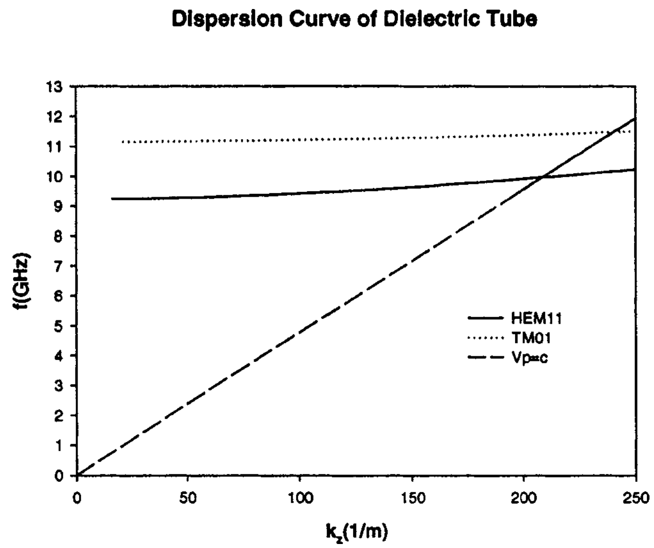

FIG. 2. Calculated dispersion curve of the dielectric tube whose parameters are shown in Table I.

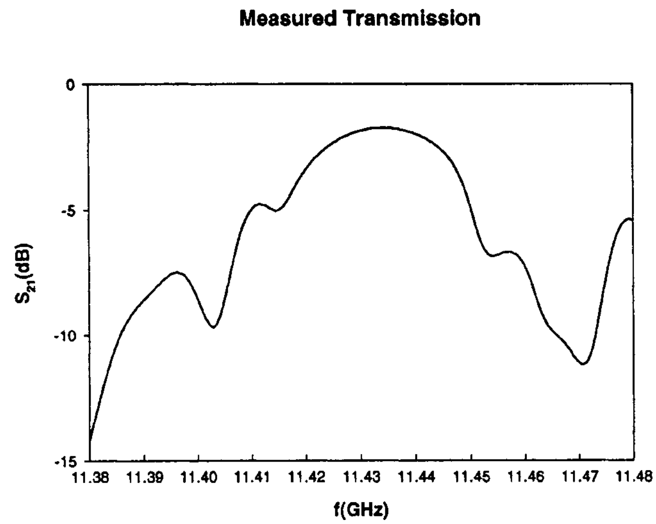

FIG. 4. Measured S_{21} between the two optimally coupled ports.

the interesting characteristics of this structure is that the frequency of the HEM_{11} mode (first deflection mode) is lower than that of the acceleration mode. Because the deflection force is a function of sin(kz), this implies very different and improved conditions for the single bunch BBU instability compared to conventional structures where the HEM_{11} is always higher in frequency than the accelerating TM_{01} mode.

The rf coupling scheme we use here is similar to the side coupled method used for conventional disk-washer rf cavities. Impedance matching of the coupling slots is more difficult in the high ϵ dielectric case because the outer radius of the dielectric tube is much smaller than the waveguide.

A 25-cm-long prototype structure was constructed with the parameters given in Table I. The dielectric materials were obtained from Trans Tech.[5] The device is a constant impedance structure with shunt impedance of 70 MΩ/m. Our goal is to obtain maximum rf transmission through the two coupling slots. We found that high efficiency coupling can be achieved by tapering the inner diameter of the dielectric tube. This tapered section serves as a broad band quarter-wave transformer for impedance matching. For the structure described here, the taper angle was chosen to be 8°. While no other angles were tested, it is not expected that the taper angle is critical. The detailed configuration of the tapered dielectric structure and coupling slots are shown in Fig. 1.

Optimal coupling was obtained by adjusting of the coupling slot dimensions and monitoring the S parameters using an HP8510C network analyzer until no further improvement was observed. Plots of the measured S parameters versus frequency for the optimized coupling case are shown in Figs. 3 and 4. The transmission coefficient S_{21} shows a broad peak with a maximum of ≈ -1.5 dB at 11.435 GHz. The reflection coefficient S_{11} at this frequency < -13 dB. (The structure in the S_{11} and S_{21} data is the result of reflections from the joints between dielectric segments from which the structure is assembled.) The optimized coupling slot dimensions are 4.7 mm (axial)$\times$5.69 mm (transverse). We calculated the attenuation of the rf in the waveguide to be 4 dB/m using the dielectric loss factor of 10^{-4} supplied by the manufacturer and the nominal resistivity of copper, in good agreement

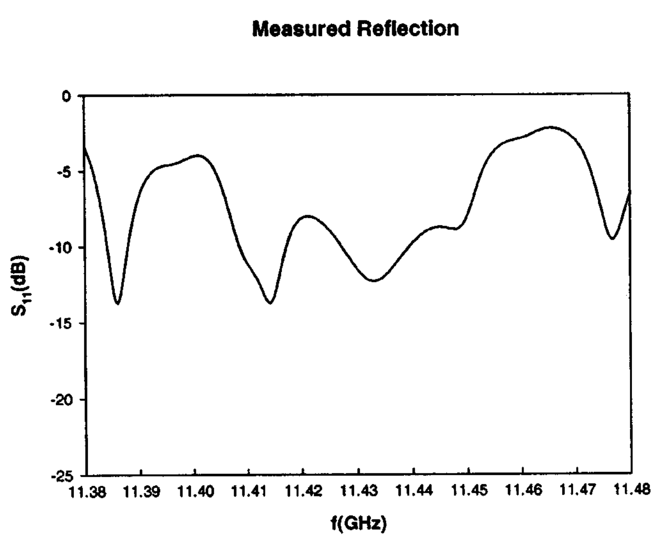

FIG. 3. Measured S_{11} for the optimally coupled waveguide.

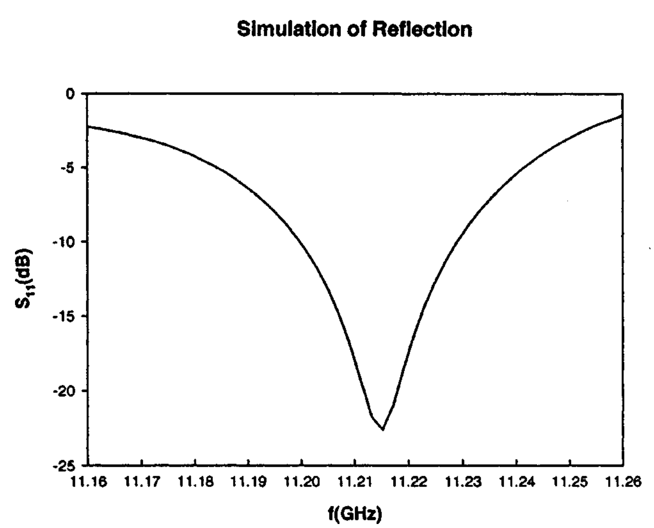

FIG. 5. Calculated S_{11} using MAFIA.

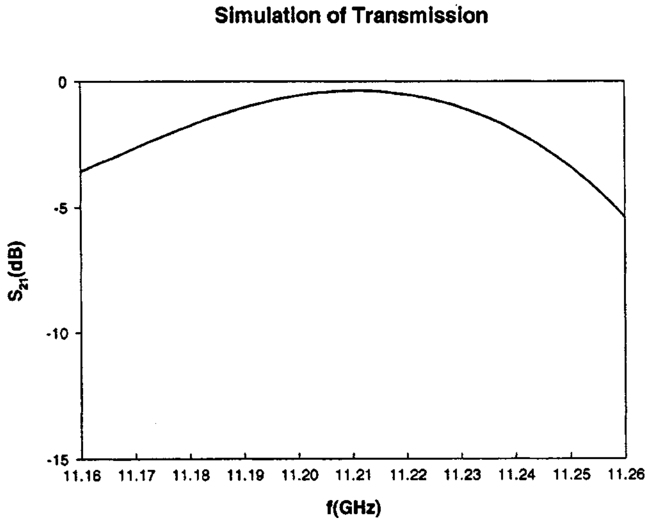

FIG. 6. Calculated S_{21} using MAFIA corresponding to the parameters in Fig. 5.

with our measurements. One interesting feature of high dielectric constant loaded waveguides is that the attenuation is dominated by the copper wall losses rather than dielectric losses. We conclude that further reduction of the loss tangent of the dielectric material will not improve the device performance unless the outer wall is replaced with a superconductor.

We plan to continue engineering studies of this accelerating structure with improved rf coupling and mechanical fixtures to allow operation in vacuum, with the eventual goal of a high power test of a demonstration dielectric accelerator section to investigate issues such as breakdown limits and thermal heating. With 100 MW *X*-band rf power available at SLAC, we can test this structure at a 60 MV/m gradient, comparable to that planned for the NLC structures.[6]

IV. NUMERICAL SIMULATIONS OF THE COUPLING PORT USING MAFIA

In order to further investigate the coupling method developed empirically, we have used the MAFIA code suite[9] to perform a full three-dimensional (3D) time domain electromagnetic simulation of the structure with the parameters described in the last section. Due to the relatively small size of the coupling slot, special attention has to be given to the finite-difference mesh size in the neighborhood of the slot to faithfully reproduce the actual device geometry.

Figure 5 shows the calculated S_{11} as a function of frequency. The optimally coupled frequency in the simulation occurs at a slightly different frequency (11.215 GHz) from the measurements because of finite mesh size effects and due to the difficulties associated with modeling high dielectric constant materials numerically. (The $\approx$200 MHz frequency shift corresponds to a $<$1% change in the inner radius of the device.) The computed S_{11} is in reasonable agreement with the network analyzer measurement since the calculation does not include dielectric or wall losses. The computed transmission parameter S_{21} is approximately -0.4 dB as shown in Fig. 6, compared to -1.6 dB obtained in the actual measurement (Fig. 4) in which wall losses dominate.

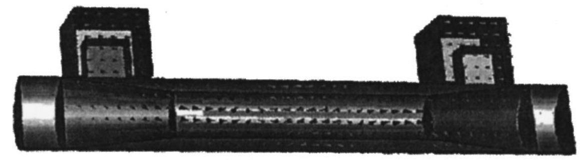

FIG. 7. Calculated TM-like mode electric field pattern displayed using Microwave Studio corresponding to the fundamental mode of the device.

In order to verify the mode coupled into the dielectric tube is indeed predominantly TM_{0n}, we have obtained the electric field pattern of the propagating wave at 11.2 GHz using Microwave Studio[10] as shown in Fig. 7. The pattern is consistent with the expected independence of the axial electric field on the radial coordinate in the vacuum channel expected for the accelerating TM_{01} mode.

We have constructed and studied an 11.43 GHz dielectric loaded structure for particle acceleration. Careful engineering considerations were implemented. We have achieved efficient coupling from port to port. A demonstration accelerator for a high power test has been designed and is under construction. Our goal is to achieve 50–100 MV/m gradients so the structure can be used as a viable alternative to conventional accelerating structures. We also simulated the parameters of this structure and the results are in qualitative agreement with the bench test results. Some practical issues concerning high power breakdown and thermal heating will be answered by future experimental studies.

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[1] G. Flesher and G. Cohn, AIEE Trans. **70**, 887 (1951).
[2] T-B Zhang, J. Hirshfield, T. Marshall, and B. Hafizi, Phys. Rev. E **56**, 4647 (1997).
[3] W. Gai, R. Konecny, and J. Simpson, in Proceedings of 1997 Particle Accelerator Conference, Vancouver BC, Canada, May 1997, pp. 636–638.
[4] E. Chjonacki, W. Gai, C. Ho, R. Konecny, S. Mtingwa, J. Norem, M. Rosing, P. Schoessow, and J. Simpson, J. Appl. Phys. **69**, 6257 (1991).
[5] Trans-Tech Inc., Catalog No. 5520 Adamstown, MD 21710.
[6] SLAC Report 474, 1996.
[7] K.-Y. Ng, Phys. Rev. D **42**, 1819 (1990).
[8] M. Rosing and W. Gai, Phys. Rev. D **42**, 1829 (1990).
[9] MAFIA Version 4.0, Gesellschaft fur Computer-Simulationstechnik, Lauteschlagerstrabe 38, D-64289, Darmstadt, Germany.
[10] Microwave Studio, Gesellschaft fur Computer-Simulationstechnik, Lauteschlagerstrabe 38, D-64289, Darmstadt, Germany.