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CONSTRUCTION AND TESTING OF AN 11.4 GHz DIELECTRIC STRUCTURE BASED TRAVELLING WAVE ACCELERATOR

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Abstract

One major challenge in constructing a dielectric loaded travelling wave accelerator powered by an external rf power source is the difficulty in achieving effcient coupling. In this paper, we report that we have achieved high effiency broadband coupling by using a combination of a tapered dielectric section and a carefully adjusted coupling slot. We are currently constructing an 11.4 GHz accelerator structure loaded with a permitivity=20 dielectric. Bench testing has demonstrated a coupling efficiency in excess of 95% with bandwidth of 600 MHz. The final setup will be tested at high power at SLAC using an X-band klystron rf source.

1 INTRODUCTION

The proposed use of rf driven dielectric based structures for particle acceleration can be traced to the early 50's [1]. Since then, numerous studies have examined the use of dielectric materials in accelerating structures[2,3]. Advantages and potential problems of using dielectric material are discussed in the references. More that recent development of high dielectric constant (ε ~ 20 - 40), low loss materials (Q~ 10,000 - 40,000) warrant a new look at the idea [4, transtech].

One faces a challenging problem when building an actual dielectric accelerator because outer diameter of the dielectric is much smaller than the rectangular waveguide which couples the external rf. Therefore, realising impedance matching becomes a difficult tasks. There is also no technical references treating this subject. We found that by using a combination of side coupled slots and a tapered dielectric near the coupling slots, one can efficiently couple the rf from the rectangular waveguide to the dielectric waveguide. In the prototype 11.4 GHz dielectric loaded accelerator as shown in Figure 1, we have achieved > 95 % power coupling.

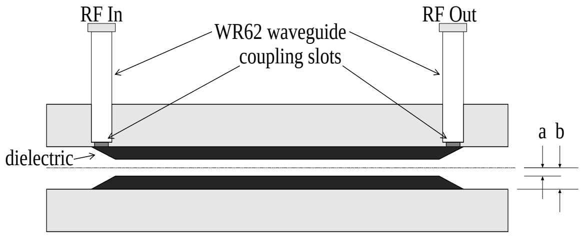

Figure 1. Schematic diagram of a dielelectric loaded travelling wave accelerator.

2 A TRAVELLING WAVE DIELECTRIC LOADED ACCELERATING STRUCTURE BASICS

The dielectric travelling wave accelerator has a simple geometry. Considering a cylindrical structure partially filled with dielectric material (ε) with inner radius a, outer radius b and conducting wall on the outside. There are also two ports on the side for RF coupling purposes, as shown in Figure 1. The axial electric fields inside the structure can be solved for exactly as

$$\begin{aligned} E_z^{(1)} &= E_0 I_0(kr) e^{i(k_z z - \omega t)} \\ E_z^{(2)} &= [B_1 J_0(s_1 r) + D_1 N(s_1 r)] e^{i(k_z z - \omega t)} \end{aligned} \qquad (1)$$

Here E_0, B_0 and D_1 are the field amplitudes in the region 0 (vacuum) and 1 (dielectric) respectively and are related by boundary conditions,and

$$\begin{aligned} k^2 &= \frac{\omega^2}{c^2}(1-\beta^2) \\ s^2 &= \frac{\omega^2}{v^2}(\beta^2 \varepsilon - 1) \end{aligned} \qquad (2)$$

where $\beta c = v = \omega / k$ is phase velocity of the wave travelling inside the tube: β determines the synchronism of the wave and the accelerated particles. By properly choosing *a*, *b* and *ε*, one can adjust the phase velocity accordingly. Thus this proposed scheme works not only for acceleration of electrons which typically has phase velocity ~ *c*, but also for low phase velocity particle acceleration, such as heavy ions. The transverse electric field can be written as

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

and the magnetic field $H_\phi = \varepsilon E_r$ everywhere inside the tube. By matching the boundary conditions at a and b (E_z and D_r continous), 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

$$U = \frac{1}{2}\sum_{0,1}\pi\int(\varepsilon\varepsilon_0 E^2 + \mu_0 B^2)rdr = E_0{}^2 u \tag{4}$$

where u is a geometric factor which depends solely on the structure geometry and dielectric constant. For a given RF power, the axial electric field in the center region of the tube can be expressed as

$$E_0 = [\frac{P}{u\beta_g c}]^{\frac{1}{2}} \tag{5}$$

where β_g is the group velocity. The dielectric loss plus wall loss per unit length is then found from

$$\eta = \frac{2\pi\delta f U_{out}}{v_g(U_{out} + U_{in})} + \frac{R_s \oint_{Wall} ds < H^2 >}{\omega U} \tag{6}$$

The electric fields in the vacuum region described by equation 1 and 3 have very interesting chraracteristics. When $k \to 0$, *i.e.*, the phase velocity of the wave is c, E_z is constant in r. This implies that there are no focusing and de-focusing forces for a relativistics particle travelling inside the vacuum chamber. This is critical for emittance preservation in the linacs, particularly for high brightness electron gun development.

3 CONSTRUCTION AND BENCH TESTING OF THE 11.4 GHZ STRUCTURES

We have developed a design for an X-band structure (11.4 Ghz) using the parameters given in table I. Choice of the dielectric is MgCaTi compound which has dielectric constant of 20. And this material can be readily obtained from commercial vendors. The group velocity for the NLC design is in the 0.03 c ~ 0.05c range [5]. Thus dielectric loaded structure is having a comparable shunt impedence and group velocity to a conventional X-band structure as indicated in the table below. As shown above, one of the interesting characteristics of this structure is that the frequency of the HEM11 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 problem compared to conventional structures where the HEM11 is always higher in frequency than the accelerating TM01 mode.

Table : Dimensions and physical properties of the 11.4 GHz dielectric tube

Material	MgCaTi
ε (diele. const.)	20
Tapered Angle	8°
Loss tangent δ	10^{-4}
Inner Radius a	0.3 cm
Outer Radius b	0.456 cm
HEM11	9.96 Hz
group velocity	0.057 c
Attenuation	4 dB/m
Power needed (10MV/m)	2.6 MW

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

Basically speaking, one would like to obtain maximum RF transmission through the two coupling slots. In order to achive high efficiency coupling, the dielectric tube near the coupling slots is tapered. The tapered angle was chosen to be 8° for initial convenience. This tapered section serves as a broad band quarter wave transformer for impedance matching. No other angles were tested, but it is not expected that the taper angle is critical. The detailed configuration of the tapered dielectric structure and coupling slots are shown in Figure 1.

A 25 cm long prototype structure was constructed with the parameters in table 1. The dielectric materials was obtained from Trans Tech. The coupling slot dimensions are 4.7 mm × 5.69 mm. By careful adjustment of the coupling slots and monitoring the S-parameters using an HP8510C network analyzer, we have achieved a reflection coefficeint S11< - 13 dB and transmission S21 > -1.5 dB @ 11.43 GHz as shown in Figures 2 and 3 respectively.

We plan to continue engineering studies of this accelerating structure with improved RF coupling and mechanical fixture to allow operation in vacuum, eventually leading to a high power test at SLAC of a demonstration accelerator section to resolve practical issues such as breakdown voltage, thermal heating etc. With 100 MW power, we can test this structure at a 60 MV/m gradient.

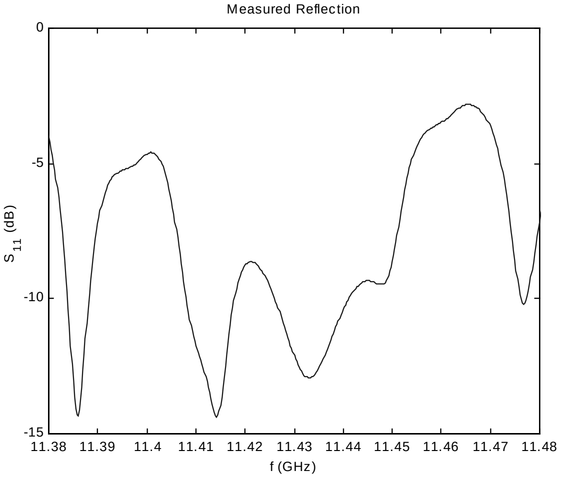

Figure 2. S11 for the optimally coupled waveguide results.

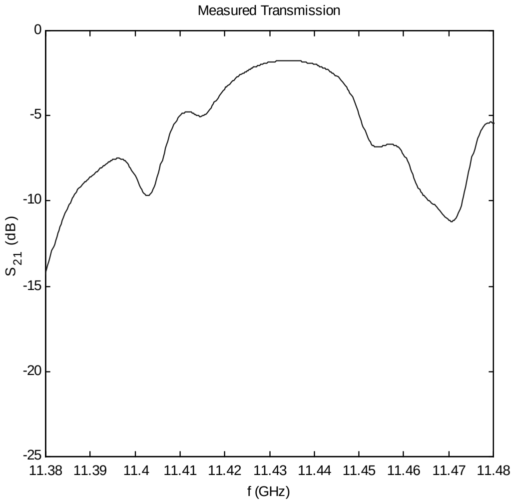

Figure 3. S21 between two optimally coupled 2 ports

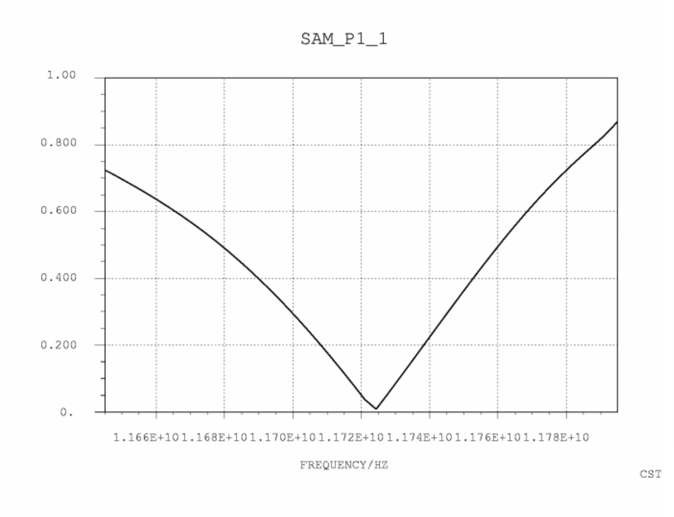

Figure 4. Calculated S11 parameter using MAFIA At 11.7 GHz, the S11 is almost 0.

4 NUMERICAL SIMULATIONS OF THE COUPLING PORT USING MAFIA

In order to verify the coupling method developed experimentally, we have used MAFIA [6] to simulate the parameters described in the last section. As expected, the simulation process was tedious and time consuming. Due to the relatively small size of the coupling slot, special attention has to be given for mesh size in the neighborhood of the slot.

Figure 4 shows the calculated S11, although it is peaked at 11.7 GHz for the given geometry, it does give qualitative agreement with the bench top measurement. In the calculation, with assumption of no dielectric loss and no wall loss, we have achieved S21 of near 1.0 as shown in Figure 5. In comparison with –1.6 dB measurement in Figure 3 where the wall losses dominated.

5 SUMMARY

In summary, we have constructed and studied a prototype 11.4 GHz dielectric loaded waveguide. Careful engineering considerations were implemented. We have achieved efficient coupling from port to port. A demonstration accelerator for high power test has been designed and is under construction. Our goal is to achieve 50 – 100 MV/m so it can be used as a viable alternative for the accelerating structures. Some pratical issues concerning high power breakdown and thermal heating will be answered through careful experimental studies and new materials development.

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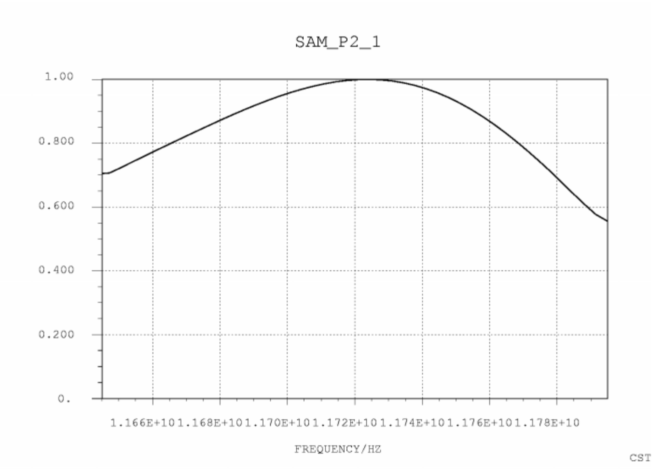

Figure 5. Calculated S21 corresponding to the parameters in the Figure 5. Almost perfect coupling was achieved here.

6 REFERENCES

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