PROGRESS TOWARDS A GAP FREE DIELECTRIC-LOADED ACCELERATOR *

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Abstract

One of the major concerns in the development of Dielectric-Loaded Accelerating (DLA) structures is the destructive breakdown at dielectric joints caused by a local electric field enhancement induced by the discontinuity of the dielectric constant at the surface of the joint gap. Our previous X-band traveling wave DLA structure design [1], for example, incorporated two separate impedance matching sections with at least two dielectric joints. In this paper, we present a new design to avoid this problem. This scheme is based on a coaxial type coupler which is able to implement mode conversion and impedance matching at the same time and therefore to eliminate joint gap induced breakdown. The new structure is under construction; bench test results will be presented.

INTRODUCTION

Dielectric based accelerating structures offer potentially significant advantages over existing conventional technologies: low cost; simplicity of fabrication, easily damped transverse modes, and potential for scaling to higher frequencies. Note the extremely high breakdown strength > 2 GV/m of materials like CVD diamond that can be used as a loading material for DLA structures. The development of dielectric based accelerators could result in lower-cost linacs, possibly broadening their use in the marketplace. To date, several dielectric materials and structures have been designed and experimentally studied [1]. One limitation to achieving high gradients in rf driven dielectric loaded accelerating structures is the occurrence of dielectric joint breakdown, a result of the local field enhancement at microscale gaps between the separate dielectric sections. This effect has been experimentally found to occur in the coupling section of the structure where the TE mode of the waveguide feeding the structure is converted to the TM accelerating mode and has so far restricted the maximum accelerating gradient that can be achieved. We have designed a new gapless DLA structure scheme based on a coaxial-type DLA coupler and ceramic brazing technology [2] that avoids vacuum gaps between the dielectric sections and thus eliminates any points for potential rf arcing. It allows us to build a new type of dielectric-based accelerating structure that provides accelerating gradients exceeding 100 MV/m.

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DIELECTRIC JOINT BREAKDOWN

Along with continuing progress in theoretical understanding, there are also considerable experimental activities in the area of external rf powered dielectric structures and beam driven wakefield acceleration. In this section, we briefly review the issue of dielectric joint breakdown observed in our previous experimental work on external rf driven dielectric accelerators.

The test structure is a modular DLA structure which consists of three functional parts (Figure 1). (1) rf couplers that convert between the TE_{10} mode in the rectangular waveguide and the TM_{01} mode in the circular copper waveguide at the input and output ends. (2) Tapered dielectric matching sections to match the impedance of the TM_{01} wave between the coupler and the acceleration section. (3) The dielectric accelerating section used to accelerate particles.

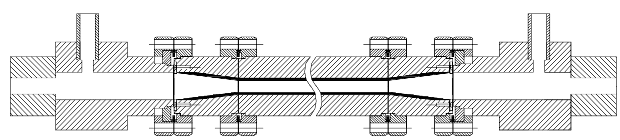

Figure 1. Schematic of the modular dielectric loaded accelerating structure used for the ANL/NRL experiments.

One tested dielectric material is $Mg_xCa_{1-x}TiO_3$ (MCT-20, ε=20). Due to its higher dielectric constant, the structure is smaller in size (a=3mm, b=4.57mm) and has a lower group velocity. It only requires 27 kW to establish a 1 MV/m accelerating gradient. However, during the high power testing, the structure arced when the incident rf power was increased beyond 1 MW and breakdown occurred at 1.9 MW input [1]. The breakdown point was at a dielectric joint between the upstream end taper and the uniform radius acceleration section and is believed to be caused by the existence of a microscale vacuum gap in the dielectric joint. Because of the large discontinuity in the permittivity at the joint, it will have a strong local electric field enhancement. Based on the continuity of the electric flux density, the local longitudinal electric field should be enhanced by 20 (ε) times compared to the ideal (continuous dielectric) case. Based on the applied rf power, we can then estimate the electric field at the gap to be 100 MV/m. The size of the vacuum gap is also directly related to the absolute energy gain for electron emission when arcing occurred. Figure 2 shows Scanning Electron Microscope (SEM) images of the MCT sample taken from the tested DLA structure. As in the case of rf

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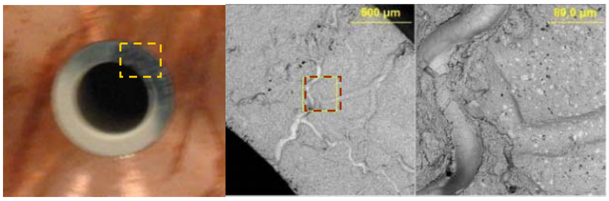
window breakdown we find streamer tree marks on the gap surface.



(a) (b) (c)

Figure 2. Breakdown signature of $Mg_xCa_{1-x}TiO_3$ tube during high power RF testing of the MCT based DLA structure. (a) Breakdown marks on the dielectric end surface (part of the copper jacket is visible outside of the dielectric tube). (b) SEM image of streamer-tree-like breakdown marks at the 500 micron scale. (c) SEM image at the 80 micron scale.

COAXIAL RF COUPLER DESIGN

Instead of using a TE-TM converter with a tapered dielectric matching section, we propose a new symmetric, double port coaxial-type coupling section to develop a true gapless Dielectric-Based Accelerator (see Fig. 3). The coaxial-type coupler implements the TE to TM mode conversion through a TEM mode so that the mode and impedance transitions can be achieved simultaneously without using a separate tapered dielectric section. This new scheme avoids vacuum gaps between the dielectric sections and thus eliminates any points for potential rf arcing. The new coupling approach also employs a double-input design to symmetrize the coupling regions in order to eliminate parasitic dipole modes and to minimize beam perturbations that could lead to beam breakup effects in the accelerator.

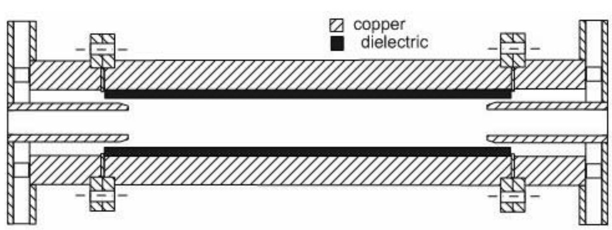


Figure 3. Schematic drawing of the gap free DLA structure based on a coaxial-type coupler.

We have developed a coaxial type rf coupler for an X-band alumina based gapless DLA structure. The 3D model is shown in Figure 4. All the dimensions are optimized using the CST Microwave Studio® EM simulation tool to optimize the design for the best rf parameters. The simulation (Fig. 5) shows that the (accelerating) TM_{01} mode has a bandwidth of more than 500 MHz at the center frequency of 11.424 GHz, where the reflections are less than -20 dB and transmission is over 99% as shown in Figure 5. At the same time, the lower hybrid mode (parasitic mode) has been suppressed below -35 dB for the entire frequency range.

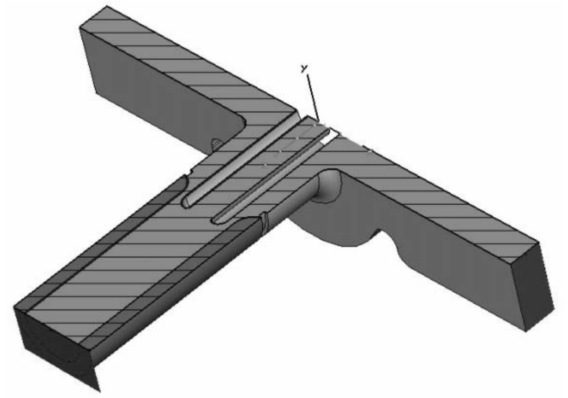


Figure. 4. 3-D model of the coaxial rf coupler in CST Microwave Studio® (cross section).

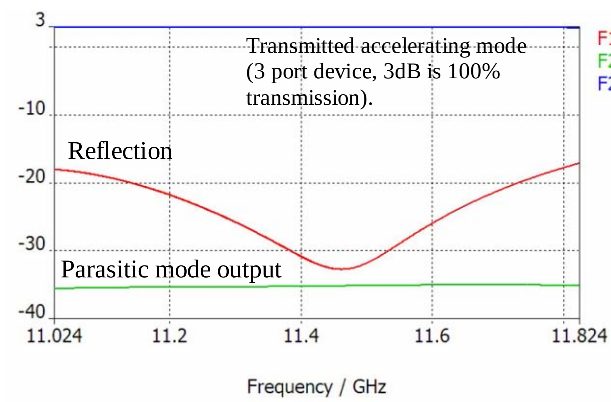


Figure 5. rf reflection and transmission properties of the X-band alumina based coupler (Microwave Studio® simulation).

Properly adjusted mechanical rounding of corners in this design decreases the field enhancement (the ratio of the maximum electric field at the surface of the dielectric end to the electric field at the surface of the regular dielectric section) to less than 14%, significantly lower than the local field enhancement in the DLA structure configuration tested previously. The highest electric field in the new coupler appears at the inner conductor tip. For 20 MW rf input (the highest level available from the X-band rf source at the Naval Research Laboratory), the electric field at the tip will reach 24 MV/m, much less than the copper breakdown voltage threshold. The amplitude of the electric field on the inner conductor surface and the inner surface of the alumina tube are presented in Fig.6.

To effectively damp hybrid dipole modes inside the structure, the designed rf couplers use a dual-port balanced rf feed in/coupling out. An X-band high power combiner has been designed and incorporated into the coaxial type rf coupler to meet the requirements of bench and high power testing. Two half height X-band rectangular waveguides (WR-90) from the rf couplers are bent together to form a full height waveguide. The 180 degree phase shift between the two waveguide arms is designed to provide 100% power transmission.

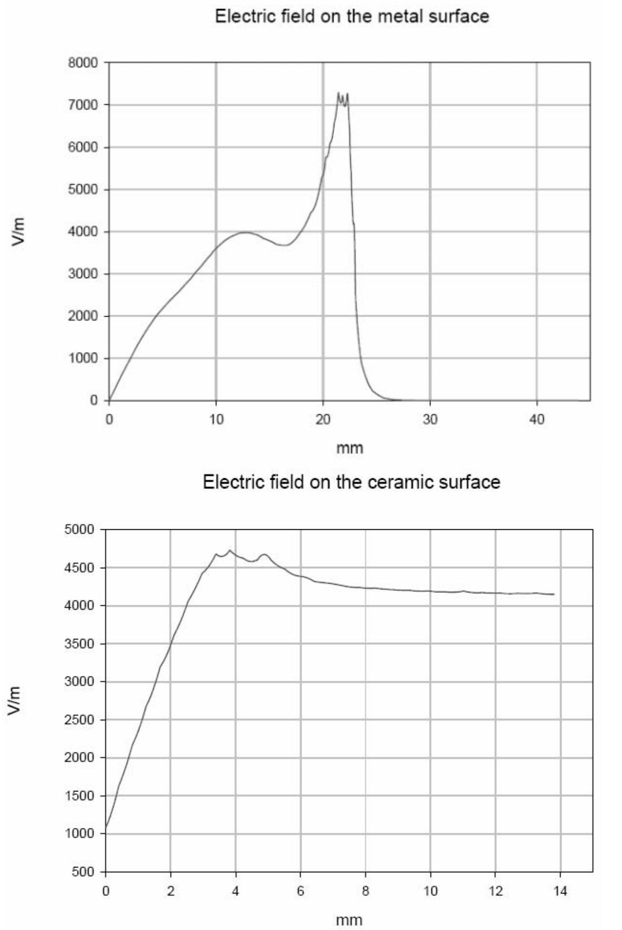


Figure 6. Plots of the surface fields in the alumina based rf coupler: (upper) The amplitude of the electric field on the inner conductor surface; (lower) the amplitude of the electric field on the dielectric surface. The field magnitudes are normalized to 1 Watt rf power.

GAPLESS DLA STRUCTURE

The final 11.424 GHz gapless DLA structure consists of an input/output coaxial rf coupler and a central DLA section connected together by ConFlat flanges. The central DLA section is loaded with one piece of alumina tube with a length of 113 mm (an elongated gapless DLA structure using the dielectric brazing technique will be investigated as well). The design incorporates a copper washer between the accelerating section and the rf coupler where they join together, that is not only used to maintain electrical contact but also to tune the performance of the whole structure. Before the flanges are brazed onto the accelerating section, we perform a bench test to try to tune the structure with several sets of different thickness copper washers. In addition, a slightly smaller copper washer ID is able to stop the loaded dielectric tube from sliding in its copper sleeve.

Figure 7 shows the assembled structure for bench testing. To evaluate the performance of the assembled coaxial rf coupler and the gapless DLA structure we have completed a set of rf bench measurements, including S-parameters, a short pulse rf time domain measurement, and a bead-pull experiment. Here we present the results from the S-parameter measurement (see Fig. 8). We can see the structure has S_{11} = -18 dB, S_{21} = -0.6 dB at the 11.424 GHz operating frequency. A bandwidth larger than 200 MHz (90% rf transmission) was also achieved.

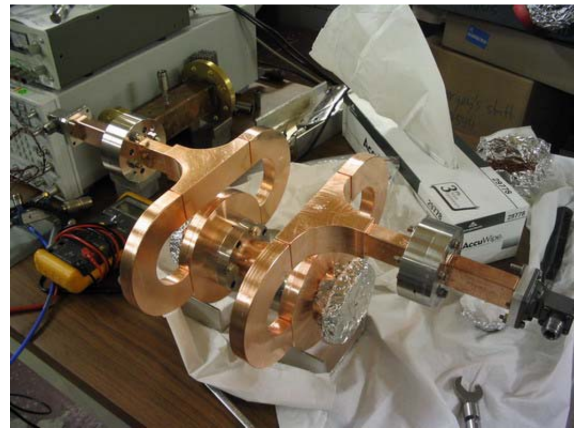


Figure 7. The assembled X-band alumina based gapless DLA structure.

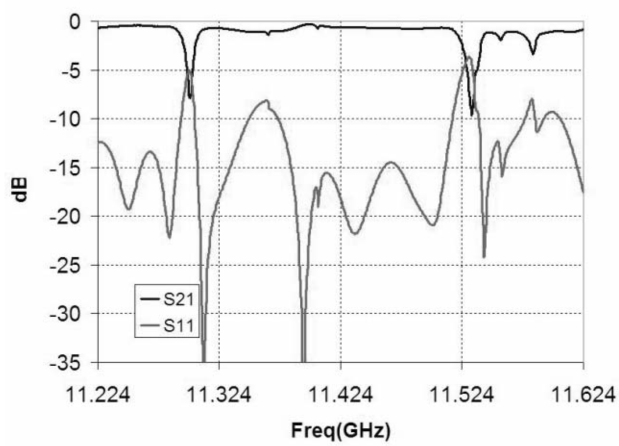


Figure 8. Cold test results of the gapless DLA structure.

CONCLUSION

We have developed an X-band gapless DLA structure. Cold testing shows good transmission over the operating frequency band. A high power rf test of the device is scheduled at NRL.

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