Development of Dielectric-Based High Gradient Accelerating Structures

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Abstract. High gradient accelerating structures using dielectric-lined circular waveguides have been developed for a number of years at Argonne National Laboratory. In this article, we first report the experimental results of high power rf testing on the quartz based Dielectric-Loaded Accelerating (DLA) structure carried out on Feb. 2006 at the Naval Research Laboratory. The motivation for this experiment is to test the multipactor effect on different materials under high power and high vacuum condition. Up to 12 MW pulsed rf went through the tube without breakdown. Multipactor appeared during the experiment but with different features compared to other materials like alumina. Photomultiplier Tube (PMT) measurements were introduced into the experiment for the first time to observe the light emission time and intensity. In the second part of this paper, ways to achieve higher gradient for DLA structures are proposed: 1) smaller ID and longitudinal gap free DLA structures to reduce multipactor and obtain higher gradient; 2) new coaxial type coupler to avoid dielectric gap and improve impedance matching; 3) double layered DLA structure to reduce rf loss and enhance shunt impedance as well.

Keywords: Dielectric-Loaded Accelerating Structures, High Gradient.
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INTRODUCTION

With a potential capability to achieve high accelerating gradient (>100MV/m), Dielectric-Loaded Accelerating (DLA) structures have been studied for years at Argonne National Laboratory (ANL) [1-7]. Two approaches have been used to pursue the highest gradient before the dielectric breaks down: experimental studies of e-beam driven standing wave wakefield DLA structures at Argonne Wakefield Accelerator (AWA) facility [1,3,4] and external rf powered traveling wave DLA structures at the Naval Research Laboratory (NRL) magnicon facility [5,6]. For the second approach, up to date, we have three generations of structure schemes developed and four different dielectric loading materials tested. No breakdown of the bulk dielectric has been observed up to 8MV/m (Alumina structure) [6]. Meanwhile, we discovered and investigated multipactoring [7] and dielectric joint breakdown due to local field enhancements [5]. In this article, we concentrate on the recent research progress on the development of external powered traveling wave DLA structures. We first report some

results of the latest high power rf testing on quartz based DLA structure. Then, several new DLA structure designs will be discussed in the near future plan.

HIGH POWER TESING OF QUARTZ BASED DLA STRUCTURE

In Refs. [5] and [7], the authors have presented experimental results on the high power rf testing on two different dielectrics, $Mg_xCa_{1-x}TiO_3$ and alumina. Both of them had anomalous rf power absorption during the high power rf fed into the structures because of the multipactoring process. To further understanding this fundamental issue, we constructed and tested a quartz based DLA structure to investigate multipactor effect of the different material under the high power rf and high vacuum condition. The theoretical multipactor model analysis based on this experiment has been discussed in Ref. [8]. Here, we just present some major experimental results.

X-Band Quartz Based DLA Structure

The selected material in this DLA structure is fused silicon (quartz), with dielectric constant of 3.78. In order to reuse the previously developed X-band couplers and to avoid using separate taper sections as were used in the alumina and MCT based DLA structures [6], we fixed the OD of the loaded quartz tube to be the same as the ID of the coupler and adjusted the ID of the quartz tube to satisfy the synchronization condition. The inner tapers were machined on both ends of the quartz tube to match the impedance. Table 1 is its major geometry and accelerating parameters.

TABLE 1. Parameters of X-band quartz based DLA structure

Geometric and accelerating parameters	value
ID of dielectric tube	17.94mm
OD of dielectric tube	24.16mm
Dielectric constant	3.78
Loss tangent	2×10-5
Length of dielectric tubes	194.8mm
Group velocity	0.38c
Shunt impedance r	27.9MΩ/m
Q	7715
r/Q	3614Ω/m
Power Attn	0.35dB/m
Input rf Power to build gradient of 1MV/m	439KW

The fabricated structure had very good bench testing results. The transmission loss was 0.2dB within a 1GHz bandwidth (defined by rf reflection less than -25dB).

High Power rf Testing

The experiment was carried on at NRL where an X-band Magnicon is available as the external rf source [9]. The setup is identical as our previous experiment [5-7]. Up to 12 MW pulsed rf went through the tube without breakdown, although the corresponding accelerating gradient is low (5.2MV/m) due to the dimensions of the structure. During the experiment, we observed and measured: 1) rf power absorption

and light emission due to the multipactoring; 2) fraction of the transmitted rf power saturated at certain incident power level; 3) color of the emitting light is blue; 4) light turn on time and intensity by using PMT; 5) Multipactor onset accelerated by applying a transverse permanent magnet field.

In this section, we will present major experimental data in a series of figures. Fig. 1 shows the fraction of the transmitted rf power while raising the incident rf power. The pulse length of input rf is around 200ns when peak power below 7MW, and shortened to be ~100ns when the peak power was above 7MW. The highest power level reached 12 MW and no sign of any breakdown signature was observed. A 180 Gauss permanent magnet was put on and off at the upstream end of the quartz tube in two cases, and both of them are presented in the data plot. Obviously, like our previous results of high power testing on alumina based DLA structure, the transmission coefficient starts dropping at a certain incident power level which is a proved signature for onset of the multipactoring. However, a saturation stage appears for this quartz based DLA structure when higher rf power is input. This phenomenon was only observed in the experiment on the TiN coated alumina tube [6]. Transverse magnetic field advances 'knee' point of the curves, and consistently makes the rf transmission worse during the further dropping stage of the curve, but no significant change for the saturation stage. The last three points in the data plot shows 5% improvement of rf transmission when incident power is above 10MW; however, we needs higher rf power to determine if the multipactor can be overcome when incident rf power higher than a certain level.

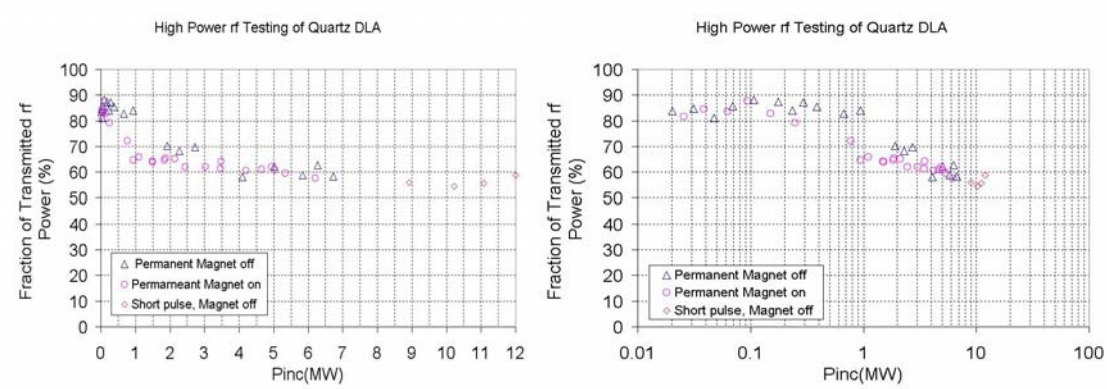

FIGURE 1. Fraction of the transmitted rf power vs. incident rf power in linear scale (left) and log scale (right).

Fig. 2 represents the time correlated scope traces of incident, transmitted rf and Photomultiplier Tube (PMT) signal in the cases of transverse magnets on or off. The light emission due to the multipactor is detected through the PMT at the upstream window of the structure. Cable lengths to transport all three signals are very close so that the time delay among signals due to the cable transmission time can be ignored. In Fig. 2, we can see that the onset time of multipactor is advanced when applying a 180 Gauss permanent magnet on the upstream end of the quartz tube. Besides, in each case, the rf signals are distorted at the moment of light emission appears. The light

signal was also recorded by CCD cameras. Images from the color camera show the emitting light of the quartz based DLA structure is blue.

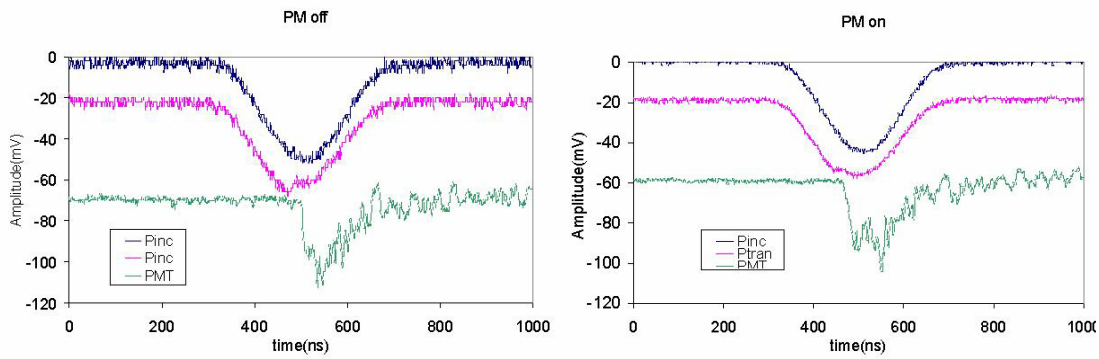

FIGURE 2. The onset time of multipactor is advanced when applying a 180 Gauss permanent magnet on the upstream end of the quartz tube. The left plot shows the scope traces of incident and transmitted rf from diode detection and the signal of Photomultiplier Tube (PMT) at the moment of around 1.9 MW rf power input with permanent magnet off; The right plot shows the signals with permanent magnet on at the same level of incident power.

The relations of both strength and starting time of the PMT signal to the peak power of incident rf are plotted in Fig. 3. The left plot shows the light intensity is proportional to the incident rf power level, and it is slightly higher when the magnet is applied. Meanwhile, in the right plot we can see the multipactor starts more slowly at low incident rf power, and the advancing time induced by a certain transverse magnetic field is roughly a constant.

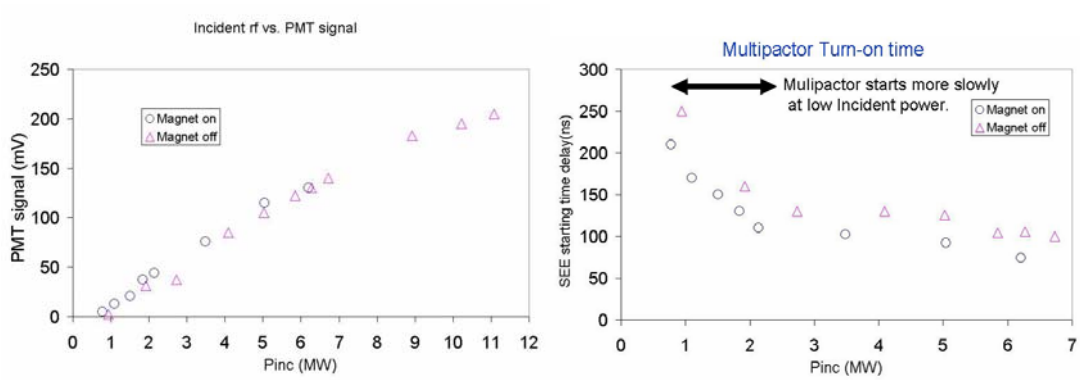

FIGURE 3. The left figure plots the relation of light intensity to the incident rf power in the case of permanent magnet on or off; the right figure shows the onset time delay of light emission from the incident rf leading edge varies with the peak power of incident rf.

NEW DESIGNS TO ACHIEVE HIGHER GRADIENT

Multipactor and dielectric joint breakdown are two major issues for the external power DLA structures. However, based on the theory of secondary electron emission,

the multipactor may be eventually suppressed once the built up gradient inside the structure is high enough to cross over the second threshold of emitted electron energy, *e2* [7]. Therefore, the key issue for the development of DLA structures is to design a gap free scheme so that the accelerating gradient of DLA structure can go higher without the limitation of local field enhancement at the dielectric joint. In this part, we will briefly describe three new designs to help improve the accelerating gradient of DLA structures: 1) smaller ID, longitudinal gap free DLA structure; 2) coaxial coupler based gapless DLA structure; 3) double layer DLA structure.

Smaller ID, Longitudinal Gap Free DLA Structure

As we present above, the tested quartz based DLA structure did not have breakdown with the available rf power source (12MW). However, due to its large ID which can eliminate the dielectric gaps induced by separate impedance matching tapers, the gradient built inside the quartz tube is relatively low (5.2MV/m). To reach higher accelerating gradient with the available rf power, we designed a new scheme of X-band DLA structure which consists of input/output coupler and center accelerating section. The mechanical sketch is shown in Fig. 4. The loaded dielectric tube (the center black part) has a smaller ID, usually 2 or 3mm, and the two flaring ends to match impedance. Because there are no longitudinal dielectric gaps in the structure where the local field would be enhanced, the dielectric joint breakdown can be eliminated. Practically, to assemble this structure, one flaring end of the dielectric tube has to be machined as a separate sleeve horn, which leads to a radial gap in between. Based on the EM simulation, the electric field inside this radial gap will be enhance 60% which is much lower than the field enhancement introduced by longitudinal gaps in the previous DLA structures.

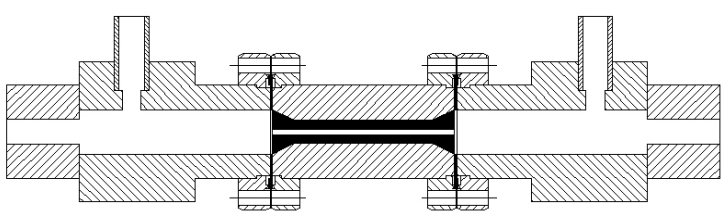

FIGURE 4. The mechanical drawing of smaller ID, longitudinal gap free DLA structure. The shaded area is copper and the center black area represents loaded materials.

The accelerating gradient built inside the structure is different depending on the different material and dimensions. Some examples are listed in Table 2, in which the quartz based one is under construction.

TABLE 2. Parameters of new designed X-band DLA structure

Loaded Material	Dimensions(mm)	Vg	Gradient per 10MW	Gradient per 100MW
Quartz (ε=3.75)	ID=2, OD=12.52	0.27c	12.3MV/m	38.9MV/m
Cordierite (ε=4.76)	ID=2, OD=10.85	0.21c	14.6MV/m	46.2MV/m
Alumina (ε=9.77)	ID=3, OD=8.23	0.1c	19.8MV/m	62.6MV/m
MCT (ε=20)	ID=3, OD=6.42	0.05c	26.5MV/m	83.8MV/m

New DLA Structure Using Coaxial Type Coupler

Another option to avoid the dielectric joint in the DLA structure is to design a new coaxial-type coupler instead of the TE-TM converter used in our previous DLA structures. This coaxial type coupler implements TE to TM mode conversion through a TEM mode so that mode and impedance transition can be achieved simultaneously without using a tapered dielectric (see Fig. 5). The loaded material is just a simple straight dielectric tube so that the local field enhancement in the dielectric joints can be eliminated. In addition, two-arm balanced rf input/output waveguide can effectively damp hybrid mode inside the structure.

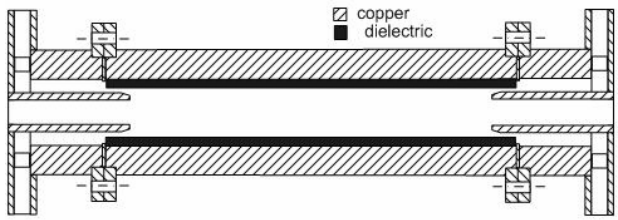

FIGURE 5. Schematic drawing of the gap free DLA structure based on coaxial-type coupler.

Fig. 6 is the EM simulation of an X-band alumina based structure. The highest field appears on the inner conductor tip of the coupler with the field enhancement ratio of 1.6 to the accelerating gradient. This structure is under construction as well.

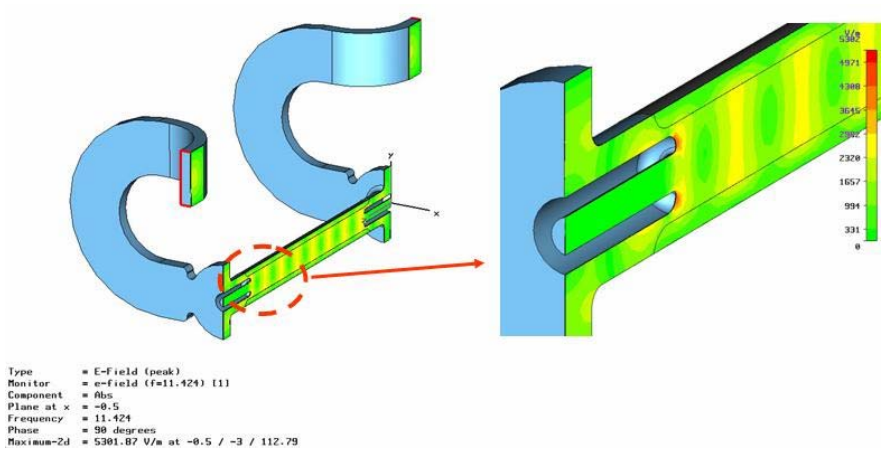

FIGURE 6. EM simulation of the DLA structure based on coaxial type coupler (using CST Microwave Studio®).

Dual Layer DLA Structure

Due to the high magnetic-induced surface current, the conventional single layer DLA structure has relatively high rf loss. One possible way to solve this problem is to use multilayered DLA structures [10]. Fig. 7 shows the pictures of an X-band double layer DLA structure for bench testing. The measurement shows that it has only 4.7 dB/m of rf power attenuation. In comparison, the theoretical rf power attenuation of

the single layer structure with the same inner radius is 20dB/m. Meanwhile, the shunt impedance of the double layer structure can be improved from 11.7 to 14.5 MΩ/m. A specific designed TM_{03} mode launcher consisting of two overlaid coaxial waveguide is used to excite TM_{03} mode for the double layered DLA structure during the bench test (see the right picture in Fig. 7). It will be replaced with a dielectric-loaded corrugated waveguide to meet the requirement of high vacuum condition for the high power rf testing.

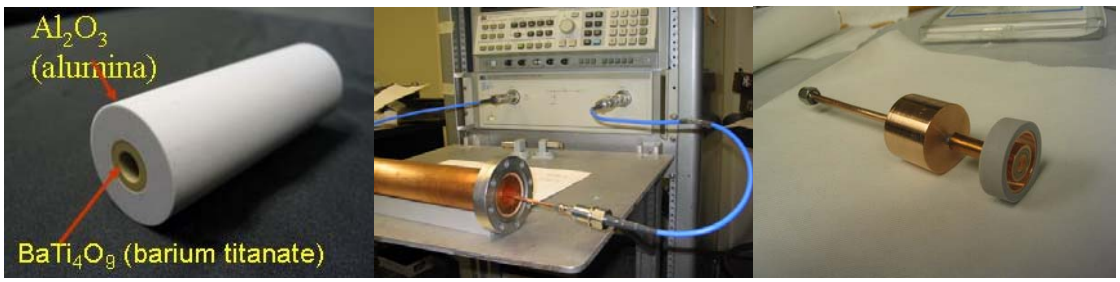

FIGURE 7. Double layer dielectric tube (left); Bench testing of double layered DLA structure (middle); TM03 mode launcher for bench testing (right).

SUMMARY

An X-band quartz-loaded traveling wave accelerating structure has been tested up to 12MW rf pulse without breakdown (equivalent to gradient of 5.2MV/m inside the tube). Three new designs to enhance the accelerating gradient under a certain level of input rf power and reduce rf loss are proposed. Their high power testing should take place in the near future.

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