NEW STUDIES OF X-BAND DIELECTRIC-LOADED ACCELERATING STRUCTURES*

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Abstract

A joint program is under way to study externally driven X-band dielectric-loaded accelerating (DLA) structures as well as dielectric-loaded CLIC-type power extraction structures. The structures are designed and fabricated by Argonne National Laboratory and Euclid Techlabs and tested at up to 20 MW drive power using the X-band Magnicon Facility at the Naval Research Laboratory, with some additional tests carried out at SLAC. Thus far, tests have been carried out on a large variety of structures fabricated from quartz, alumina, and MCT-20, and the principal problems have been multipactor loading and rf breakdown. Multipactor loading occurs on the inner surface of the dielectric, a region of strong normal and tangential rf electric fields; rf breakdown occurs principally at discontinuities in the dielectric. Gap-free DLA structures have been tested at 15 MV/m without breakdown. New tests are being prepared to address these two issues. New gap-free structures will make use of a metallic coating on the outer surface of the dielectric in order to permit tapering of both the inner and outer diameters for rf matching using a single dielectric section, while new multipactor studies will examine the use of grooved surfaces to suppress multipactor. Also, new higher gradient standing-wave and traveling-wave structures experiments are planned.

INTRODUCTION

The high gradient limits of conventional (i.e., non-superconducting) rf linear accelerators are under intense investigation, motivated in part by the requirements of future linear colliders. As part of this investigation, a variety of alternative rf structures are being studied. In dielectric-loaded accelerating (DLA) structures, a dielectric-lined metal tube replaces the periodic metal structure of a conventional accelerator [1]. This paper presents an update on a joint study of X-band DLA structures that is under way at Argonne National Laboratory, Euclid Techlabs LLC, and the Naval Research Laboratory, with the assistance of the SLAC National Accelerator Laboratory.

A DLA structure can be used for rf acceleration by choosing an appropriate liner material, typically a low-loss ceramic with high dielectric constant, and choosing the inner and outer radii of the dielectric to match the phase velocity of the TM_{01} accelerating mode to *c*. The DLA geometry is simpler and may be easier to fabricate than a conventional copper slow-wave structure; it can also have comparable shunt impedance, and provides straightforward methods to suppress higher-order modes [2]. In addition, DLA structures have no field enhancements at the dielectric surface, while conventional disk-loaded structures have a typical factor-of-two field enhancement on the metal irises, suggesting a high-gradient capability. However, there are problems unique to DLA structures, including strong single-surface multipactor, due to the normal and tangential components of the rf electric field at the dielectric surface, and the presence of field enhancements at any discontinuities in the dielectric liner. These phenomena are under intensive investigation [3–6]. The DLA structures are developed by ANL and Euclid Techlabs, and then brought to NRL for high-gradient testing. (Structures that perform well in these tests are sometimes taken to SLAC for additional tests at higher power levels.) This paper presents a progress report on the DLA structure development and testing, as well as a discussion of future plans.

NRL MAGNICON FACILITY

Figure 1 shows a diagram of the NRL Magnicon Facility. The facility was built around a high-power magnicon amplifier tube that was developed jointly with Omega-P, Inc. [7]. The magnicon operates over the frequency range of 11.424–11.430 GHz, and can produce up to 25 MW of output power in 200-ns FWHM pulses at

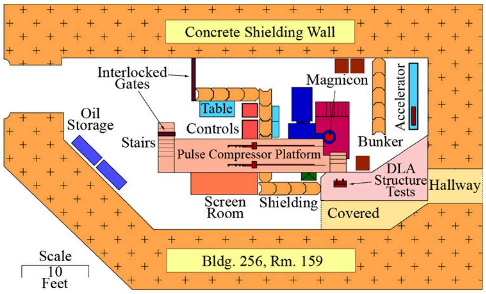

Figure 1: Diagram of NRL Magnicon Facility.

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Table 1: Summary of DLA structure tests.

Material	Al$_2$O$_3$ [±TiN]	Mg$_x$Ca$_{1-x}$TiO$_3$	SiO$_2$[±TiN]	SiO$_2$	SiO$_2$
Dielectric constant	9.4	20	3.78	3.78	3.8
Loss tangent	2x10^{-4}	3x10^{-4}	2x10^{-5}	2x10^{-5}	2x10^{-5}
Inner radius	5 mm	3 mm	8.971 mm	1.5 mm	3 mm
Outer radius	7.185 mm	4.567 mm	12.079 mm	6.45 mm	7.37 mm
R/Q	6.9 kΩ/m	8.8 kΩ/m	3.6 kΩ/m	15 kΩ/m	10.8 kΩ/m
Group velocity	0.134 c	0.057 c	0.38 c	0.265 c	0.27 c
RF power for 1MV/m	80 kW	27 kW	439 kW	73.4 kW	105 kW
Demonstrated Gradient @200ns	8 MV/m	6 MV/m	5 MV/m (9 MV/m @50ns)	15 MV/m	12 MV/m

up to 10 Hz, and 10 MW in 1-μs flattop pulses. Its output is extracted through two SLAC-style WR-90 waveguide lines, each with a high power TE$_{01}$ output window, and SLAC-style directional couplers. These two lines are connected to a power combiner assembly that was developed by SLAC. This permits the power from both lines to drive a single load, or to drive two separate loads with an adjustable power split. Two test stands are located adjacent to the magnicon output. The first, a 5'x25' raised platform, 8' high, is used for pulse compressor experiments [8], and passes over the concrete shielding wall. The second, a 10'-high concrete deck area, is used for testing DLA structures. A 6'x10' concrete bunker in the upper right corner of the diagram houses a compact X-band test accelerator. Figure 2 shows a photograph of the magnicon output switchyard taken from the top of the bunker. The pulse compressor platform is shown in the upper right and the DLA test stand is in the upper left of the picture.

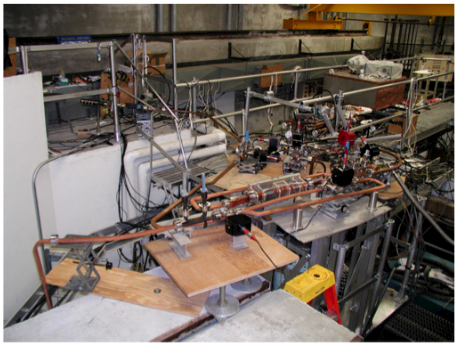


Figure 2: Magnicon output switchyard.

DLA STRUCTURE TESTS

Table 1 summarizes a series of tests, which were carried out over a period of years, of DLA structures of various internal radii and employing several different ceramic materials, including magnesium calcium titanate (MCT), alumina, and quartz. Some of the structures tested the effects of TiN coatings to reduce the multipactor on the inner surface of the dielectric liner. Many of the early tests were limited by rf breakdown at dielectric joints.

GAP-FREE STRUCTURES

The earlier DLA structures made use of several separate ceramic inserts, in order to accommodate tapers at either end of the structure and the uniform-diameter section in the middle. The principal breakdown problems occurred at joints between dielectric sections. To solve this problem, a structure was tested in which a single doubly-tapered insert was clamped between two metal half shells within the outer vacuum jacket. This permitted us to reach 15 MV/m without rf breakdown in a doubly-tapered quartz structure. In order to eliminate the clamshell, new gap-free DLA structures will make use of a metallic coating on the outer surface of the dielectric in order to provide the required conductive boundary condition. The 1st metalized quartz DLA structure has been built (see Fig. 3) and will be tested at NRL in a few months.

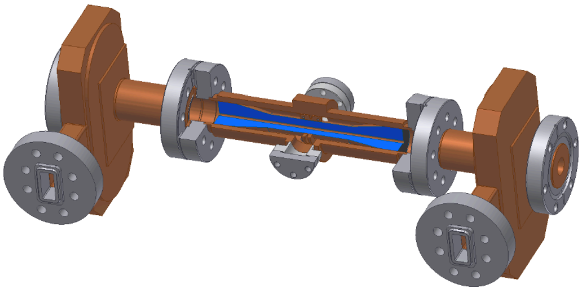
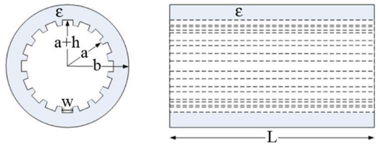


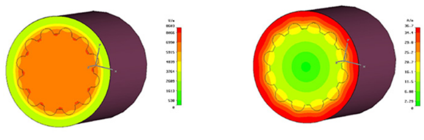
Figure 3: Diagram of metal-coated gap-free structure.

GROOVED STRUCTURES

One of the goals of our program is to explore new means to suppress the secondary emission avalanche that leads to multipactor loading of the rf drive power. If it is not possible to reduce the mean secondary emission coefficient of the uniform dielectric surface below unity directly, such as by employing a thin TiN coating, then an alternative means to accomplish this might be to trap a fraction of the secondary electrons in grooves on the inner surface of the dielectric. If the trapped fraction is large enough to reduce the mean secondary yield below unity, the multipactor might be suppressed at a very low level.



DLA structure with axially grooved inner surface



Electric Field Magnetic Field

Figure 4: Axially grooved structures.

Figure 4 shows diagrams for an axially grooved structure, as well as field calculations carried out with CST Microwave Studio®. Axial grooves have a possible advantage because the grooves lie along the direction of the axial electric field. However, azimuthally grooved structures are also being considered as a means to suppress secondary electron multiplication. These grooved structures will be the subject of future experiments.

HIGH GRADIENT STRUCTURES

One of our goals is to extend the tests to higher gradients. This requires the development of higher gradient DLA structures. One approach is to use traveling-wave structures employing small inner diameters and high dielectric constant materials. One structure that is under development would use an MCT liner with a dielectric constant of 15.7 and an inner diameter of 5 mm to reach 28 MV/m at 20 MW drive power.

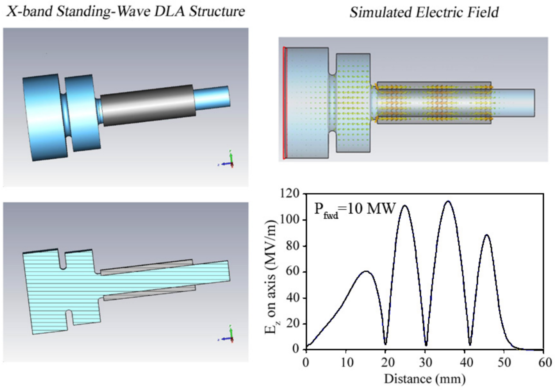


Figure 5: Standing-wave structure.

Another approach to achieving higher gradients is to make use of standing-wave structures. Figure 5 shows a preliminary design of a standing-wave DLA structure that employs a separate matching cavity at the entrance to the dielectric-lined region. The geometry as well as the electric field pattern and the calculated axial electric field profile in the DLA cavity and the matching cavity are shown.

SUMMARY

The experimental program to study rf-driven DLA structures has found that there is substantial additional microwave attenuation at high rf drive powers in all the structures that have been tested. The rf loading is due to a multipactor discharge along the inner surface of the dielectric liner. The distributed loss is a more serious problem in a traveling-wave accelerating structure than for an rf window, because it is a loss that will scale upwards with the length of the structure. Also, the multipactor physics is different than for an rf window because it involves strong normal and tangential rf electric fields, resulting in higher energy secondary electrons than for the case of purely tangential rf electric fields.

Various methods to mitigate this problem have been investigated, and the use of a thin TiN layer applied using Atomic Layer Deposition has substantially reduced, but not eliminated the multipactor loading. Planned new experiments will look at other methods to suppress the secondary electron avalanche that occurs along the surface, including the use of a grooved inner surface.

Other planned new experiments will investigate the use of DLA structures with a metallic coating on the exterior surface of the dielectric, which can help eliminate the use of multi-section dielectrics that are prone to breakdown in the joint regions. Also, higher gradient structures, both traveling-wave and standing-wave, are planned, in order to extend the experimental gradients to a multiple of the 15 MV/m that have been tested to date.

Practical applications of these structures, either as particle accelerators or as decelerators to extract rf power from bunched electron beams, will require further development of methods both to suppress multipactor and to eliminate the problems of breakdown at dielectric discontinuities.

REFERENCES

[1] P. Zou *et al.*, *Rev. Sci. Instrum.* **71**, 2301 (2000).
[2] E. Chojnacki *et al.*, *J. Appl. Phys*. **69**, 6257 (1991).
[3] J.G. Power *et al.*, *Phys. Rev. Lett.* **92**, 164801 (23 April 2004).
[4] J.G. Power and S.H. Gold, AIP Conf. Proc. **877**, pp. 362–369 (2006).
[5] C. Jing *et al.*, *IEEE Trans. Plasma Sci.* **33**, 1155 (2005).
[6] C. Jing *et al.*, IEEE Trans. Plasma Sci. **38**, 1354 (2010).
[7] O.A. Nezhevenko *et al.*, in *Proc. 2005 Particle Accelerator Conf.*, IEEE, Piscataway, NJ, 2005, pp. 1979–1981.
[8] A.L. Vikharev *et al., Phys. Rev. ST Accel. Beams*, **12**, 062003 (2009).