

## HIGH POWER TESTING OF X-BAND DIELECTRIC-LOADED ACCELERATING STRUCTURES\*

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### Abstract

A program is under way at Argonne National Laboratory, in collaboration with the Naval Research Laboratory (NRL), to develop RF-driven dielectric-loaded accelerating (DLA) structures, with the ultimate goal of demonstrating a compact, high-gradient linear accelerator based on this technology. In this paper, we report on the most recent results from a series of high power tests that are under way at NRL's X-band Magnicon facility. The design of the latest DLA structure has been fundamentally changed from the previous generation; it now has a modular construction that separates the RF coupler from the dielectric section. In this paper we present a detailed description of the design of the new structure and of the experimental setup used during the high power tests. In addition, we will report on experimental results of high power tests carried out on an alumina-based ( $\epsilon=9.4$ ) DLA structure.

### INTRODUCTION

In recent years, much research has been done to develop new types of high gradient accelerating structures [1]. One of the most promising of these technologies is the dielectric loaded accelerating (DLA) structure, where a cylindrical copper tube is lined with a dielectric sleeve, driven by an external RF source. Although the proposed use of a dielectric-based structure for acceleration dates back to the 1950's, the first high power testing of these devices has taken place only recently [2-4].

Argonne National Laboratory, in collaboration with the Naval Research Laboratory, is carrying out high-power tests of DLA structures to investigate their suitability for use in high-gradient RF linear accelerators. In an experiment carried out at the NRL in 2002 [4], one X-band traveling-wave (TW-DLA) and one X-band standing-wave (SW-DLA) structure, both made of a MCT20-ceramic, underwent high power testing at the NRL 11.424-GHz Magnicon Facility [5]. During the tests approximately 10 MW of power was available, and the incident, reflected, and transmitted (TW only) powers were\* monitored. In the TW-DLA test, the incident power that the structure could accept was limited to 600 kW, corresponding to a transmitted power of 170 kW, while in the SW-DLA test the limit was 100 kW. In both cases, when the incident power was raised above the stated limits, the reflected power and the vacuum pressure near the input coupler increased dramatically. Examination of the structures after the experiment revealed evidence of

arcing in the input coupler. This result is similar to what was observed during a high power test of an S-band TW-DLA structure carried out at Yale [3]. In that case, the power that could be delivered into the tube was limited to 200 kW. This limit was caused by arcing in the input coupler, as evidenced by a blackened alumina surface.

The failure of the input couplers in both cases is thought to be due to the presence of dielectric at the coupling slot. This creates two problems: (1) the triple-point of vacuum-to-metal-to-dielectric in a region of high electric field that is expected to cause breakdown problems; and (2) high power density in the dielectric, since all the power passes through a small area of dielectric. In this paper, we report on high power tests carried out on a new DLA structure.

### THE NEXT GENERATION DESIGN

Based on our analysis of the failures of the input couplers in both of the previous structures, we have designed a new DLA structure [6]. This structure has a modular construction that separates the coupling sections from the acceleration section and is based on the most recent NLC structure designs by Tantawi and Nantista [7]. Moving from left to right in Fig. 1, the new TW-DLA device consists of an all-metal  $TE_{10}$ - $TM_{01}$  input coupler, a dielectric-lined, tapered input matching section, a dielectric-lined accelerating section, a dielectric-lined, tapered output matching section, and an all-metal  $TM_{01}$ - $TE_{10}$  output coupler. This modular construction is expected to have good high power handling capabilities for two reasons: (1) the all-metal couplers have no triple-points; and (2) the power in the bulk dielectric is now distributed over the entire cross-section rather than just in the small area of the coupler slot.

In order to test the new structure design as quickly as possible, we chose to use  $Al_2O_3$  in the matching sections and  $Al_2O_3$  doped with  $Mg$  in the accelerating section for the dielectric material, since an alumina-based DLA structure is relatively easy to fabricate. In approximately six months, we designed, constructed, characterized, and UHV vacuum tested this structure. The TW-DLA structure parameters are: (1) the accelerating section dielectric is 200 mm long,  $I.D. = 10$  mm,  $O.D. = 14.36$  mm and  $\epsilon_r = 9.4$ ; and (2) the matching section's dielectric is  $I.D. = 24.16$  mm at the wide end and tapers to  $I.D. = 10$  mm at the narrow end over a distance of 54.24 mm with  $\epsilon_r = 9.7$ . In bench-top tests, we measured  $S_{21} = -0.1$  dB in coupler-to-coupler configuration and measured  $S_{21} = -2$  dB for the complete structure. For this  $TM_{01}$  mode structure, the field in the vacuum is of the form

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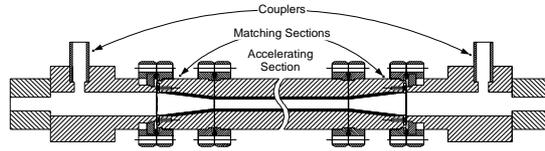


Figure 1: Cross section of the new modular DLA structure

$E_z(r, z, t) = E_0 I_0(k_r, r) \cos(\omega t - k_z z)$  with normalization such that 80 kW of power produces an axial accelerating gradient of  $E_0 = 1 \text{ MV/m}$ .

### SETUP & PROCEDURE

The configuration used during the high power tests is shown in Figure 2. The magnicon (not shown) output is delivered through WR-90 vacuum waveguide, equipped with a 55.5 dB bi-directional coupler connected to calibrated crystal detectors, and into the input coupler of our device under test (D.U.T.). The output of the D.U.T. is delivered through short section of WR-90, equipped with an identical bi-directional coupler, and into a SLAC-type high-power load. The diagnostics available to monitor the D.U.T. during high power conditioning included (1) bi-directional couplers on both the input and output waveguide to monitor the incident, reflected, and transmitted power; (2) four ion pumps to provide vacuum and monitor pressure; (3) a Faraday cup downstream of the structure to monitor dark current; and (4) cameras to look for visible light along the axis of the structure in the event of a breakdown.

### RESULTS & DISCUSSION

The testing of each D.U.T. was conducted by slowly increasing the output power of the magnicon, beginning from a low power level, while monitoring all the diagnostics to look for signs of breakdown. Typically, after an increase in the power level, the voltage signals from the bi-directional couplers were acquired with an oscilloscope and the vacuum pressure was recorded in the log. If either a visible light flash on the monitor or a non-zero reading on the Faraday cup ammeter were observed, the event was to be noted in the log.

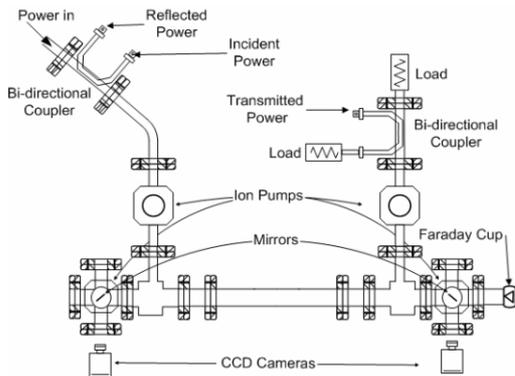


Figure 2: Diagram of the DLA structure installed at NRL's Magnicon Facility.

### Coupler to Coupler Test

In this test, the D.U.T. was the two coupling sections connected directly to one another. The couplers were easily conditioned to the maximum available output power of the magnicon (10 MW) at an RF pulse length of 150 ns (FWHM) with no arcing observed. The transmission ( $S_{21}$ ) through the coupler-to-coupler device was approximately 90 % during the entire test. In short, the high power test of the couplers was a total success.

### DLA Structure Test

In this test, we installed the complete DLA structure (Fig. 1), with its input coupler connected to the magnicon and its output coupler connected to the load. After a short conditioning period, we were able to increase the incident power to 5 MW ( $E_z \approx 8 \text{ MV/m}$ ) at an RF pulse length of 150 ns (FWHM) with no signs of breakdown observed at any time. This is the first time that over a MW of RF power was coupled into a DLA structure.

Measurement of the transmission coefficient ( $S_{21}$ , Fig. 3) and the reflection coefficient ( $S_{11}$ , Fig. 3) was as expected as long as the incident power remained below 0.1 MW, with  $S_{21} \approx 75 \%$  and  $S_{11} \approx 0.5 \%$ . (The other 25% of the power is lost due to a combination of resistive losses and manufacturing imperfections of the structure.) However, when the incident power was increased above 0.1 MW the transmission coefficient decreased, without a corresponding increase in the reflection coefficient. This means that some of the incident power was unaccounted for, or missing. For the remainder of this paper, we refer to this as the *missing power*. For example, at the highest incident power point (4.7 MW), the transmitted power was measured to be 1.2 MW and the reflected power was negligible. Estimating the power lost to attenuation in the DLA structure to be 1.2 MW implies that the missing power is about 2.4 MW. This calculation was repeated for all points and the result is shown in Figure 5.

Over the same range of incident power that the missing power appeared, we also observed light emission (Fig. 4) that appeared to be coming from the surface of the dielectric. By measuring the RS-170 analog video output from the CCD camera with an oscilloscope, triggered at the same rate as the magnicon, we were able to measure the light intensity as a function of incident power (Fig. 5). The lowest incident power for which the light intensity was observed was 0.6 MW. The reason the light intensity seems to turn-on later than the missing power (0.1 MW) is most likely due to the fact that we can measure power with greater sensitivity.

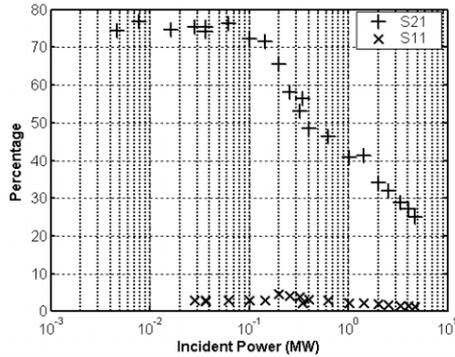


Figure 3: The measured values of the S parameters (in percentage) as a function of incident power made during the high-power test of the DLA Structure.

### Secondary Electron Emission

Our preliminary investigation into this phenomenon leads us to believe that missing power and the light emission were caused by secondary electron emission (*SEE*) from the dielectric — similar to what others have observed on dielectric RF windows. To test this hypothesis during the high power test, we placed a horseshoe-shaped, permanent magnet (PM) of about 100 Gauss near the structure, since magnetic fields are often used to suppress *SEE*. The PM caused a slight decrease in the light intensity and a change in the transmitted power signal. At the minimum, this means that low energy electrons (< few keV) are involved in the missing power process, which is most likely due to *SEE*.

### FUTURE WORK

We are currently developing a model of the secondary emission process in a cylindrical DLA structure that will be the subject of a future publication. Our preliminary investigation indicates that the *SEE* is causing single-surface multipactoring, since a resonant process does not appear to be involved, and the light emission is seen to be originating from the surface. In this case, a secondary electron migrates to the surface with initial kinetic energy of only a few eV, is accelerated by the RF fields, and then re-impacts the surface with enough kinetic energy to make more secondaries. We think that the *SEE* electrons

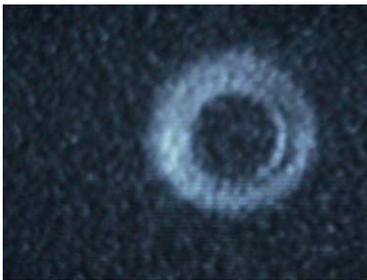


Figure 4: Image of light observed during the high power test. The dark region in the center of the ring is the vacuum hole inside the dielectric tube.

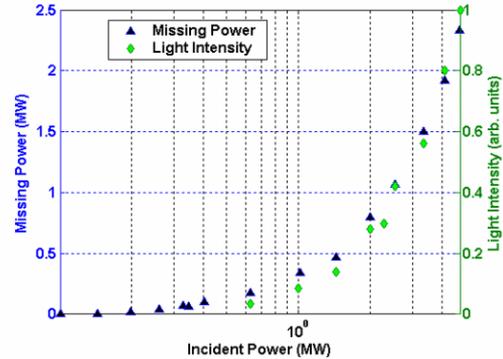


Figure 5: The missing power and light intensity as functions of the incident power.

continue to multiply in this manner until the electron cloud produces a large enough DC electric field to suppress additional secondaries. The electron cloud, thus produced, is what actually drains the energy from the RF field.

We are taking a two-pronged approach to suppress the secondary electron emission: (1) we are developing the expertise to coat the inside of the dielectrics with *TiN*, well known for its ability to suppress secondary emission by lowering  $\delta$ ; and (2) we will use other dielectric materials with lower  $\delta$  — since alumina can be as high as 9. We suspect that if the secondary emission coefficient,  $\delta$ , of the dielectric were reduced below 2, the single-surface multipactor could be suppressed.

### CONCLUSION

A high power test has demonstrated for the first time that a DLA structure is capable of withstanding 5 MW of incident power with no signs of dielectric breakdown. In addition, a new DLA structure design has solved the problem of arcing inside the coupler. The new design achieved  $S_{21} = -1.2$  dB when the incident power was below 100 kW, but power transmission decreased rapidly above that level. It is believed that *SEE* is responsible for this missing power. Future experiments will address this issue.

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