

HIGH-GRADIENT TESTING OF METALLIC PHOTONIC BAND-GAP (PBG) AND DISC-LOADED WAVEGUIDE (DLWG) STRUCTURES AT 17 GHz*

B. J. Munroe[†], J. X. Zhang, M. A. Shapiro, R. J. Temkin, MIT PSFC, Cambridge, MA 02139, USA

Abstract

Photonic Band-gap (PBG) structures continue to be a promising area of research for future accelerator structures. Previous experiments at 11 GHz have demonstrated that PBG structures can operate at high gradient and low breakdown probability, provided that pulsed heating is controlled. A metallic single-cell standing-wave PBG structure has been tested at 17 GHz at MIT to investigate how breakdown probability scales with frequency in these structures. A single-cell standing-wave disc-loaded waveguide (DLWG) was also tested at MIT as a reference structure. The PBG structure achieved greater than 90 MV/m gradient at 100 ns pulse length and a breakdown probability of 1.1×10^{-1} /pulse/m. The DLWG structure achieved 90 MV/m gradient at 100 ns pulse length and a breakdown probability of 1.2×10^{-1} /pulse/m, the same as the PBG structure within experimental error. These tests were conducted at the MIT structure test stand, and represent the first long-pulse breakdown testing of accelerator structures above X-Band.

INTRODUCTION

Photonic band-gap (PBG) structures, which use a lattice of metallic or dielectric rods to confine an accelerator mode while damping higher-order modes (HOMs), are a topic of ongoing experimental and theoretical work [1–5]. Previous experimental work has demonstrated successful acceleration using a traveling-wave PBG structure [1] as well as suppression of wakefields [4, 6]. More recent work by MIT and SLAC National Accelerator Lab has shown that metallic PBG structures can operate at high gradient and low breakdown probability, achieving gradients of greater than 100 MV/m with a breakdown probability of less than 10^{-3} per pulse per meter of structure [5].

In order to compare breakdown performance as a function of frequency, two standing wave high-gradient structures have been designed and fabricated for breakdown testing at 17 GHz at MIT. A round-rod PBG structure (MIT-PBG), for direct comparison to the PBG-R structure tested at 11 GHz, and a disc-loaded waveguide structure (MIT-DLWG), to serve as a reference for structure performance at 17 GHz, have been tested. The PBG and DLWG designs are electrically very similar to the structures tested at SLAC, although the mechanical designs of both structures are modified to use a clamped, as opposed to brazed, assembly. Each structure consists of one coupling cell on each side of central



Figure 1: Expanded three quarter section view of the solid model of the 17 GHz PBG structure, showing two coupling cells and central PBG cell. Power is coupled in from the left.

high-gradient cell; power is provided axially in the TM_{01} -mode through a mode launcher provided by SLAC National Accelerator Lab. A model of the PBG structure tested at MIT is shown in Fig. 1; the DLWG structure differs only in the center cell pieces. The details of the structure design can be found in [7].

EXPERIMENTAL SETUP

The standing-wave structure test stand at MIT is powered by a 25 MW traveling-wave relativistic klystron designed by Haimson Research Corporation (HRC) and coupled to the test stand through a 4.4 dB hybrid, also from HRC. The test stand is instrumented with incident and reflected power detection via a directional coupler, current monitors both upstream and downstream to detect dark current and breakdown electrons, and an optical diagnostic to look for light emission during breakdowns. In addition to these dedicated diagnostics the pressure in the chamber, which is vacuum-isolated from the rest of the rf system, can be monitored using the chamber ion pump.

The incident and reflected rf power signals are detected using Hewlett Packard HP 8473B low-barrier Schottky diodes coupled into at LeCroy LT264M oscilloscope. The diode traces are recorded by the associated computer system and used to calculate the gradient and peak surface temperature rise in the structure, which are calibrated using HFSS simulations and vector network analyzer measurements. The upstream and downstream current monitors are both composed of copper plates isolated from the body of the mode launcher and structure, respectively. The current monitor signals are used both to monitor the dark current during normal operation and to detect breakdown events. Breakdowns to be detected as a binary signal; if the current monitor signal goes off-scale, then a breakdown is determined to have occurred.

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[†] brian.j.munroe@gmail.com, now at Schlumberger-Doll Research Center, Cambridge, MA 02139, USA

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Because of the open nature of the clamped 17 GHz PBG structure, optical diagnostics are also available at the MIT test stand. During the PBG structure testing a video camera was used to visually observe the locations of breakdown during testing. Bright flashes can be seen during breakdown events, and the location of the brightest part of the flash is assumed to correspond to the initiation site of the breakdown. Observation of these flashes was used to provide confirmation of the observation of breakdown using the current monitor signals, although the agreement was only qualitative.

Both structures were tested at a flat-top pulse length, i.e. the length of time during which the gradient in the structure is within 90% of the peak value, of 100 ns. This limits the temperature rise in the PBG structure to safe levels while still reaching the target gradient for both structures of at least 90 MV/m.

DLWG STRUCTURE TESTING

Testing of the MIT-DLWG structure proceeded in multiple phases. Phase 1 of testing began with the initial conditioning of the structure at a flat-top pulse length of 70 ns. This pulse length was increased to the desired 100 ns flat top after the initial day of conditioning, and the power level in the structure was increased as-tolerated by the limitation on number of breakdowns per hour. The structure reached a gradient of approximately 65 MV/m at a pulse length of 100 ns before breakdowns at the joint between the structure and the mode launcher were detected. This is a known problem with the type of rf flange used to make the joint, however the joint is easily repaired and testing was resumed with minimal delay.

After the poor joint between the structure and launcher was corrected, the structure was quickly reconditioned to 65 MV/m at the beginning of Phase 2 of testing, and no problems with the joint were observed. The structure was then processed at large breakdown probabilities up to a maximum gradient of 87 MV/m at a pulse length of 100 ns. Processing was observed, as both the dark current from the structure measured by the downstream current monitor and the breakdown probability at constant power levels decreased. When gradient was increased above 90 MV/m, periods of stable operation were observed before reaching a threshold-like behavior. This does not appear to be a true threshold, as continued operation at a pulse length of 100 ns at a gradient of 90 MV/m increased the duration of these stable periods of operation at greater than 90 MV/m. The structure may be capable of reaching higher gradients with continued processing. In total Phase 1 comprised approximately 140,000 pulses. The rapid return to previous operating levels at the start of Phase 2 occurred from 140,000 to 150,000 pulses into testing. Phase 2 continued for a total of 210,000 pulses, making the total number of pulses seen by the DLWG structure approximately 350,000.

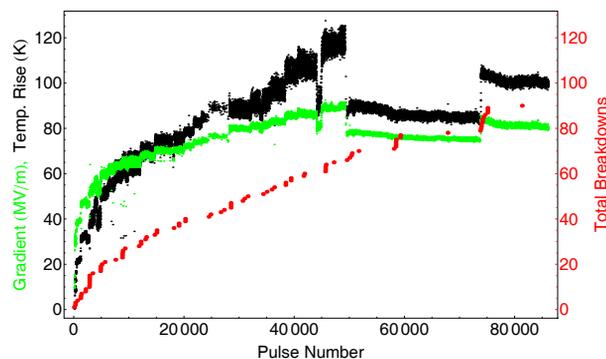


Figure 2: Summarized results showing the gradient (green), temperature rise (black), and total number of breakdowns (red) for the MIT-PBG testing. Note the extremely low breakdown rate even during initial processing.

PBG STRUCTURE TESTING

Testing of the MIT-PBG structure proceeded in a single phase, with no problems at the joint between the structure and mode launcher observed. Processing of the structure proceeded extremely quickly, with the structure ultimately reaching the maximum allowed gradient of 90 MV/m in fewer than 50,000 pulses. This gradient limit is established to prevent temperature rises in the structure of more than 120 Kelvin, which could damage the structure in very few pulses. This is in contrast to the MIT-DLWG structure which took over 300,000 pulses to reach a gradient of 90 MV/m. One possible explanation for the rapid processing of the MIT-PBG-2 structure is the re-use of the coupling cells from the MIT-DLWG structure. These cells were already processed up to a gradient of 90 MV/m during the MIT-DLWG testing, and some minor surface changes were observed as a result of that conditioning. Very few total breakdowns were observed during this processing, and almost all of those breakdowns occurred in groups of fewer than five events. The gradient, temperature rise, and total number of breakdowns during testing can be seen in Fig. 2. It is expected that, if the temperature limit was relaxed, the structure would achieve higher gradients at the same pulse length without any limiting behavior due to breakdowns.

The MIT-PBG structure reached a maximum gradient of 89 MV/m at pulse length of 100 ns and a breakdown probability of 1.1×10^{-1} per pulse per meter of structure. This breakdown probability was consistent throughout the duration of processing the structure from approximately 65 MV/m to the maximum gradient of 89 MV/m. This processing can be seen in Fig. 3 as the series of data points at constant breakdown probability of 1.1×10^{-1} per pulse per meter of structure. The initial processing to 65 MV/m happened very quickly and is not shown on Fig. 3.

Once the maximum gradient was confirmed, the power was reduced to begin collecting statistics to determine the breakdown probability at gradients below the maximum processed value. The minimum breakdown probability was

3.2×10^{-2} per pulse per meter of structure at a gradient of 76 MV/m and a pulse length of 100 ns. This is nearly identical to the breakdown probability of 3.3×10^{-2} per pulse per meter of structure at a gradient of 81 MV/m and a pulse length of 100 ns obtained later in testing. This suggests that the structure has not reached a final steady-state breakdown probability, and more testing is required to determine the final performance of the structure.

COMPARISON WITH SLAC DATA

The MIT-PBG and MIT-DLWG structures can be compared to two PBG structures, SLAC-PBG-R and SLAC-PBG-E, and one DLWG structure, SLAC-DLWG, previously tested at SLAC. For all of these structures the aperture for the high-gradient irises relative to wavelength, a/λ , and the thickness of the irises relative to the wavelength, t/λ , were kept constant. The MIT-PBG structure is a scaled version of the SLAC-PBG-R structure; both use round rods for the PBG lattice. The SLAC-PBG-E structure uses elliptical rods, as discussed in [5]. Following the discussion in [5], the SLAC-PBG-R structure was damaged early in testing and underperformed relative to the SLAC-PBG-E and SLAC-DLWG structures. Breakdown probability as function of gradient for both the MIT and SLAC structures is shown in Fig. 3. For the MIT-DLWG structure only data taken after the structure returned to high-gradient operation during Phase 2 is shown. Because of the limited amount of data available for the MIT-PBG-2 structure, all data for that structure is shown. The SLAC data is only shown for a flat-top pulse length of 150 ns, as this is the shortest pulse length tested at SLAC.

Current results show that the MIT-PBG structure performed comparably to the SLAC PBG-R structure, and that continued testing of the MIT-PBG structure may improve upon this performance. Both the MIT-DLWG and MIT-PBG structures saw fewer than 10^6 pulses, which is an order of magnitude fewer pulses than is typical in SLAC structure testing. This suggests that both structures did not reach their maximum achievable gradient, and improved performance may be observed with continued testing.

RESULTS

To expand on the PBG structure breakdown testing conducted at X-band, two standing wave structures, a disc-loaded waveguide structure (DLWG) and a round-rod photonic band-gap structure (PBG), were tested at Ku-band at MIT. The DLWG structure achieved 90 MV/m gradient at 100 ns pulse length and a breakdown probability of 1.2×10^{-1} /pulse/m. The PBG structure achieved greater than 90 MV/m gradient at 100 ns pulse length and a breakdown probability of 1.1×10^{-1} /pulse/m. At this gradient and pulse length the surface temperature rise in the MIT-PBG structure was 120 K, which is the maximum temperature rise allowed in the structure according to the testing methodology. Continued

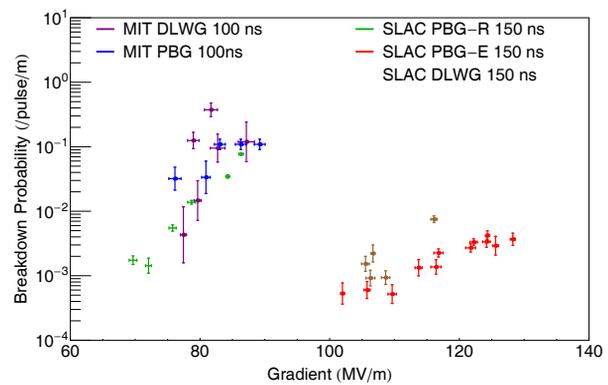


Figure 3: Breakdown probability as a function of gradient for MIT-PBG, MIT-DLWG, SLAC PBG-R, SLAC PBG-E, and SLAC DLWG structures. For the MIT-DLWG structure only data after the return to high-gradient operation in Phase 2 is shown.

operation of the MIT-PBG structure at lower gradients and the same pulse length of 100 ns showed both a decrease in breakdown probability with gradient as expected, and continued processing of the structure.

Comparison with SLAC data shows that the MIT-PBG and MIT-DLWG structures performed comparably with the SLAC-PBG-R structure. While performance of the MIT structures lagged behind the SLAC-PBG-E and SLAC-DLWG structures, this may be the result of insufficient processing time for the MIT structures. The performance of the MIT-PBG structure is also comparable to the performance of the MIT-DLWG structure, suggesting that PBG structures are viable candidates for future accelerator applications requiring high-gradient, low breakdown probability operation with wakefield damping. These results represent the only currently available long-pulse breakdown testing at frequencies above X-band.

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