# EXPERIMENTAL HIGH-GRADIENT TESTING OF AN ELLIPTICAL-ROD PHOTONIC BAND-GAP (PBG) STRUCTURE AT X-BAND *

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*Abstract*

An 11.4 GHz photonic band-gap (PBG) structure where the rods in the inner row have an elliptical cross-section has been designed at MIT and manufactured and tested at high power and high repetition rate at SLAC. This structure exhibits lower surface magnetic fields on the rods relative to previous PBG structures tested at SLAC, which reduces the ohmic heating of the rod surface in an effort to reduce pulsed heating damage. The structure demonstrated greater than 100 MV/m gradient at a breakdown probability of less than $10^{-3}$ per pulse per meter for 150 ns pulses at 60 Hz repetition rate, performance comparable to an undamped disc-loaded waveguide (DLWG) structures previously tested at SLAC. This level of performance demonstrates that elliptical-rod PBG structures, which exhibit intrinsic wakefield damping, could be candidates for future accelerator applications.

## 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, 2, 3, 4]. Previous experimental work has demonstrated successful acceleration using a traveling-wave PBG structure [1] as well as suppression of wakefields [4, 5]. More recent work by MIT and SLAC National Accelerator Lab has investigated the breakdown properties of standing-wave PBG structure under high gradient and high repetition rate operation [3].

An improved PBG design was made based on results of this initial high gradient, high repetition rate testing of a PBG structure [6]. This design changes the shape of the rods immediately surrounding the defect region to reduce the peak surface magnetic field in the structure; this reduces pulsed heating and cyclic fatigue in the structure. This improved lattice has been incorporated into a single-cell standing wave structure for high-power testing at SLAC, a model of which is depicted in Fig. 1. This structure follows the general design used extensively in previous SLAC single-cell standing wave structure testing [7, 8, 9], with a matching cell on either side of a single PBG test cell. The structure is designed to have the highest electric and magnetic fields in the test cell and significantly reduced fields in the matching cells. The structure is axially powered via a reusable $TM_{01}$ mode launcher [10], which remains with the structure for the duration of all cold and hot tests; this mode launcher design has been thoroughly tested with disc-loaded waveguide (DLWG) structures. The details of the structure design are presented in [6] and [11]. Note that special care was taken to avoid gaps between the rods and the end plates during brazing.

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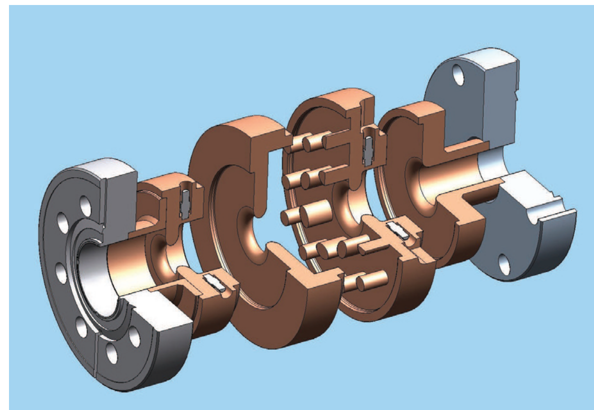

Figure 1: Expanded three-quarter view of solid model of elliptical-rod PBG structure, showing two coupling cells and central PBG cell. Power is coupled in from the left.

### *Structures for Comparison*

The results of the testing of the elliptical-rod PBG structure (PBG-E) will be compared to two other structures, a round-rod PBG structure (PBG-R) tested at high power at SLAC and reported in [3], and an undamped disc-loaded waveguide structure (DLWG) fabricated at INFN-Frascati, also tested at high power at SLAC and reported in [9]. All three structures have the same iris geometry.

## EXPERIMENTAL SETUP AND PROCEDURE

The elliptical-rod PBG structure (PBG-E) was tested at SLAC using klystron XL4-6B operating at 60 Hz (see [11] for a schematic of the test stand). This klystron is computer controlled to maintain both resonance and the desired power level during operation, and the test stand is monitored by peak power meters and crystal detectors, as well as current monitors on either end of the structure. The peak power meters provide fully calibrated measurements of the




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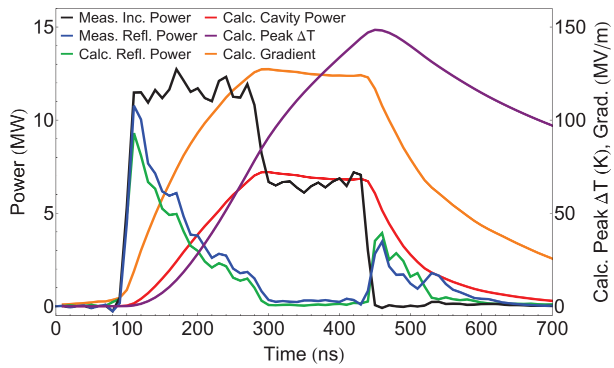


Figure 2: Sample traces from the peak power meter for a 150 ns pulse at a gradient of 126 MV/m. The incident and reflected power measured by the peak power meter are shown in black and blue respectively. The calculated reflected power and power coupled into the structure are shown in green and red respectively. The calculated gradient is shown in orange, and the calculated peak surface temperature rise is shown in purple.

klystron output power, power incident on the structure, and power reflected by the structure; these traces are recorded every 2 seconds. Additional detectors record uncalibrated power and current monitor signals for every breakdown, as indicated by a spike in the current monitor signal, as well as the shot directly preceding the breakdown event.

The structure is tested using variable-length shaped rf pulses, with a higher-power portion filling the structure rapidly, after which the power decreases to maintain a constant power coupled into the structure for the duration of the pulse, as seen in Fig. 2; the quoted pulse power and pulse length reflect this constant-power portion of the pulse. Testing of the PBG-E structure was intentionally limited to a steady-state breakdown rate of approximately 10 per hour, and a maximum calculated peak surface temperature rise of 150 K. Within these limits the structure was tested at pulse lengths (after a 180 ns fill time) of 150 ns, 200 ns, 400 ns, and 600 ns. The 150 ns pulse length was done both at the very beginning of testing (Run 1) and the end of testing (Run 2). The structure was limited by the breakdown rate limit to a maximum gradient of approximately 130 MV/m at 150 ns, and approximately 100 MV/m at 600 ns.

## DATA ANALYSIS

Data is collected in the form of peak power meter traces and breakdown events, both of which have time stamps. These time stamps can be used to correlate breakdown events with the power incident on the structure as measured by the peak power meter. This incident power can in turn be converted into various structure quantities such as cavity power, gradient, and peak surface temperature rise, using MATHEMATICA [12] and calibrated HFSS [13] models; this is shown by the red, orange, and purple traces in Fig. 2.

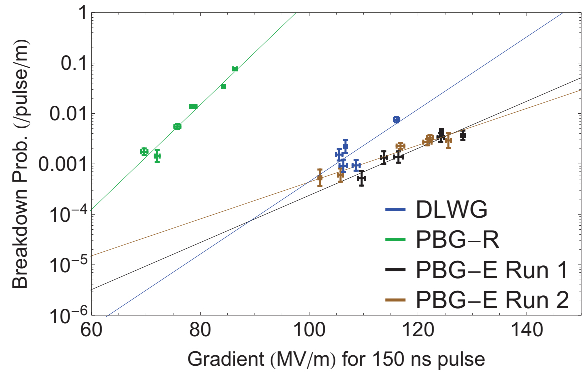


Figure 3: Breakdown probability per pulse per meter of structure vs. gradient at 150ns pulse length for the PBG-R, PBG-E, and an undamped conventional disc-loaded waveguide structure with the same iris geometry (DLWG). The two data sets for the PBG-E represent the beginning and end of testing.

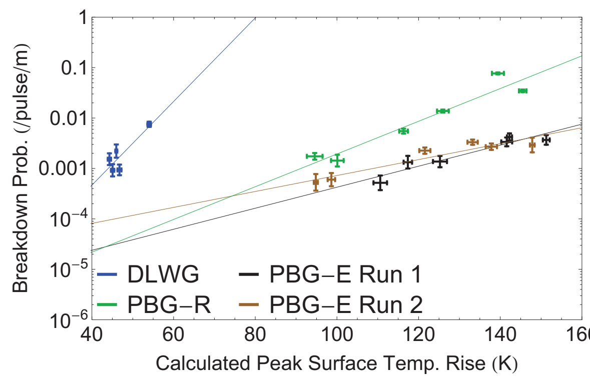


Figure 4: Breakdown probability per pulse per meter of structure vs. calculated peak pulsed heating for the PBG-R, PBG-E, and a conventional disc-loaded waveguide structure with the same iris geometry (DLWG) at a pulse length of 150ns.

Breakdown probability must be calculated from portions of the data during which the number of breakdowns counted increases approximately linearly and the incident power is approximately constant. This is done by a manual inspection of the data to isolate time intervals during which both of these conditions are met. The peak power meter data is then used to find average values of the gradient, temperature rise, etc. during the same time interval. This results in plots like Fig. 3, showing the breakdown probability per pulse per meter of structure versus gradient for the PBG-E structure, the round-rod PBG-R structure, and an undamped conventional disc-loaded waveguide structure, DLWG, at 150 ns pulse length and Fig. 4, showing the breakdown probability versus peak temperature rise for the same structures at 150 ns pulse length.

From these plots it can be seen that the PBG-E structure,

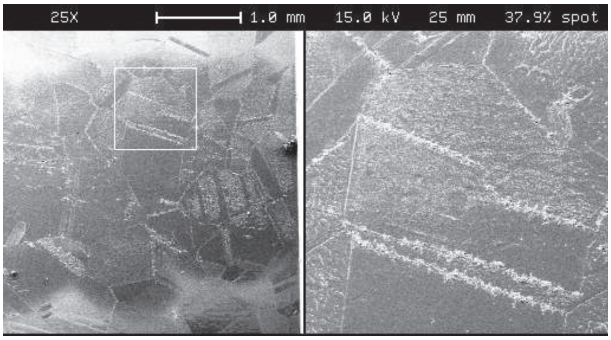


Figure 5: Detail micrograph of the high-field side of the inner rod of the PBG-E, showing grain boundaries even at the highest-field region.

which features intrinsic damping of all HOMs, exhibits both high gradient and low breakdown probability simultaneously, with performance comparable to the undamped disc-loaded waveguide structure. The PBG-E structure was operated to a gradient of 128 MV/m with a breakdown probability of $3.6 * 10^{-3}$ per pulse per meter and a minimum breakdown probability of $5.2 * 10^{-4}$ per pulse per meter at a gradient of 109 MV/m. This level of performance demonstrates that PBG structures are viable options for future accelerator applications.

## AUTOPSY

After high-power testing the structure was cold-tested, indicating a decrease in Q of the operational mode from 7792 to 7393, a decrease of 5% from the original value. After this cold test the structure was cut in half such that no inner rod was bisected and imaged using a scanning electron microscope (SEM). The SEM was used to investigate possible surface damage to the high-field irises and the inner rods. This imaging showed some damage to iris surfaces, consistent with that seen before in similar tests of disc-loaded waveguide-type structures at SLAC, as well as surface damage to the high rf magnetic field side of the inner rods. This damage is shown in detail in Fig. 5, showing a qualitative difference in the damage experienced by the PBG-E structure; even at the highest rf magnetic field regions (middle of the image) grain boundaries are still visible and the surface looks relatively smooth within the grains. This is in contrast to the PBG-R structure where the grain boundaries were overwhelmed at the highest-field regions.

## DISCUSSION

The high-gradient testing of the elliptical-rod PBG structure indicated that PBG-type structures are viable for high-gradient acceleration. Comparison of the breakdown probability for the PBG-E design and a conventional undamped disc-loaded waveguide structure indicates that the PBG structure can achieve the same gradients as the conventional structure at comparable or even lower breakdown probability, greater than 100 MV/m at a breakdown probability of less than $10^{-3}$ per pulse per meter for 150 ns pulses. This represents a significant advance in high-gradient structure testing, as the PBG design incorporates intrinsic wakefield damping, which is lacking in the disc-loaded waveguide structures.

This test did not seek to investigate the lifetime of the structure. Clearly the surfaces showed some damage after high-power testing, and the decrease in Q is indicative of this change in the surface. Examination of data taken at the beginning and end of the testing, however, indicates that the high-power performance of the structure did not change significantly during testing. The structure was still able to operate at comparable gradients and breakdown probabilities early and late in the testing. At a pulse length of 150 ns, the temperature rise for a gradient of 100 MV/m is approximately 94K. For the PBG-E structure operation at 100 MV/m corresponds to a breakdown probability of approximately $5 * 10^{-4}$ per pulse per meter, and an accumulation of approximately 10 breakdowns per run day. This is the lowest breakdown probability which was practical for this experiment, which explains the lack of data at lower peak pulsed heating values.

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