X-BAND PHOTONIC BANDGAP (PBG) STRUCTURE BREAKDOWN EXPERIMENT*

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Abstract

In order to understand the performance of photonic bandgap (PBG) structures under realistic high gradient operation, an X-band (11.424 GHz) PBG structure was designed for high power testing in a standing wave breakdown experiment at SLAC. The PBG structure was hot tested to gather breakdown statistics, and achieved an accelerating gradient of 65 MV/m at a breakdown rate of two breakdowns per hour at 60 Hz, and accelerating gradients above 110 MV/m at higher breakdown rates, for a total pulse length of 320 ns (150 ns charging, and 170 ns flat). High pulsed heating occurred in the PBG structure, with many shots above 270 K, and an average of 170 K for 35×10^6 shots. Damage was observed in both borescope and scanning electron microscope imaging. No breakdown damage was observed on the iris surface, the location of peak electric field, but pulsed heating damage was observed on the inner rods, the location of magnetic fields as high as 1 MA/m. Breakdown in accelerator structures is generally understood in terms of electric field effects. PBG structure results highlight the unexpected role of magnetic fields on breakdown. We think that relatively low electric field in combination with high magnetic field on the rod surface may trigger breakdowns.

INTRODUCTION

PBG structures are a novel accelerator concept incorporating simultaneous damping of all higher order modes (HOMs). A metallic PBG accelerator has been demonstrated [1]. HOMs in PBGs have been simulated, and PBG wakefields have also been measured [2]. The operation of PBG structures under high power and high rep rate, especially with respect to breakdown performance has not been studied. To obtain first results on both electric and magnetic field effects in PBG structures at realistic operating conditions, a single cell standing wave structure has been designed and tested at SLAC, along the lines of [3].

The same test stand is used for the PBG test as has been used for previous single cell structures. TM_{01} mode launchers convert from WR-90 rectangular waveguide to 0.9 inch diameter circular waveguide. The circular waveguide connects to the PBG structure, which consists of two pillbox matching cells, and a central PBG test cell. The PBG structure is shown in Fig. 1, with labels indicating the input and end matching cells, and the PBG test cell.

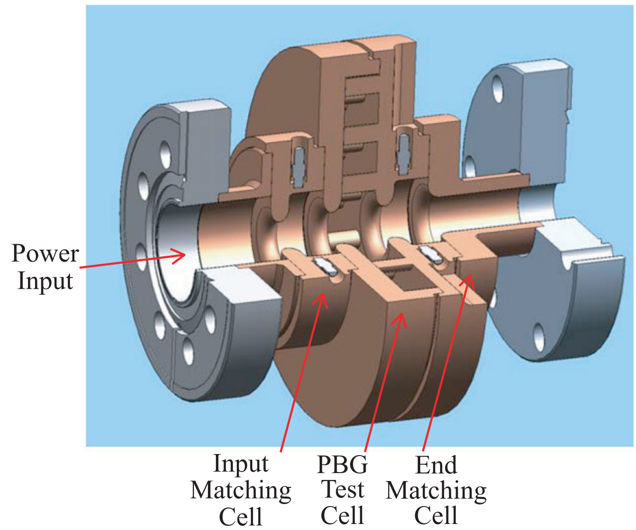

Figure 1: Single cell standing wave PBG structure.

EXPERIMENT

The PBG breakdown structure was designed using *HFSS*, and the baseline SLAC design for 1C-SW-A5.65-T4.6-Cu [4]. The iris geometry of the PBG structure, 1C-SW-A5.65-T4.6-Cu-PBG was made identical to that of 1C-SW-A5.65-T4.6-Cu, so that the PBG cell impact on structure performance could be isolated. The PBG design required: an operating mode with half field in each matching cell and full field in the PBG cell, a mode frequency of 11.424 GHz, and near critical coupling into the entire structure. The PBG cell was machined from a single block of OFHC copper including one of the cell iris plates, the other iris was included in the facing cell piece, into which the PBG lattice rods were brazed. Cold test of the structure showed a mode frequency of 11.436 GHz, slight undercoupling, and very good agreement with design field pattern.

The PBG breakdown structure was installed at SLAC on klystron test station #4, which operates the X-band klystron XL4–6B and related microwave diagnostics. The tube is driven and controlled by computer, allowing pulse shaping and frequency tuning on a shot to shot basis. Filling of the standing wave structures is accomplished in a shaped manner; a high power level initially fills the structure, and then the power is lowered to maintain a constant level over the nominal power pulse length. Two HP8990A peak power

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meters measure the fully calibrated klystron power, and the power being fed into the breakdown structure under test: the forward and reverse power. The forward and reverse structure power can be used to calculate the fields in the structure. Precise calibration was accomplished using *HFSS* simulations. Breakdown events were recorded by observing the reflected power from the structure, and the Faraday cup dark current measurements, which spiked during breakdown shots. The total number of breakdowns in a given time span provides a breakdown rate, quoted as number per hour at 60 Hz [3].

For the PBG structure, breakdown rates were observed for 150, 170, 300, 360, and 600 nanosecond pulse lengths (not including the charging portion of the pulse). Comparison of PBG and pillbox breakdown rates are shown as a function of peak surface electric field in Fig. 2 for 170 nanosecond pulse length. The electric field achievable in the PBG structure is less than that reached in the pillbox structure. This can be alternatively phrased that for a given gradient or peak surface electric field, the breakdown rate in the PBG structure was higher than that in the pillbox structure.

Breakdown phenomena are generally understood in terms of maximum surface electric field. This is not what is seen in Fig. 2. The performance of the two structures is not identical when compared in terms of peak surface electric field. The PBG structure has a surface field of 208 MV/m for a 100 MV/m accelerating gradient, compared to 211 MV/m peak surface field for the pillbox structure. These nearly identical values would predict that only minor fabrication differences would significantly impact the breakdown performance of the structures. This is not what is seen in Fig. 2.

Comparison of PBG and pillbox breakdown rates are shown as functions of peak surface magnetic field in Fig. 3 for 170 nanosecond pulse length. The peak magnetic field is much higher in the PBG structure. This large variation in magnetic field performance is of great interest because all single cell standing wave breakdown tests prior have been done with structures of nearly identical magnetic field performance.

AUTOPSY

After high power testing, the PBG structure was cold tested, and a decrease in the unloaded Q of the operating mode was observed from 4700 to 4200. The PBG structure was cut in half, so that no inner rod was intercepted. SEM micrographs were taken, and examples are shown in Fig. 4 and Fig. 5 of the PBG structure iris and an inner rod, respectively. The iris is undamaged, and pulsed heating damage is observed on the inner surface of the inner row of rods. A detailed micrograph is shown in Fig. 6, showing visible grain boundaries, with increased surface roughness at the grain boundaries, and the location of peak magnetic field, near the center of the rod. The PBG structure experienced very high pulsed heating temperature rises, with peak excursions to > 270 K, and an average of 170 K for 35×10^6 shots.

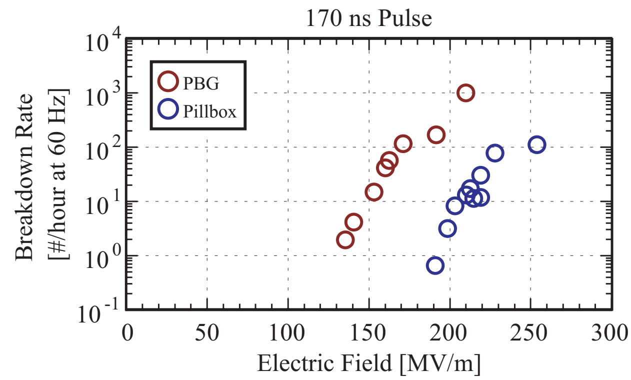

Figure 2: PBG and pillbox breakdown rate vs. maximum surface electric field.

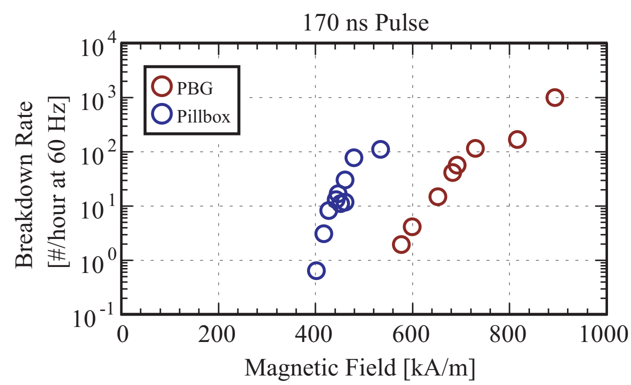

Figure 3: PBG and pillbox breakdown rate vs. maximum surface magnetic field.

DISCUSSION

Pulsed heating damage on the inner rods is observed over the peak magnetic field region, as shown in Fig. 7. For 100 MV/m gradient, or 5.9 MW input power, a peak magnetic field of 890 kA/m is present over the red re-

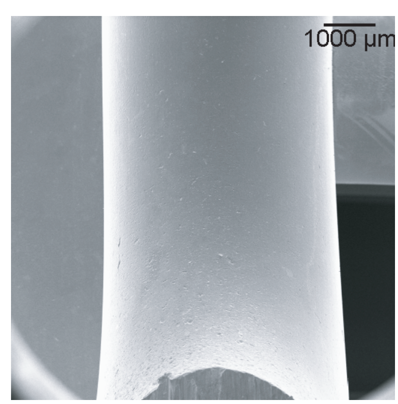

Figure 4: SEM micrograph of PBG iris.

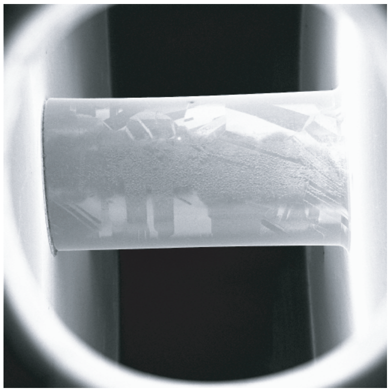

Figure 5: SEM micrograph of inner rod.

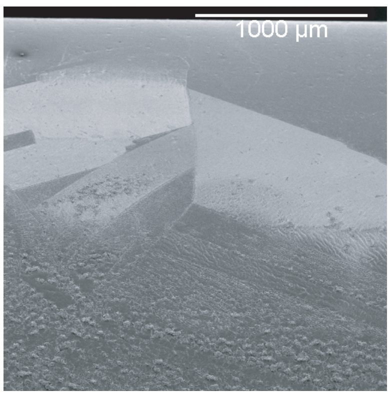

Figure 6: SEM micrograph showing detail of inner rod pulsed heating damage.

gion in Fig. 7. This high magnetic field results in pulsed heating temperature rises, in accordance with Eq. 1 [5], which increase the rod surface roughness. The extensive damage seen on the surface in Fig. 5 and Fig. 6, enhance the 14 MV/m electric field on the rod, which is shown in Fig. 8 for 100 MV/m accelerating gradient, or 5.9 MW input power.

$$\Delta T = 430 \sqrt{t_P\,[\mu s]}\;|H_{peak}\,[MA/m]\,|^2 K \qquad (1)$$

The PBG structure breakdown testing represents very exciting first results on high gradient damped structures. Very high magnetic fields are present in the PBG structure, and the effect of these fields on breakdown is not fully understood. It is possible that the pulsed heating temperature rise damage on the inner surface of the rods is sufficient to cause conventional electric field induced breakdown on the rods, because of the enhanced surface fields in the vicinity of damaged spots. If this is the case, asymmetry would be expected on the rod surface damage, in accordance with Fig. 8. It is possible that such damage is present, but obscured by overlying pulsed heating damage.

Future single cell breakdown testing of another PBG structure is planned. Advanced PBG structures incorporating reduced symmetry [6], or elliptical rods [7] may be attempted.

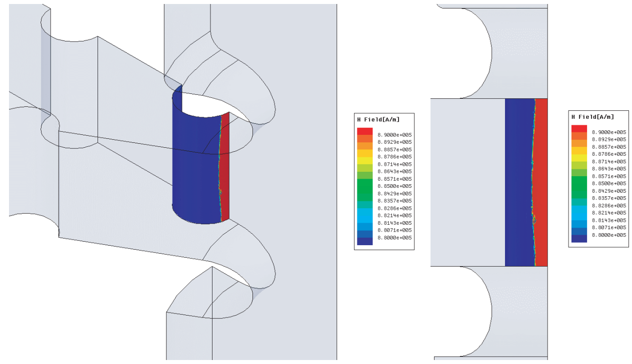

Figure 7: 890 kA/m magnetic field on inner rod for 5.9 MW, or 100 MV/m gradient.

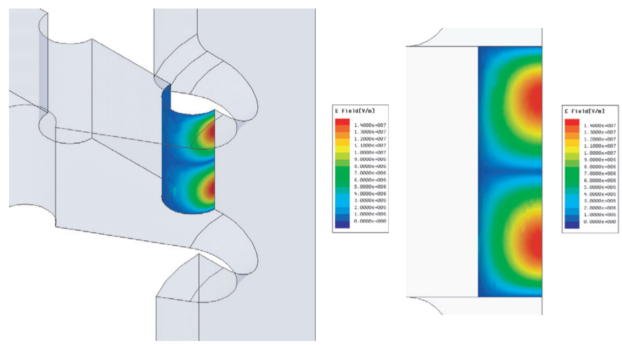

Figure 8: 14 MV/m electric field on inner rod for 5.9 MW, or 100 MV/m gradient.

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