Final Progress Report

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This research program started in 1991 but the final report covers the most recent renewal period, as specified in DOE guidelines. The period covered is: Dec. 1, 2009 through April 30, 2013

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4. Final Progress Report (2010-2013)

4.1 X-Band Breakdown Experiment Using Improved Photonic Bandgap (PBG) Accelerator Structure with Elliptical Rods

The results of testing of the first X-band PBG accelerator structure at SLAC were published in “X-Band Photonic Bandgap Accelerator Structure Breakdown Experiment”, R. A. Marsh, M. A. Shapiro, R. J. Temkin, V. A. Dolgashev, L. L. Laurent, J. R. Lewandowski, A. D. Yeremian, and S. G. Tantawi, PRSTAB, Vol. 14, Article Number: 021301 (2011). That structure had round rods. The tests revealed that the breakdown rate is determined by the high pulsed heating of the cylindrical rods of the PBG structure. A new PBG structure was designed, this time using an elliptical profile for the inner row of rods (Fig. 1) in order to reduce the pulsed heating. Table 1 compares the expected performance of the elliptical-rod structure with the original round-rod structure.

The initial testing of the PBG structure was conducted with strict limits on the pulsed heating that was tolerable, with the intention of collecting breakdown rate data at a safe pulsed heating level. During this phase of the testing the gradient was limited to below 100 MV/m, and very few breakdowns were observed. After some initial processing at a variety of power levels and pulse lengths, shown in Fig. 2, 12 hours of data was taken at a power level of 1.9 MW and a pulse length of 200 ns. During the 12 hour period of constant power operation there was one unique breakdown event, followed by 14 consecutive breakdown shots. This gives a preliminary estimated breakdown probability of 3×10^{-5} /pulse/m at 69 MV/m gradient. The data presented in Fig. 3 show the performance of the elliptical-rod PBG (PBG2) structure in comparison with two other structures, the original round-rod PBG (Marsh) and a disk-loaded waveguide structure (Frascati #2). All three structures have the same iris geometry, with an iris thickness of 4.6 mm and an aperture of 5.65 mm. The two data sets for the PBG2 structure represent the initial high-gradient operation at a flat-top pulse length of 150 ns, and then a return to a flat-top pulse length of 150 ns after several million pulses at other pulse lengths. In both cases the data were taken by going to the maximum power that kept the steady-state breakdown rate below 10 per hour. These correspond to the farthest-right points on each PBG2 line. After these points were taken the power was decreased in approximately 10% increments to collect the other data displayed. It should be noted that the lines on the plot are merely there to provide a guide for the eye to see the trend in the data and do not represent a theory as to why the data follow that trend.

Figure 1: Elliptical-rod PBG structure under test at SLAC.

Table 1: Comparison of Round- and Elliptical-rod PBG Structure at 100 MV/m

Quantity	Round	Elliptical
Power	5.9 MW	4.4 MW
Peak Surface Electric Field	208 MV/m	207 MV/m
Peak Surface Magnetic Field	890 kA/m	713 kA/m
Pulsed Heating, 150 ns pulse	131 K	84 K

These data show for the first time that it is possible to make an accelerator structure that has intrinsic damping which performs as well as, or better than, a conventional un-damped structure. Even after a full run of testing the elliptical-rod PBG structure still displays a lower breakdown rate than the un-damped, pill-box structure by more than an order of magnitude. These results were published in “High power breakdown testing of a photonic band-gap (PBG) accelerator structure with elliptical rods,” B. J. Munroe, A. M. Cook, M. A. Shapiro, R. J. Temkin, V. A. Dolgashev, L. L. Laurent, J. R. Lewandowski, A. D. Yermian, S. G. Tantawi, and Roark A. Marsh, Phys. Rev. – Special Topics Accel. Beams, Vol. 16, 012005 (2013).

Figure 2: This figure summarizes the initial testing of the elliptical-rod PBG structure at SLAC. The gradient is shown in red (left) and the pulse length is shown in black (right). The pulsed heating was limited to below 50 K temperature rise; these power limits resulted in very few breakdown events.

Figure 3: Breakdown probability of PBG2 structure (with elliptical rods, black) in comparison with PBG1 (round rods, green) and the Frascati #2 DLW structure (blue).

4.2 Calculation of Wakefields in a 17 GHz Beam-Driven Photonic Bandgap Accelerator Structure

We have carried out the theoretical analysis and computer simulation of the wakefields in a 17 GHz photonic band-gap (PBG) structure for accelerator applications. Using the commercial code CST PARTICLE STUDIO, the fundamental accelerating mode and dipole modes are excited by passing an 18 MeV electron beam through a seven-cell traveling-wave PBG structure. The characteristics of the longitudinal and transverse wakefields, wake potential spectrum, dipole mode distribution, and their quality factors are calculated and analyzed theoretically. Unlike in conventional disk-loaded waveguide (DLW) structures, three dipole modes (TM_{11} -like, TM_{12} -like, and TM_{13} -like) are excited in the PBG structure with comparable initial amplitudes. These modes are separated by less than 4 GHz in frequency and are damped quickly due to low radiative Q factors. Simulations verify that a PBG structure provides wakefield damping relative to a DLW structure. Simulations were done with both single-bunch excitation to determine the frequency spectrum of the wakefields and multibunch excitation to compare to wakefield measurements taken at MIT using a 17 GHz bunch train. These simulation results will guide the design of next-generation high-gradient accelerator PBG structures. These results were published in: “Calculation of Wakefields in a 17 GHz Beam-Driven Photonic Bandgap Accelerator Structure,” Min Hu, B. J. Munroe, M. A. Shapiro, and R. J. Temkin, Phys. Rev. – Special Topics Accel. Beams Vol. 16, 022002 (2013).

4.3 Breakdown Experiment at MIT/HRC Accelerator Facility with 17 GHz PBG structure

MIT has constructed a dedicated test facility for testing breakdown in novel accelerator structures at 17.1 GHz. The test stand at MIT will be powered by the MIT/HRC klystron operating at 17.1 GHz. The klystron output that can be coupled to the test stand is limited to 12 MW. When coupled through a 4.2 dB hybrid, the power available at the test stand is 4 MW. Because the power density increases with frequency, this amount of power is more than

sufficient to conduct breakdown experiments similar to the X-Band tests at SLAC. The MIT test stand will also utilize diagnostics not readily available in testing at SLAC in addition to diagnostics similar to those in use in the SLAC testing. This is made possible through the use of an external vacuum chamber used to contain the device under test. This allows line of sight diagnostic access to the high-field regions of the PBG structure through viewports in the vacuum chamber. A fast camera will be used to observe and locate breakdown events, and a spectrometer will be used to identify the gas species created in the breakdown process. The test stand has been assembled and is awaiting completion of the first test structures.

4.4 Overmoded Dielectric PBG Accelerator Structure Research at 17 GHz

A 17 GHz PBG accelerator structure made of a lattice of dielectric rods (Fig. 4(a)) is under construction. The sapphire rods are set between copper plates. The cavity formed by the defect in the center is an overmoded cavity, operating in a TM_{02} -like mode (Fig. 4(b)), without competition from the lower- frequency TM_{01} -like mode. Rods are removed in single-file rows extending from the defect for the purpose of damping high-order modes (HOMs). The ratio a/b of the rod radius a to the spacing b between the rods is chosen to be 0.35 to provide HOM suppression. The HOMs (Fig. 4(c,d)) have very low radiative quality factors Q_{rad} , due to the radial damping channels. The TM_{31} -like mode (Fig. 4(c)) has $Q_{rad}=600$, while the TM_{32} -like mode has $Q_{rad}=50$.

Table 2 compares the 17 GHz TM_{02} cavity with a conventional TM_{01} disk-loaded waveguide (DLW) having identical iris geometry. The effective radius of the TM_{02} cavity defect region is approximately twice the radius of the DLW cavity. The shunt impedance is affected by the amount of energy stored in the cavity for a given gradient, and the cavity Q . The DLW cavity has a higher shunt impedance than the TM_{01} cavity, due to its smaller size. The TM_{02} cavity has a higher total Q . Q_{tot} in each cavity is dominated by ohmic losses; dielectric and radiation losses, with Q s on the order of 10^5 , have a small effect on Q_{tot} in the TM_{02} cavity.

Our simulations indicate that the peak H field on the copper surface is about 500 kA/m, similar to the peak H field in the disk-loaded structure. For comparison, in a 17 GHz TM_{01} PBG structure with circular metal rods, the peak H field at the inner rods reaches 900 kA/m for a 100 MV/m gradient. The TM_{02} cavity may have an advantage in terms of lower pulsed heating of the copper surface. Testing of the TM_{02} PBG structure at high power will reveal interesting information about vacuum breakdown on copper/dielectric interfaces at high microwave frequencies.

Table 2: 17.14 GHz Standing-wave Cavity Parameters

	TM_{01} DLW	TM_{02} PBG
Iris radius (mm)	3.76	3.76
Cavity radius (mm)	7.71	16.28
Length (mm)	8.74	8.74
Rod radius (mm)	-	1.65
Rod spacing (mm)	-	4.7
Q_{tot}	7150	1.0×10^4
Shunt impedance ($M\Omega/m$)	65	30
Gradient (MV/m)	$86.2\sqrt{P_{in}[MW]}$	$58.5\sqrt{P_{in}[MW]}$

Figure 4: (a) Cross-section of TM₀₂-mode cavity, showing dielectric rod arrangement. (b) TM₀₂-like operating mode at 17 GHz (E -field amplitude). (c), (d) HOMs radiating out of lattice.

4.5 Collaborative Research with Haimson Research Corp.

Haimson Research Corp. (HRC) has built a 17 GHz high power choppertron. The choppertron is installed on the MIT accelerator lab high voltage modulator. During the past year, MIT has worked closely with Dr. Jake Haimson in the successful testing of the Choppertron.

4.6 Measurement of wakefields in a 17 GHz photonic bandgap accelerator structure

We report the experimental measurement of wakefields in a 17.14 GHz metallic photonic bandgap accelerator structure and its comparison with theory. Damping of wakefields is a critical issue in the next generation of high gradient electron accelerators, and photonic bandgap (PBG) structures have unique properties for suppressing and damping wakefields. In the experiments the wakefields were generated by passing an 18 MeV electron beam through the six cell 17.14 GHz structure. The wakefield radiation was measured at two locations: the structure output port, and at a window viewing port located at the side of the structure. The electron beam consisted of a train of bunches spaced at 17.14 GHz, so that only radiation at 17.14 GHz and its harmonics was observed. Wakefields at up to the fifth harmonic (85.7 GHz) were detected by a heterodyne receiver system. The wakefield power levels were measured at 17 and 34 GHz for average currents between 20 and 300 mA. The results were compared with full wakefield simulations using the code ANALYST. The measured power level at 17 GHz was in excellent agreement with the theoretical estimate, but the measured power at 34 GHz was significantly lower than the theoretical estimate. At both 17 and 34 GHz the measured power level increased as the beam current squared, as expected from theory. The experimental results demonstrate the weak excitation of high order mode wakefields in a photonic bandgap structure. This research was published in: “Measurement of Wakefields in a 17 GHz Photonic Bandgap Accelerator Structure,” R. A. Marsh, M. A. Shapiro, R. J. Temkin, E. I. Smirnova, J. F. DeFord, Nucl. Instr. and Methods in Phys. Res. Vol. A618, pp. 16–21 (2010).

5. List of Papers (2010-2013)

1. “High power breakdown testing of a photonic band-gap (PBG) accelerator structure with elliptical rods,” B. J. Munroe, A. M. Cook, M. A. Shapiro, R. J. Temkin, V. A. Dolgashev, L. L. Laurent, J. R. Lewandowski, A. D. Yeremian, S. G. Tantawi, and Roark A. Marsh, Phys. Rev. – Special Topics Accel. Beams, Vol. 16, 012005 (2013).
2. “Calculation of Wakefields in a 17 GHz Beam-Driven Photonic Bandgap Accelerator Structure,” Min Hu, B. J. Munroe, M. A. Shapiro, and R. J. Temkin, Phys. Rev. – Special Topics Accel. Beams Vol. 16, 022002 (2013).
3. “Experimental High-Gradient Testing of an Elliptical-Rod Photonic Band-Gap Structure at X-Band,” B. Munroe, M. Shapiro, R. Temkin, R. Marsh, V. Dolgashev, S. Tantawi, A. Yeremian, Proceedings of IPAC2012, New Orleans, Louisiana, USA Paper TUPPR071 (2012).
4. “Calculation of Wakefields in 17 GHz Beam-Driven Photonic Bandgap Accelerator Structure,” Min Hu, Brian Munroe, Michael Shapiro, Richard Temkin, Proceedings of IPAC2012, New Orleans, Louisiana, USA Paper TUPPR069 (2012).
5. “High-Gradient Photonic Band-gap (PBG) Structure Breakdown Testing at Ku-Band,” B.J. Munroe, A.M. Cook, M.A. Shapiro, R.J. Temkin, Proceedings of IPAC2012, New Orleans, Louisiana, USA Paper TUPPR070 (2012).
6. “Active negative-index metamaterial powered by an electron beam,” M. A. Shapiro, S. Trendafilov, Y. Urzhumov, A. Alu, R. J. Temkin, and G. Shvets, Phys. Rev. B Vol. 86, 085132 (2012).
7. “High-Gradient Testing of Photonic Band-gap (PBG) Accelerator Structures at 11 GHz and 17 GHz,” B. Munroe, M. Shapiro, R. Temkin, R. Marsh, D. Yeremian, V. Dolgashev, and S. Tantawi, Book of Abstracts: 2012 Advanced Accelerator Concepts Workshop, Austin, TX, June 10-15, 2012.
8. “Overmoded Dielectric and Metallic Photonic Bandgap Structures,” M. A. Shapiro, A. M. Cook, B. J. Munroe, E. A. Nanni, J. X. Zhang, and R. J. Temkin, Book of Abstracts: 2012 Advanced Accelerator Concepts Workshop, Austin, TX, June 10-15, 2012.
9. “X-Band Photonic Bandgap Accelerator Structure Breakdown Experiment”, R. A. Marsh, M. A. Shapiro, R. J. Temkin, V. A. Dolgashev, L. L. Laurent, J. R. Lewandowski, A. D. Yeremian, and S. G. Tantawi, PRSTAB, Vol. 14, Article Number: 021301 (2011).
10. “Design and testing of Advanced Photonic Band-Gap (PBG) Accelerator Structures”, B. J. Munroe, M. A. Shapiro, R. J. Temkin, R. A. Marsh, V. Dolgashev, S. G. Tantawi, and A. D. Yeremian, Particle Accelerator Conference, New York, NY, USA, March-April 2011, Paper THOBN5.

11. “17 GHz Overmoded Dielectric Photonic Band Gap Accelerator Cavity”, A. M. Cook, B. Munroe, M. A. Shapiro, and R. J. Temkin, Particle Accelerator Conference, New York, NY, USA, March-April 2011, Paper MOP041.
12. “Design and High Power Test of Photonic Bandgap Structures for Accelerator Applications”, B. J. Munroe, R. A. Marsh, M. A. Shapiro, and R. J. Temkin, Int. Particle Accelerator Conference, Kyoto, Japan, May 2010, Paper THPD063, page 4428.
13. “Design of an Overmoded Dielectric Photonic Bandgap Accelerator at 17 GHz,” A. Cook, B. Munroe, M. Shapiro, and R. Temkin, Book of Abstracts: 2010 Advanced Accelerator Concepts Workshop, Annapolis, MD, June 2010.
14. “Breakdown Studies of Photonic Bandgap Accelerator Structures”, B. Munroe, M. Shapiro, R. Temkin, R. Marsh, S. Tantawi, and V. Dolgashev, Book of Abstracts: 2010 Advanced Accelerator Concepts Workshop, Annapolis, MD, June 2010.
15. “Complementary Metamaterial for Accelerator Applications”, M. A. Shapiro, R. J. Temkin, W. Frierson, S. Trendafilov, and G. Shvets, Book of Abstracts: 2010 Advanced Accelerator Concepts Workshop, Annapolis, MD, June 2010.
16. “Measurement of Wakefields in a 17 GHz Photonic Bandgap Accelerator Structure”, R. A. Marsh, M. A. Shapiro, R. J. Temkin, E. I. Smirnova, and J. DeFord, Nuclear Instruments & Methods in Physics Research A **618** (2010) 16-21.

6. List of Personnel

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