Final Report

- **Federal Agency and Organization Element to Which the Report is Submitted:**

  Department of Energy, Office of High Energy Physics

- **Federal Grant or Other Identifying Number Assigned by Agency**

  DE-SC0010075

- **Project Title**

  High Gradient Accelerator Research

- **Project Director/Principal Investigator (PD/PI) Name, Title and Contact Information (email address and phone number)**

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- **Submission Date**

  July 12, 2016

- **DUNS and EIN Numbers**

  DUNS 001425594

  EIN 042103594

- **Recipient Organization (Name and Address)**

  Massachusetts Institute of Technology

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  Cambridge, MA 02139

- **Recipient Identifying Number or Account Number, if any**

  MIT OSP Number 6927807

- **Project/Grant Period (Start Date, End Date)**

  04/01/2013 to 03/31/2016

- **Reporting Period End Date**

  3/31/2016

- **Final Report**

1. Major Goals of the Project

The goal of the MIT program of research on high gradient acceleration is the development of advanced acceleration concepts that lead to a practical and affordable next generation linear collider at the TeV energy level. Other applications, which are more near-term, include accelerators for materials processing; medicine; defense; mining; security; and inspection. The specific goals of the MIT program are:

- Pioneering theoretical research on advanced structures for high gradient acceleration, including photonic structures and metamaterial structures; evaluation of the wakefields in these advanced structures
- Experimental research to demonstrate the properties of advanced structures both in low power microwave cold test and high power, high gradient test at megawatt power levels
- Experimental research on microwave breakdown at high gradient including studies of breakdown phenomena induced by RF electric fields and RF magnetic fields; development of new diagnostics of the breakdown process
- Theoretical research on the physics and engineering features of RF vacuum breakdown
- Maintaining and improving the Haimson / MIT 17 GHz accelerator, the highest frequency operational accelerator in the world, a unique facility for accelerator research
- Providing the Haimson / MIT 17 GHz accelerator facility as a facility for outside users
- Active participation in the US DOE program of High Gradient Collaboration, including joint work with SLAC and with Los Alamos National Laboratory; participation of MIT students in research at the national laboratories
- Training the next generation of Ph. D. students in the field of accelerator physics

2. What Was Accomplished Under These Goals

2.1 Experimental Studies of Novel Accelerator Structures at 11 GHz and 17 GHz

Photonic band-gap (PBG) structures are promising candidates for electron accelerators capable of high-gradient operation because they have the inherent damping of high order modes required to avoid beam breakup due to instabilities. A key challenge for PBG structures is high-gradient operation without structure damage due to rf-field-induced breakdowns. This research summary reports theoretical results on the design of PBG structures and the generation of wakefields in such structures. It also reports experimental results on PBG structure breakdown testing at high power at both 11 and 17 GHz.

A single-cell photonic band-gap (PBG) structure was designed with an inner row of elliptical rods (PBG-E) to reduce ohmic heating relative to a round-rod structure. The PBG-E structure was built and tested at high power at a 60 Hz repetition rate at X-Band (11.424 GHz) at the SLAC accelerator test stand, achieving a gradient of 128 MV/m at a breakdown probability of 3.6×10^{-3} per pulse per meter at a pulse length of 150 ns. The PBG-E structure showed major improvement in breakdown rate relative to a round-rod PBG structure designed at MIT and previously tested at SLAC.

A test stand was designed and built at MIT for testing single-cell structures at 17.1 GHz, a frequency 50% higher than the SLAC frequency. This test stand provides comparable diagnostics to those used at SLAC, adding optical diagnostic access which can be used for open PBG structures. A conventional disc-loaded waveguide structure, MIT-DLWG, was tested at MIT at up to a 2 Hz repetition rate. This structure reached a maximum gradient of 87 MV/m at a breakdown probability of 1.19×10^{-1} per pulse per meter. A round-rod PBG structure, MIT-PBG-2, has also been tested at MIT at up to a 2 Hz repetition rate and 100 ns pulse length, demonstrating operation up to 89 MV/m at a breakdown probability of 1.09×10^{-1} per pulse per meter.

These test results show that a PBG structure can simultaneously operate at high gradients and low breakdown probability, while also providing wakefield damping. This makes PBG structures viable candidates for future collider applications.

The simulation of wakefield damping in PBG structures using a PIC code is a significant advance. Previous simulation work assumed that only a single dipole mode was relevant and that the Q of the mode as predicted by eigenmode simulations was an accurate measure of wakefield damping. The use of a PIC code confirmed that eigenmode Q values are appropriate measures of damping, allowing for simple estimates of damping in future designs. The use of a PIC code also indicated that eigenmode simulations must look for and include multiple dipole modes within the dipole band to accurately predict damping.

Demonstration of high-gradient, low-breakdown-probability testing of the PBG-E structure at SLAC was a ground breaking step in the advancement of PBG structures for future collider applications. While the PBG-R structure showed that it is possible for a structure with wakefield damping to operate at high gradients, it could not do so at an acceptable breakdown probability. Proving that a structure could operate simultaneously at high gradient, low breakdown probability, and with wake-field damping makes the PBG-E structure a viable candidate for future colliders. This testing also showed that the methodology used in processing structures with high surface magnetic fields is important. It also showed that PBG structures can be modified to reduce surface magnetic fields while still operating at high fields. This technique has since been used in designs for superconducting PBG structures.

Testing of the breakdown performance of single-cell high-gradient structures at 17 GHz provides a unique opportunity to investigate the physics of breakdowns in accelerator structures. No other comparable test facility is currently available, making these experiments unique. While testing of the MIT-PBG structure did not show the results expected based on the SLAC testing, the structure also did not show damage as a result of pulsed heating. This, combined with the promising results of the MIT- DLWG structure, suggests that future testing of PBG structures at 17 GHz will provide useful comparisons to PBG structure testing at 11 GHz.

2.2 Experimental Studies of Hybrid Photonic Band Gap Accelerator Structures

This research reports the first high power tests of a hybrid photonic band gap (PBG) accelerator structure. PBG structures can support a single electromagnetic mode, thus damping higher-order modes (HOMs) generated by wake fields. We have designed, built and successfully tested a 17.14 GHz hybrid PBG (HPBG) structure containing both dielectric and metallic elements. Dielectric elements have low loss and the potential to survive high surface electromagnetic fields. The HPBG structure was constructed as a triangular lattice array with sapphire rods inside and copper rods outside sandwiched between copper plates. The lattice parameter and the rod pattern were adjusted to excite a high-Q TM_{02} mode and to suppress HOMs. This overmoded operation is a unique and novel feature of the hybrid design. The design included the birefringence of sapphire. Simulations showed relatively high surface fields at the triple point where sapphire, copper and vacuum meet as well as in any gaps between components in the clamped assembly.

Three structures were tested with later structures designed to sequentially reduce the surface electric field. The third structure used sapphire rods with pin extensions at each end and obtained the highest gradient of 19 MV/m, corresponding to a surface E field of 78 MV/m, with a breakdown probability of 0.5/pulse/m in 45-ns pulses.

The hybrid PBG structure was constructed as a triangular array of rods sandwiched between two flat copper plates. Rods were removed from the cavity center to form a defect cavity to confine the TM_{02} mode at 17.14 GHz. The PBG rod array consisted of inner rows with a total of 60 sapphire rods plus a row of 24 copper rods added at the outside to provide a higher overall cavity Q. The diameter and the spacing of the sapphire rods were adjusted to excite only the TM_{02} mode and to suppress higher-order modes (HOMs). The lower order TM_{01} mode is not confined in the structure, neither is the TM_{11} dipole mode. This overmoded operation is a novel and unique feature of the hybrid cavity design. All designs were simulated by 3D design codes and included the birefringence of the sapphire material. Simulations of the hybrid structures showed relatively high surface fields at the triple point where sapphire, copper and vacuum meet as well as in any gaps between the rods and the metal plates.

Operation above 20 MV/m gradient led to runaway breakdowns with extensive light emission and eventual damage. For all three structures, multipactor light emission was observed at gradients well below the breakdown threshold. Breakdown damage was found at the triple point where surface fields peaked. The deposition of copper onto sapphire resulting from breakdowns might eventually degrade the cavity quality. This research indicated that multipactor triggered at the triple point limited the operational gradient of the hybrid structure.

These experiments represent the first high power tests of a hybrid PBG structure. The gradient achieved of 19 MV/m is the highest achieved with a dielectric structure. The gradient was found to be limited by multipactor and breakdown. The overmoded cavity with relatively large beam apertures might still find applications at high frequency or in high current transmission.

2.3 Cryogenic testing of the 2.1 GHz Five-cell superconducting RF cavity with a photonic band gap coupler cell

We obtained results from cryogenic tests of a multi-cell superconducting radio frequency (SRF) cavity with a photonic band gap (PBG) coupler cell. Achieving high average beam currents is particularly desirable for future light sources and particle colliders based on SRF energy-recovery-linacs (ERLs). Beam current in ERLs is limited by the beam break-up instability, caused by parasitic higher order modes (HOMs) interacting with the beam in accelerating cavities. A PBG cell incorporated in an accelerating cavity can reduce the negative effect of HOMs by providing a frequency selective damping mechanism, thus allowing significantly higher beam currents. The multi-cell cavity was designed and fabricated of niobium. Two cryogenic (vertical) tests were conducted. The high unloaded Q-factor was demonstrated at a temperature of 4.2 K at accelerating gradients up to 3V/m. The measured value of the unloaded Q-factor was 1:55*10**8, in agreement with prediction. This research was primarily funded by Los Alamos National Laboratory, under the direction of Dr. Evgenya Smirnova Simakov, and by an SBIR grant to Niowave, Inc. The MIT grant provided partial support for the graduate student, Mr. Sergey Arsenyev.

3. What opportunities for training and professional development has the project provided?

A list of those students partially or fully supported by your grant who were awarded a PhD during your final renewal period.

3.1 Experimental Studies of Hybrid Photonic Band Gap Accelerator Structures by JieXi ZHANG,

Submitted to the Department of Physics in partial fulfillment of the requirements for the degree of

Doctor of Philosophy at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY February 2016

3.2 Experimental Studies of Novel Accelerator Structures at 11 GHz and 17 GHz by Brian J. Munroe Submitted to the Department of Physics in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY February 2015

3.3 Photonic Band Gap Structures for Superconducting Radio-frequency Particle Accelerators by

Sergey A. Arsenyev Submitted to the Department of Nuclear Science and Engineering in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Nuclear Science and Engineering at the MASSACHUSETTS INSTITUTE OF TECHNOLOGY September 2016

4. How were the results disseminated to communities of interest?

Results were published in journal articles and conference proceedings. The journal articles are listed below under Products.

Products

Journal Articles (all acknowledge project support by DOE HEP)

1. “Experimental High Gradient Testing of a 17 GHz Photonic Band-Gap Accelerator Structure,” B. J. Munroe, J. X. Zhang, M. A. Shapiro and R. J. Temkin, Phys. Rev. Spec. Topics – Accel. Beams 19, 031301 (2016).

2. "High Power Experimental Studies of Hybrid Photonic Band Gap Accelerator Structures," J. X. Zhang, B. J. Munroe, H. Xu, M. A. Shapiro and R. J. Temkin, Physical Review Accelerators and Beams (submitted, 2016).

3. “Higher Order Mode Damping in a Five-cell Superconducting RF Cavity with a PBG Coupler Cell,” S. A. Arsenyev, R. J. Temkin, D. Yu. Shchegolkov, E. I. Simakov, C. H. Boulware, T. L. Grimm, and A. R. Rogacki, submitted to PR-AB (2016).

4. Cryogenic testing of the 2.1 GHz five-cell superconducting RF cavity with a photonic band gap coupler cell,” Sergey A. Arsenyev, Richard J. Temkin, W. Brian Haynes, Dmitry Yu. Shchegolkov, Evgenya I. Simakov, Tsuyoshi Tajima, Chase H. Boulware, Terrence L. Grimm, and Adam R. Rogacki, Applied Phys. Lett. 108, 222603 (2016).

5. Inventions, patent applications, and/or licenses

There were no patents, no patent applications and no licenses during this research period.