Final Report

Institution: Los Alamos National Laboratory
Project title: Early Career: Advancing our Understanding of Photonic Band Gap Structures for Accelerators
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Abstract

The U.S. Department of Energy (DOE) Office of Science Early Career Research Program funded a project at Los Alamos National Laboratory with an objective to advance our knowledge about the Photonic Band Gap (PBG) accelerator cavities for the next generation of particle accelerators for high energy physics. It has been long recognized that PBG structures have great potential in reducing and even completely eliminating long-range wakefields in accelerators. This property is especially beneficial for the next generation of superconducting colliders with multi-hundred GeV to TeV beam energies, because in order to obtain high luminosity of the beam and avoid bunch to bunch beam breakup, the accelerating cavities must be selective with respect to the operating mode, and wakefields must be suppressed. Using PBG structures to reduce wakefields in superconducting particle accelerators allows moving forward to significantly higher beam luminosities and leads towards a completely new generation of colliders for high energy physics. The first ever demonstration of acceleration in PBG structures was conducted by Dr. Smirnova in 2005. Since then, the importance of that device has been recognized by many research institutions in the US and world-wide. However, the technology of fabrication of PBG accelerator cells was still immature at room temperature and non-existent at superconducting temperatures before this project. In the framework of this project we developed fabrication and demonstrated high gradient operation of superconducting radio-frequency (SRF) cavities with PBG cells, both single-cell and multi-cell cavities with PBG couplers. We also fabricated and demonstrated operation of a 16-cell traveling-wave room-temperature 11.7 GHz PBG accelerating structure on a beamline. Technology of fabrication of multi-cell PBG accelerating cavities was developed. Suppression of wakefields in the PBG accelerating structure was clearly demonstrated in an experiment. We believe that PBG accelerators have the potential to revolutionize the field of high-energy colliders. In addition, superconducting PBG accelerator technology will deliver ideal structures for novel free-electron lasers (FELs) producing extremely intense, short-wavelength laser radiation, where very high current electron beams are required.

Introduction and Background

The ultimate goal of this project was to experimentally demonstrate the applicability of photonic band gap (PBG) accelerator cells for wakefield suppression in both, superconducting RF and room-temperature high-energy accelerators of the future. A PBG structure or simply, photonic crystal, represents a periodic lattice of macroscopic components (e.g., rods), metallic, dielectric or both. One can design and construct photonic crystals with photonic band gaps, preventing light of certain frequencies from propagating in certain directions. A “PBG cavity" is formed by removing a rod in the periodic structure. The mode with a frequency in the band gap cannot propagate out transversely through the bulk of the PBG structure and thus will be localized inside of the PBG cavity around the defect. The field pattern of the mode can be made to resemble the field pattern of the TM_{01} accelerating mode of a pillbox cavity, and the cavity can be employed as an accelerator cavity. However, the modes with frequencies outside of the band gaps (such as the higher order wakefield modes in accelerator cavities) will be free to propagate through the PBG structure. In this regard, the PBG resonator intrinsically acts as an extremely efficient higher order mode (HOM) coupler.

An experimental demonstration of acceleration in PBG resonators was a subject of the PI’s PhD dissertation at Massachusetts Institute of Technology (MIT). This project is a logical continuation of the MIT work with the two main goals:

- Design, build, and demonstrate high gradient operation of superconducting radio-frequency (SRF) PBG accelerator structures.
- Design, build and conduct an experiment to demonstrate suppression of wakefields in an X-band room-temperature traveling-wave PBG accelerator.

Technical Progress

Year 1:

The first year of the project was focused on theoretical and computational investigations of the ability of PBG resonators to suppress wakefields in SRF accelerators and on the design of a 700 MHz SRF PBG resonator. It was discovered, that a fundamental difference must exist between the designs of an SRF PBG resonator and a room-temperature resonator. Unlike its copper predecessor, the SRF resonator could not be designed as an open structure for two reasons. First, the SRF resonator must be lowered into a cryostat which is filled with liquid helium and cooled down to superconducting temperatures. Therefore, the PBG structure must be enclosed by a solid wall that would prevent penetration of the liquid helium into the cavity. Second, any truncated PBG structure has a finite diffraction Q, which is determined by the losses that the accelerating mode experiences by leaking out of the periodic structure. In resonators which were previously designed by the PI for the 17 GHz PBG experiment at MIT the diffraction Q was of the order of 10^5, which was almost 2 orders of magnitude larger than the ohmic Q of the structure, determined by the ohmic losses in copper. However, since the ohmic losses in superconducting niobium are very low, the diffraction Q of the superconducting PBG resonator must be orders of magnitude higher than 10^9, which is a typical ohmic Q of the superconducting resonators. The diffraction Qs of that magnitude are impossible to achieve in a truncated PBG structure of a reasonable size. As a result, SRF PBG resonators must incorporate an enclosing wall, which would affect the confinement of the fundamental mode together with the other components of the PBG structure. The enclosing wall, in turn, must be designed with the couplers, which work in conjunction with the PBG structure to filter out the higher order modes and do not affect the confinement of the fundamental mode. Above said, an SRF PBG resonator cannot be regarded as a trivial panacea against wakefields. Instead, it must be treated as a novel, elegant, and very effective way to incorporate HOM couplers and the fundamental mode coupler as a part of the accelerating structure. Unlike the conventional couplers and ferrite HOM dampers that are located in beam pipes, the new PBG-based couplers do not occupy additional space on the beamline and increase the real estate gradient, and therefore decrease the length and cost of the future superconducting colliders for high energy physics.

After the completion of the conceptual design, the project progressed as follows.

- The 700 MHz SRF PBG resonator was designed with the CST Microwave Studio consisting of 2 rows of rods and an enclosing niobium wall.
- The HOM couplers were designed in form of three WR-770 waveguids located on the enclosing wall. The HOM couplers reduced the Qs of the HOMs to below 100, while leaving the accelerating mode intact. A possibility was also considered to replace one of the HOM couplers with a fundamental mode coupler in form of the WR-975 waveguide. However, the WR-975 waveguide represents a significant heat leak in a cryogenic system and therefore the co-axial couplers might be more appropriate for the 700 MHz system.
- The co-axial couplers were designed to be placed in the beam pipe of the structure in order to conduct the high gradient tests of the PBG resonator in the LANL SRF laboratory.

Apart from performing the design work, the PI established a working collaboration with Niowave, Inc. in Michigan, which was selected to be the fabrication vendor for the 700 MHz SRF PBG resonator. Niowave was funded through a separate SBIR Phase I project to develop the fabrication procedure for PBG resonators. Dr. Chase Boulware at Niowave was assigned as a main point of contact for their collaboration with LANL and continued to stay as a main point of contact through the whole project. The PI forwarded her initial designs of the PBG resonators to Niowave to evaluate possibility of fabricating the structure out of niobium. Niowave fabricated a scaled copper prototype of the resonator and delivered it to LANL (see the photograph in Figure 1, with the dimensions listed in Table 1).

The prototype was constructed with reduced-diameter beam ports to reduce leakage of the fundamental mode through these ports. A removable copper outer sleeve was designed to analyze the impact of closing the photonic band gap structure just outside the first two rows of rods. The prototype was cold-tested at LANL and the measured room-temperature cavity Q was 3400 with the sleeve removed, and 11500 with the sleeve clamped on. The measurement suggested that the impact of the enclosure was significant. The computed and measured frequencies and Q-factors of the structure are summarized in Table 2.

Figure 1. Copper prototype of an SRF PBG resonator.

Table 1: Dimensions of the copper prototype cavity.

Spacing between the rods, p	1.693 inches
Diameter of the rods, d	0.508 inches = 0.3*p
Outside diameter, D0	8.8 inches
Length of the cell, L	2.56 inches
Diameter of the beam pipe, Rb	0.5 inches
Radius of the beam pipe blend, rb	0.25 inches

Table 2: Computed and measured characteristics of the copper prototype.

	Computed	Measured
Frequency	2.728 GHz	2.708 GHz
Q of the fundamental mode (closed cavity) = Ohmic Q	12500	11500
Q of the fundamental mode (open cavity)	4500	3400
Diffraction Q of the fundamental mode	7000	4900

The behavior of HOMs was also studied in the copper prototype with two electrical probes inserted through the beam ports. It was confirmed that HOMs radiate out of the open structure, as predicted, and the fundamental mode and its harmonic, the TM_{011} mode, stay mostly confined. The results of the transmission measurement with two electrical probes are shown in Figure 2.

The PI started assisting at the SRF laboratory at LANL and learning about experimental equipment, completed the required Cryogen Safety Training and the Incidental Crane Operation training.

The PI involved a mechanical engineer to design an upgrade for a cryostat in the SRF laboratory. The new upgraded cryostat was designed to be 48 inches in diameter, wide enough to easily fit the new 700 MHz PBG resonators. The order for the cryostat went through LANL procurement.

The PI identified a graduate student who planned to join the project in summer of the 2011 and assist with the upcoming experiments.

The PI attended the US Particle Accelerator Conference in New York, NY and presented the results of the project.

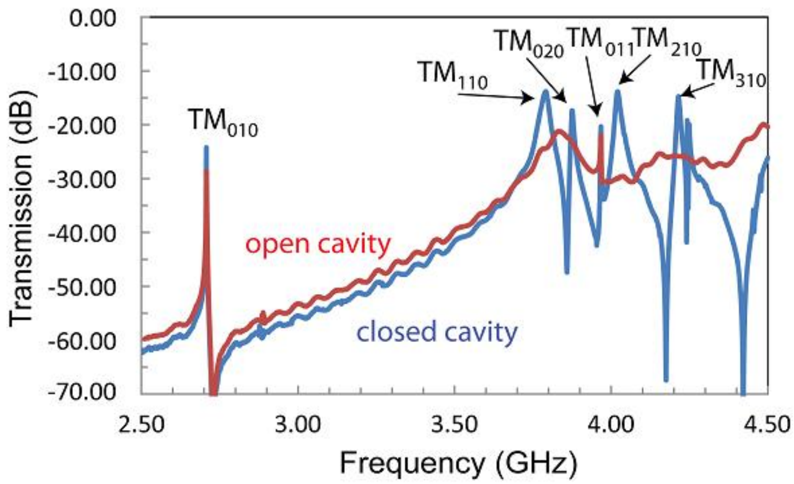


Figure 2. HOM measurement in the copper prototype with and with no outside copper enclosure.

Year 2:

The second year of the project was focused on two main goals. The first goal was fabrication of superconducting PBG cells for high gradient tests and preparation of the tests. The second goal was the design of the X-band room-temperature traveling-wave PBG wakefield experiment to be conducted at Argonne Wakefield Accelerator (AWA) user facility.

In order to achieve the first goal, the PI worked with both major US niobium manufacturers, the Niowave, and the Advanced Energy System. Both manufacturers conducted engineering evaluations of fabrication of the 700 MHz SRF PBG resonators and concluded that they will be unable to manufacture this low frequency design within the available budget. Niowave suggested to move the design up to the higher frequency of 2.1 GHz. The equipment available at LANL's SRF laboratory was evaluated and the conclusion was made that the high gradient experiment could be conducted at 2.1 GHz with little modification to the experimental hardware.

Next, the 700 MHz design of the SRF PBG resonator was scaled up to the higher frequency of 2.1 GHz. The PBG resonator was designed with the CST Microwave Studio consisting of 2 rows of rods and an enclosing niobium wall. The dimensions and the expected accelerator characteristics of the 2.1 GHz SRF PBG resonator are summarized in Table 3. The PI visited Niowave in April, 2011 and worked with their engineers to adjust the design of the cavity and simplify manufacturing. The purchase order was submitted for two cavities. The co-axial couplers were designed to be placed in the beam pipes for high gradient tests. All hardware was procured. Modifications were done to the SRF laboratory. This included the assembly of the new phase-lock-loop for tuning to the correct frequency of the cavity, which was now capable of operating at frequencies up to 3 GHz. The new 48 inch-diameter cryostat was delivered to LANL in June, 2011 and placed into the SRF laboratory.

Table 3: Dimensions and accelerator characteristics of the 2.1 GHz SRF PBG accelerator cell.

Spacing between the rods, p	56.56 mm
OD of the rods, d	17.04 mm = 0.3*p
ID of the equator, D0	300 mm
Length of the cell, L	60.73 mm (λ/2)
Beam pipe ID, Rb	1.25 inches = 31.75 mm
Radius of the beam pipe blend, rb	1 inch = 25.4 mm
Q_0 (4K)	$1.5*10^8$
Q_0 (2K)	$5.8*10^9$
R/Q	145.77 Ohm
E_{peak}/E_{acc}	2.22
B_{peak}/E_{acc}	8.55 mT/(MV/m)

Figure 3. The 2.1 GHz SRF PBG resonator.

The SRF cavities (shown in Figure 3) were delivered to LANL at the end of December, 2011. The safety paperwork for the SRF laboratory was completed and operation was approved starting in February 2012. The tests were planned for March and April 2012, which was more than half a year ahead of the original schedule.

The PI also started planning and preparing for the X-band wakefield experiment at the Argonne Wakefield Accelerator facility. The PI visited AWA in April, 2011 and talked about the details of the experiment. It was decided to fabricate the PBG structure to operate at 11.7 GHz. The traveling-wave cells of the structure and the couplers were designed. Three sample traveling-wave cells were ordered from Custom Microwave and delivered to LANL in December 2011 (Figure 4). The cells were tested at low power. The transmission tests proved that the frequencies of the cells were within the limits determined by the manufacturing tolerances. This confirmed the design.

The graduate student started his studies at MIT in Fall 2011. He visited LANL during the school breaks and got introduced to the project and obtained all required safety training.

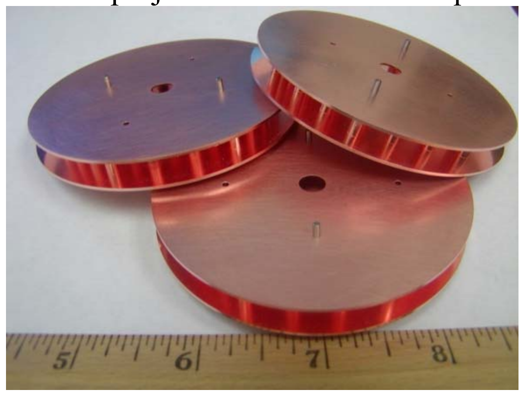


Figure 4: The 11.7 GHz PBG cells ready for tuning and brazing.

Year 3:

The third year of the project was focused on two main goals. The first goal was testing of the superconducting PBG cells for high gradient performance. The second goal was to continue preparing for the X-band room-temperature traveling-wave PBG wakefield experiment to be conducted at Argonne Wakefield Accelerator user facility.

The 2.1 GHz SRF PBG resonators delivered from Niowave were installed in a vertical cryostat for high power testing. Each resonator underwent 2 days of testing. The 4 K measurement was carried out on the first day. On the second day more liquid helium was added and the cryostat was pumped down for a 2 K measurement. The dependence of the qualify factor on the accelerating gradient was measured in a CW regime and the gradient limitations were determined.

Table 4: Measured performance of two 2.1 GHz SRF PBG resonators and comparison to theory.

	Theory	Cavity #1	Cavity #2
Frequency	2.100 GHz	2.10669 GHz	2.09984 GHz
Q_0 (4K)	$1.5*10^8$	$8.2*10^7$	$1.2*10^8$
Q_0 (2K)	$5.8*10^9$	$1.1*10^9$	$3.9*10^9$
Maximum E_{acc} (4K)		9.5 MV/m	10.6 MV/m
Maximum E_{acc} (2K)		9.1 MV/m	15.0 MV/m
B_{peak} (4K)		81 mT	91 mT
B_{peak} (2K)		78 mT	129 mT

The results of the testing are summarized in Table 4 and Figure 5. Cavity #1 was the first one to be tested and was opened up in the clean room a few times during the preparation stages. It may explain its slightly worse performance at 4K. Also, during the 2K testing, cavity #1 developed a super-leak, which resulted in a quite poor performance. Measured characteristics of the Cavity #2 were very close to theoretical predictions. The achieved accelerating gradients were as high as 15 MV/m, limited by the magnetic quench at the surface field of about 130 mTesla. The results of the tests were published in Physical Review Letters.

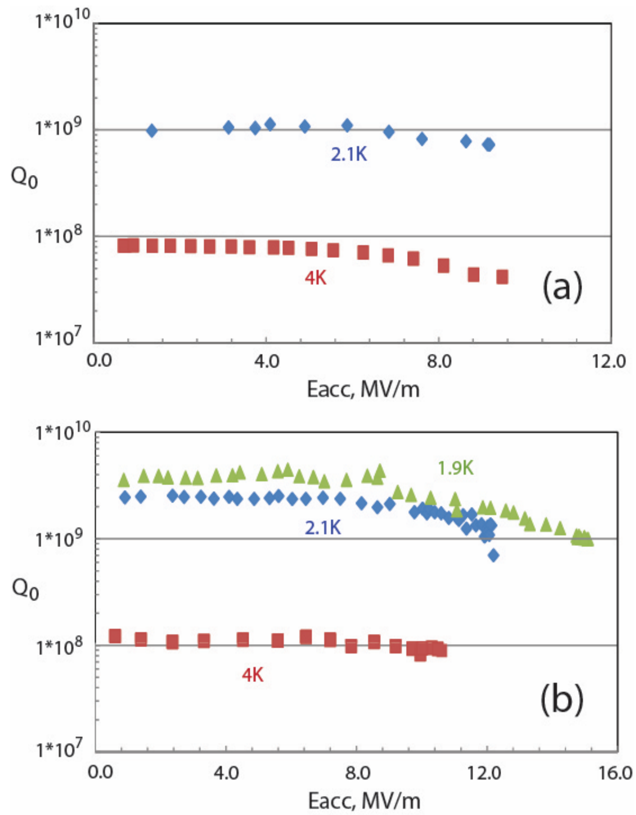


Figure 5: Unloaded qualify factor (Q_0) as a function of accelerating gradient (E_{acc}) off the 2.1 GHz SRF PBG cavities: (a) cavity #1 tested on 3/30/12, and (b) cavity #2 tested on 4/27/12.

The PI and the graduate student started the design of a multi-cell SRF accelerating structure which incorporated a PBG cell with HOM couplers. The conceptual design of the structure is shown in Figure 6. The PBG cell replaces a regular elliptical accelerating cell in the middle of the five-cell accelerating module and incorporates a WR430 waveguide for the fundamental mode coupling and two HOM waveguides.

For the room-temperature 11.7 GHz wakefield experiment, the PI continued the cold-testing and tuning of the copper cells. The initial cold-testing indicated that the frequencies of the prototype cells were a little high, which was in agreement with the design. The iterative etching was performed to bring the frequencies of the cells down to 11.700 GHz. The 3 test cells were brazed together to benchmark the brazing process. However, brazing was not successful. It was discovered, that electroformed cells had some internal stresses that resulted in deformations when heated to the temperatures anywhere above 500 F.

A new order for 25 cells was placed for Custom Microwave to build the 16-cell structure for the wakefield experiment. The dimensions and the computed accelerating characteristics of the proposed structure are summarized in Table 5. The PI worked on designing the layout and diagnostics for the experiment at AWA. Two 50MW loads were ordered from Euclid Techlabs to absorb the power generated during the wakefield experiment.

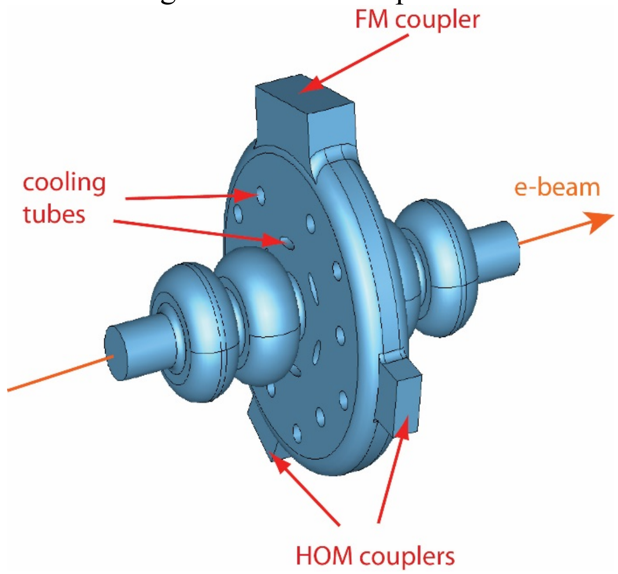


Figure 6: The 5-cell 2.1 GHz SRF accelerating module with a PBG coupling cavity.

Table 5: Dimensions and accelerator characteristics of the 11.7 GHz traveling-wave PBG accelerator.

Frequency	11.700 GHz
Phase shift per cell	2π/3
Q_w	5000
r_s	72.5 MΩ /m
$[r_s/Q]$	14.5 kΩ /m
Group velocity	0.015c
Gradient	15.4 √P[MW] MV/m
Rod radius, *a* (TW cell/coupler cell)	1.55 mm/1.54 mm
Lattice vector, *b* (TW cell/coupler cell)	10.33 mm/10.30 mm
a/b	0.150
Length of the cell	8.53 mm
Diameter of the iris	6.31 mm = 0.250 in
Thickness of the iris	1.90 mm = 0.075 in
OD of the cavity	76 mm = 3 in

The MIT graduate student was attending classes and preparing for his qualifying exams. LANL was paying the student's tuition and salary through a contract to MIT.

The PI attended the International Particle Accelerator Conference in New Orleans, LA and the Advanced Accelerator Concepts workshop in Austin, TX and reported the results of the project. The graduate student also attended the Advanced Accelerator Concepts workshop and made his first presentation.

Year 4:

The fourth year of the project was again focused on two main goals. Now the major goal was fabrication and tuning of the 16-cell 11.7 GHz traveling-wave room-temperature accelerating structure for the wakefield experiment. The second goal was finishing up the design of a multi-cell SRF accelerating module with a PBG coupler cell.

For the first goal, 25 traveling-wave and 4 end cells were electroformed by Custom Microwave and delivered to LANL for tuning. A structure was assembled from 14 traveling-wave cells and 2 end cells with WR-90 waveguides and tested with a network analyzer. The photograph of the assembled 16-cell structure on the test bench is shown in Figure 7. Initially the cells were found to be higher in frequency than the target. This was in accordance with the design. The field profile in the structure was measured with a bead-pull and demonstrated some expected detuning. The series of etches were performed to lower the frequencies of the cells, to obtain the correct field profile, and the correct frequency for the $2\pi/3$ accelerating mode.

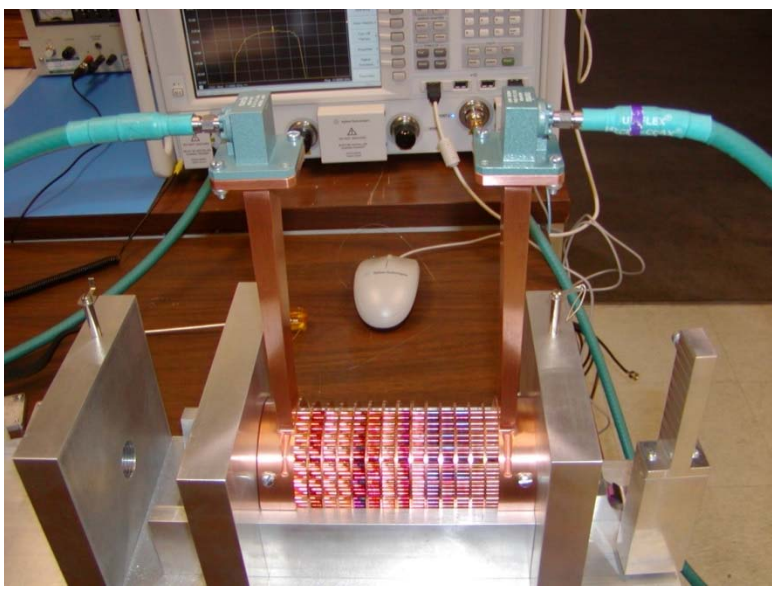


Figure 7: The 11.7 GHz PBG accelerating structure on a test bench.

The transmission and reflection from the tuned and clamped together structure of 16 PBG cells is shown in Figure 8. The $2\pi/3$-mode is the 6^{th} dip from the right on the reflection curve, at the frequency of 11.697 GHz in air. Figure 9(a) shows the electric field profile in the tuned structure measured with a bead pull method. Figure 9(b) shows the Smith chart measured on a network analyzer during the bead pull, where the measured signal is proportional to the square of the complex magnitude of the electric field in the structure. Both figures illustrate that the accelerator structure was tuned and operated in the $2\pi/3$ accelerating mode.

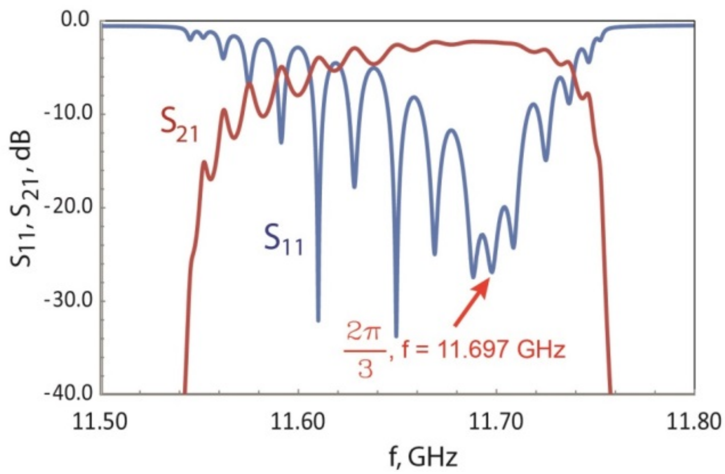
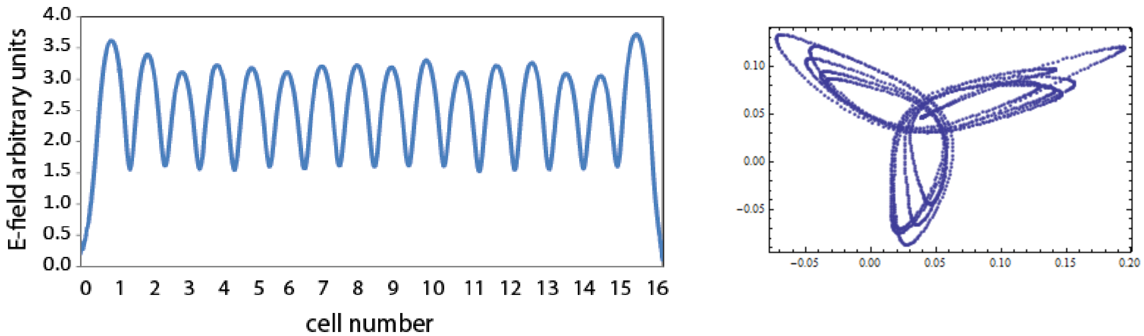


Figure 8: Transmission and reflection in the tuned 16-cell PBG structure.



(a) (b)

Figure 9: Field profile (a) and the Smith chart (b) measured with a bead pull in the tuned 16-cell PBG structure.

The vacuum chamber and the components for the wakefield experiment were all prepared. The structure was awaiting the final bonding, installation on the beam line and the final beam tests.

For the second goal, the PI worked with a graduate student to finalize the design of a multi-cell SRF accelerating structure which incorporates a PBG cell with couplers. The dimensions and accelerator characteristics of the final design are listed in Table 6. The PBG cell was designed with a small detune so that the gradient in the PBG cell was lower than the gradient in other elliptical cells in the structure (as shown in Figure 10). This way the peak surface magnetic fields in the PBG cells were the same as the peak surface magnetic fields in elliptical cells, and the PBG cell was no more likely to quench than any other cell of the accelerating module. The HOM spectrum of the designed structure was analyzed with the CST Particle Studio (as shown in Figure 11). The waveguides attached to the PBG cell were carefully tuned to achieve good coupling for the fundamental mode and low Q-factors for all dangerous HOMs. In the final design all HOMs had Q-factors lower than 800. The copper prototype of the designed structure was ordered from Niowave.

Table 6: Accelerating characteristics of the five-cell accelerating module with a PBG cell and comparison to the five-cell all elliptical cell module.

	With a PBG cell	All elliptical cells
Frequency	2.100 GHz	
Shunt Impedance, R/Q	515 Ohm	525 Ohm
Geometry factor, G	265 Ohm	276 Ohm
E_{peak}/E_{acc}	2.65	2.50
B_{peak}/E_{acc}	4.48 mT/(MV/m)	4.27 mT/(MV/m)

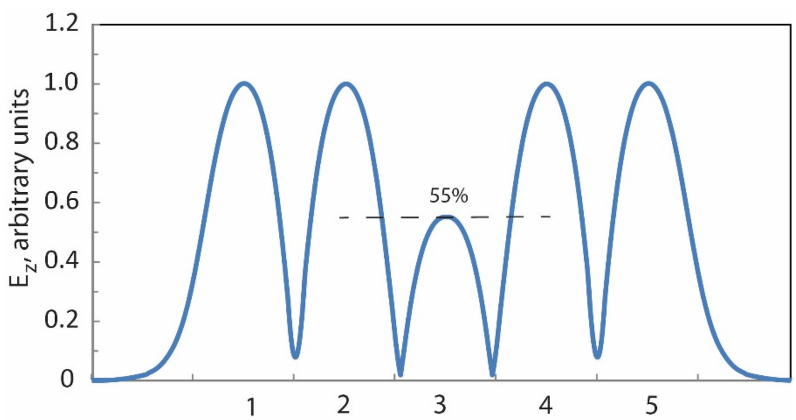


Figure 10: The profile of the electric field in the 2.1 GHz SRF accelerating module with a PBG coupling cavity.

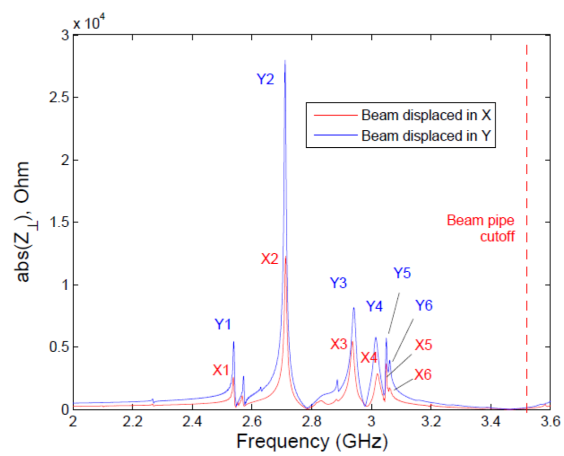


Figure 11: Transverse wake potential in a 5-cell SRF structure with the PBG coupler as calculated with the CST Particle Studio. The biggest peaks correspond to the 12 most dangerous modes.

The progress on the project was reported at the North American Particle Accelerator Conference in Pasadena, CA, which was attended by both, the PI and the graduate student. The

PI also attended the Superconducting RF Workshop in Paris, France, where she presented an invited talk on SRF testing of the single-cell PBG resonators from Year 3. The design of the SRF structure was also included in the paper published in Applied Physics Letters.

The MIT graduate student finished attending his classes, passed his qualifying exams, and relocated to LANL to work on the multi-cell SRF accelerating structure. He also attended the USPAS several times and took classes in Accelerator Physics. LANL was paying the student's tuition and salary through a contract to MIT.

Year 5:

Year 5 was mostly focused on experimental work and final testing. First, the PI finished fabrication of the 16-cell 11.7 GHz traveling-wave PBG accelerating structure and conducted the wakefield experiment at the Argonne Wakefield Accelerator. Second, the PI and the student finished fabrication and testing of the copper prototype of the 2.1 GHz SRF accelerating structure. Third, the PI and the graduate student conducted high gradient SRF testing of the 5-cell SRF PBG accelerating module fabricated by Niowave in the framework of an SBIR Phase II project.

The electroformed PBG cells that were fabricated and tuned in Year 4 could not be brazed due to internal stresses. Thus the tuned structure underwent bonding with a vacuum-compatible non-conductive Hyson EA9394 epoxy. The electrical contact between the cells was ensured by having elevated rings around the beam holes polished to the mirror finish which were not covered by the epoxy and touched the neighboring cells. First, we bonded four trial cells to confirm that the bonding process worked. Next, we bonded the full 16-cell structure, choosing the best 14 traveling-wave cells, which ended up closest to the target frequency. The bonded structure was again cold-tested and the results were nearly identical to the cold-test results of the clamped structure described above.

(a) (b)

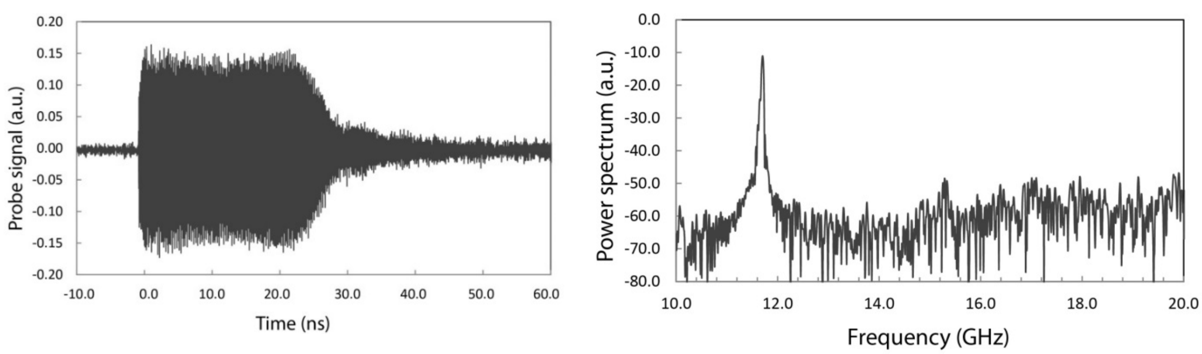
Figure 12: The 16-cell PBG structure installed on a 10-inch stainless steel flange (a); the 10-inch experimental chamber with the PBG structure installed on the beamline at AWA (b).

The structure was installed on a beamline at Argonne Wakefield Accelerator (Figure 12). The structure was mounted on a flange of a 10-inch vacuum chamber and the chamber was installed at the end of the beamline at AWA. An electron beam with the energy of approximately

65 MeV was passed through the structure, and the transmitted charge varied between 0.25 nC and 7 nC. The spectrum of the excited wakefields was recorded with different probes. Two probes were installed on directional couplers at the input and output waveguides. Also four loop antennas were installed on the periphery of the structure in four different cells to couple to the magnetic field of the HOM modes.

The rf signal in the downstream coupling waveguide was studied first. The length of the measured rf pulse was approximately 30 ns, in a very good agreement with simulations (Figure 13(a)). The Fourier spectrum of the forward signal was dominated by the fundamental mode at 11.700 GHz with no power transmitted at any other frequencies (Figure 13(b)). The power coupling into the 11.700 GHz mode scaled quadratically with the transmitted charge as predicted (Figure 14).

The rf signal picked up by the loop antennas was analysed next. The most downsteam antenna picked up the clearest signal and the least noise. The Fourier spectrum of the antenna signal revealed the presence of the fundamental mode (leaking at a low level through the PBG structure) and a number of low-Q HOMs at the frequencies in between 15 GHz and 18 GHz (Figure 15). The HOM spectrum was recorded in different configurations: in a PBG structure wrapped in foil and in an open PBG structure, with 6 SiC absorbers attached to the sides of the structure. The level of HOMs varied depending on the boundary conditions as expected. The structure with SiC absorbers had the most attenuated higher order modes which were only slightly visible above the noise level (Figure 15(b)); in the structure wrapped in foil, the level of HOMs was much higher since HOMs were not being filtered out of the structure (Figure 15(a)). The measurements clearly confirmed the effectiveness of the PBG structure for suppression of HOMs.



(a) (b)

Figure 13: The rf signal in the downstream coupling waveguide of the PBG structure: (a) time-domain; (b) Fourier transform.

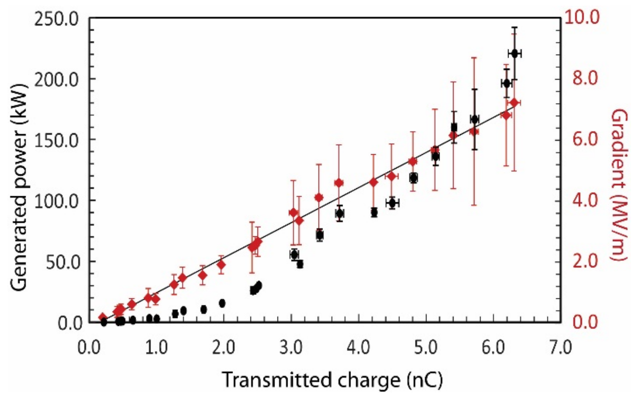


Figure 14: Power in the downstream coupling waveguide of the PBG structure as a function of the transmitted charge. The gradient in the structure computed from the measured power is also shown.

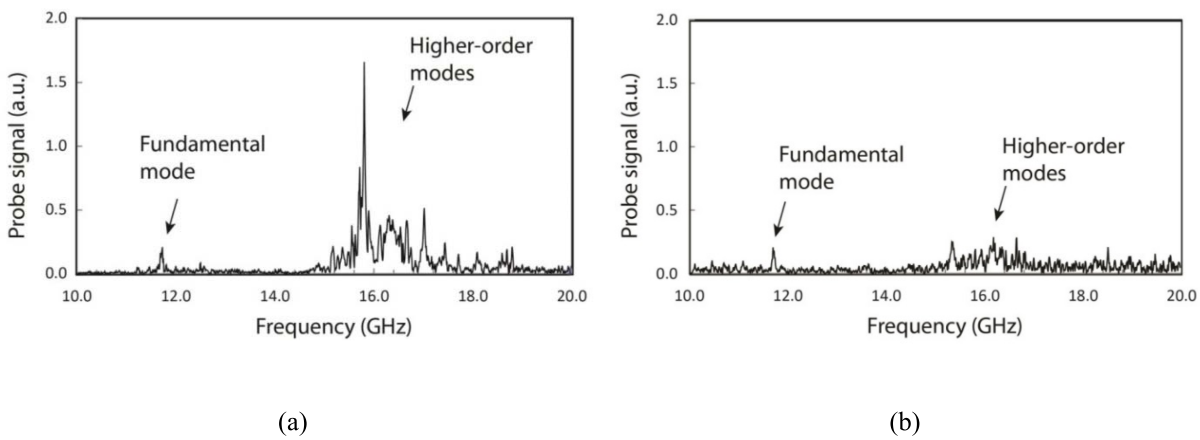


Figure 15: The rf spectrum of the signal picked up by a loop antenna at the periphery of the PBG structure: (a) the structure wrapped in foil; (b) the structure with 6 SiC absorbers.

The photograph of the copper prototype of the 2.1 GHz SRF accelerating module with a PBG cell fabricated by Niowave in shown in Figure 16. Each elliptical cell was machined with extra 0.1'' of material at the equator which was later trimmed during the tuning procedure. The tuning was performed by the graduate student who travelled to Niowave for this purpose. Tuning was done in multiple steps starting with the cells closest to the PBG cell and finishing with the end cells. Each tuning step involved a bead pull measurement. The results of the bead pull were plugged into the circuit model of the cavity and an estimate was made on how much trimming was needed for the next step. The tuning was continued until the desired field profile was obtained for the fundamental mode with 5 percent accuracy. The external Q-factor was measured for the fundamental power coupler next and was found to be $2.2*10^4$, in good agreement with the design.

The magnetic loop probes were inserted through the beam pipe to excite HOMs. The Q-factors of major HOMs were calculated from the measured data and compared to the design, and to calculated Q-factors in "as-fabricated" structure. The Q-factors of HOMs are summarized in Table 7. It was found that some HOMs were very sensitive to the small geometry changes introduced by the way that the cavity was tuned. The agreement between measured and calculated quality factors was very good, that demonstrated the validity of the design.

Figure 16: The copper prototype of the 2.1 GHz 5-cell SRF accelerating module with a PBG cell.

Table 7: Measured performance of two 2.1 GHz SRF PBG resonators and comparison to theory.

HOM	Q_e, as designed	Q_e, as fabricated	Q_e, measured
X1	$1.2*10^3$	$3.7*10^3$	$4.2*10^3$
X2	$7.3*10^2$	$1.3*10^3$	$1.4*10^3$
X3	$3.3*10^2$	$2.9*10^2$	$1.8*10^2$
X4	$1.9*10^2$	$2.0*10^2$	$1.6*10^2$
X5	$1.3*10^4$	$1.0*10^4$	$7.8*10^3$
X6	$4.7*10^2$	$4.4*10^2$	$4.8*10^2$
Y1	$1.0*10^3$	$4.4*10^3$	$7.4*10^3$
Y2	$8.6*10^2$	$1.9*10^3$	$1.7*10^3$
Y3	$2.5*10^2$	$2.6*10^2$	$1.8*10^2$
Y4	$2.7*10^2$	$1.7*10^2$	$3.0*10^2$
Y5	$1.8*10^3$	$1.5*10^3$	$8.9*10^2$
Y6	$7.8*10^2$	$6.3*10^2$	$3.7*10^2$

The 2.1 GHz 5-cell accelerating cavity with the PBG coupler was fabricated at Niowave and shown in Figure 17. The cavity was tuned at Niowave and the final field profile is shown in Figure 18. The cavity was shipped to LANL where it was assembled with the adjustable drive probe and a pickup probe in the cleanroom and installed on the insert of a cryostat. The cavity was baked at 120 C for 2 days and pumped down to below $5*10^{-8}$ torr.

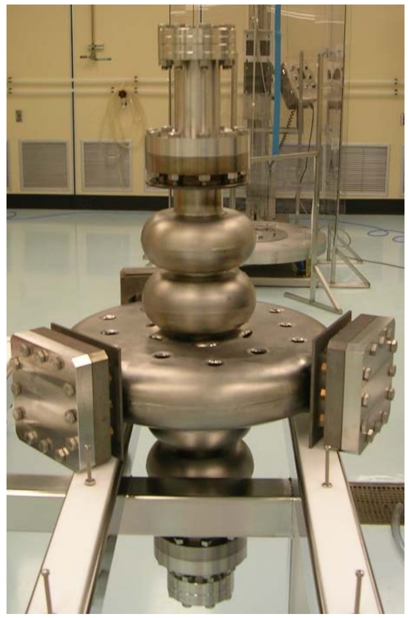


Figure 17: The 2.1 GHz 5-cell SRF accelerating module with a PBG cell.

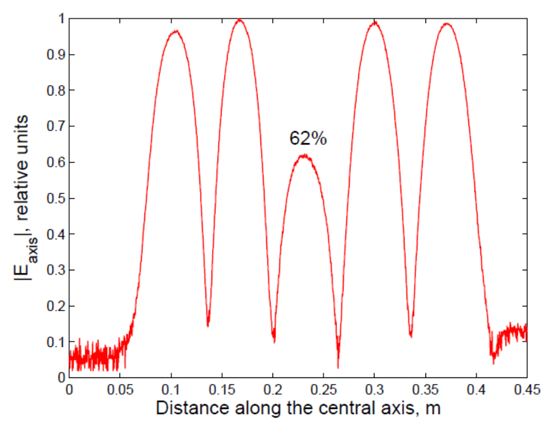


Figure 18: Magnitude of the electric field measured along the axis of the 2.1 GHz 5-cell SRF accelerating module after the tuning.

The cavity was lowered into the cryostat and cooled down to 4 K with liquid helium. The network analyzer was used to find the accelerating (π) mode and its spatial variations 4π/5, 3π/5, and 2π/5 modes. The frequency of the accelerating mode was found to be 2.1062 GHz, very close to the design value of 2.100 GHz. However, it was discovered that even when the drive probe was moved all the way in (strongest coupling), the fundamental mode was still undercoupled. The phase-lock loop was used to measure the Q-factor for the fundamental mode which was found to be $1.6*10^6$, much lower than expected. The Q-factor for the 3π/5 was also low, 9.3*10^5. The 4π/5 and 2π/5 had somewhat higher Qs, 2.7*10^8 and 2.2*10^8 respectively, but still lower than one would expect given the conductivity of niobium at 4K. We were able to achieve critical coupling and drive some power into 4π/5 and 2π/5 modes. The Q-curves were measured and are shown in Figure 19.

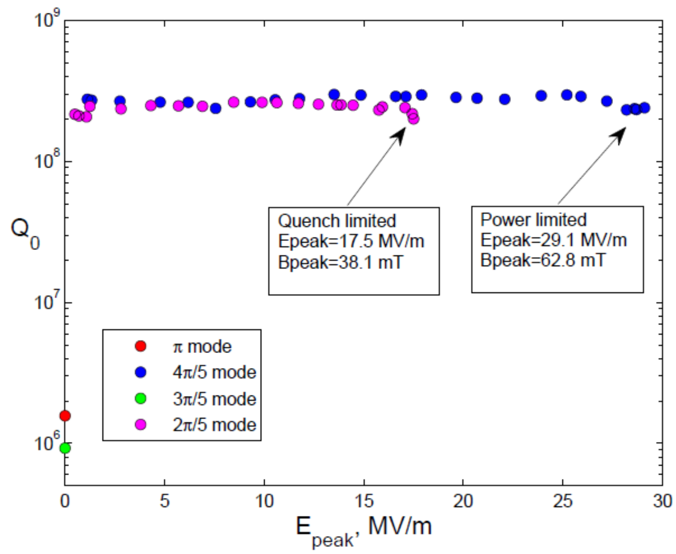


Figure 19: Q-factors for different modes in the 5-cell 2.1 GHz SRF cavity with the PBG cell as a function of the peak field on the surface of the cavity.

We noted that both the 4π/5 and 2π/5 modes had low fields in the PBG cell while both the π and 3π/5 modes had significant fields in the PBG cell. We suggested that the defect in the cavity which caused the reduction of Q-factors was located in the PBG cell. The cavity was shipped back to Niowave and taken apart. It was discovered that the low Q-factor was the result of the poor electrical contact of the niobium cover and the waveguide in the fundamental power coupler of the PBG cell. Niowave will have to modify their design of the gaskets in the fundamental power coupler and HOM couplers to achieve proper Q-factors for the cavity's modes.

The results of this work were reported at the Advanced Accelerator Concepts workshop in San Jose, CA in July of 2014 and then at the International Particle Accelerator Conference in May of 2015, which both the student and the PI attended. The paper is being prepared for submission to Physical Review Letters to report the results of the wakefield experiment at AWA.

The MIT graduate student relocated to Lansing, MI in March of 2015, where he will continue working on his PhD thesis in the framework of Niowave's SBIR Phase II project on a 5-cell SRF PBG accelerating module. Thesis defense is expected in December, 2015.

Relationship to other projects

The project on the design and testing of superconducting PBG accelerator cells came out to be very synergistic to other research activities conducted by the AOT-AE group at LANL and at other DOE laboratories. In particular, it grew up to be relevant and inter-dependent to the LANL's Navy Free Electron Laser (FEL) project. The ability of PBG resonators to reduce and even completely eliminate HOMs in accelerators is very beneficial for superconducting electron accelerators for high power FELs, which are intended to provide high current continuous duty electron beams. Using PBG structures to reduce the prominent beam-breakup phenomena due to

HOMs will allow significantly increased beam-breakup thresholds, and consequently will allow the increase of the frequency of SRF accelerators and the development of novel compact high-current accelerator modules for FELs. Increasing brightness and reducing the footprint of future FELs will directly benefit the research programs for the Office of Naval Research. The DOD High Energy Lasers Joint Technology Office funded a synergistic project at AOT-AE to improve the high gradient performance of SRF PBG resonators at 2.1 GHz. Two new SRF PBG resonators were tested at LANL in FY13, and the maximum demonstrated accelerating gradient was 18.3 MV/m. The 5-cell 2.1 GHz SRF accelerating module has recently found another application as a possible 5th harmonic linearizing cavity for eRHIC. The PBG coupler in the proposed structure is highly effective for suppression of HOMs in the linearizing cavity excited by a very high current beam in eRHIC. A DOE SBIR Phase II project was awarded to Niowave to build and test a niobium prototype of the linearizing cavity.

Presentations:

1. Evgenya I. Simakov, Sergey A. Arsenyev, Cynthia E. Buechler, Randall Edwards, William Romero, Manoel Conde, Gwanhui Ha, John Power, Eric Wisniewski, and Chunguan Jing, *Experimental Study of Wakefields in an X-band Photonic Band Gap Accelerating Structure,* 2015th International Particle Accelerator Conference (IPAC’15), Richmond, VA, May 3-8, 2015 (poster).
2. S. Arsenyev, W.B. Haynes. D. Shchegolkov, E. Simakov, T. Tajima, C.H. Boulware, T.L. Grimm, and A.R. Rogacki, *High Gradient Testing of the Five-Cell Superconducting RF Module with a PBG Coupling Cell,* 2015th International Particle Accelerator Conference, Richmond (IPAC’15), VA, May 3-8, 2015 (poster).
3. S. Arsenyev, D. Shchegolkov, E. Simakov, C.H. Boulware, T.L. Grimm, and A.R. Rogacki, *Five-Cell Superconducting RF Module with a PBG Coupling Cell: Design and Cold Testing of the Copper Prototype,* 2015th International Particle Accelerator Conference (IPAC’15), Richmond, VA, May 3-8, 2015 (poster).
4. Evgenya I. Simakov, Sergey A. Arsenyev, Cynthia E. Buechler, Randall Edwards, and William Romero, *Experimental Study of Wakefields in an X-band Photonic Band Gap Accelerating Structure,* 16th Advanced Accelerator Concepts Workshop (AAC 2014), San Jose, CA, July 13-18, 2014 (oral).
5. Sergey Arsenyev and Evgenya Simakov, *PBG Resonators for Effective HOM Suppression in SRF Accelerators,* 16th Advanced Accelerator Concepts Workshop (AAC 2014), San Jose, CA, July 13-18, 2014 (poster).
6. Evgenya I. Simakov, Sergey A. Arsenyev, W. Brian Haynes, Sergey S. Kurennoy, Dmitry Yu. Shchegolkov, Natalya A. Suvorova, Tsuyoshi Tajima, Chase H. Boulware, and Terry L. Grimm, *Superconducting photonic band gap structures for high current applications,* 16th International Conference on RF superconductivity, Paris, France, September 22-27, 2013 **(Invited oral)**.
7. Sergey Arsenyev and Evgenya I. Simakov, *Update on the Design of a Five-Cell Superconducting RF Module with a PBG Coupler Cell*, 2013 North American Particle Accelerator Conference, Pasadena, CA, September 29 – October 4th, 2013 (poster).
8. Evgenya I. Simakov, Randall L. Edwards, Samuel Elson, Cynthia Heath, David Lizon, William Romero, and Sergey Arsenyev, *Update on Fabrication and Tuning of the Photonic Band Gap Accelerating Structure for the Wakefield Experiment*, 2013 North American Particle Accelerator Conference, Pasadena, CA, September 29 – October 4th, 2013 (poster).

9. Evgenya I. Simakov, W. Brian Haynes, Mike A. Madrid, Frank P. Romero, Tsuyoshi Tajima, Walter Tuzel, Charles H. Boulware, Terry Grimm, *An Update on a Superconducting Photonic Band Gap Structure Resonator Experiment*, the 2012 International Particle Accelerator Conference, New Orleans, LA, May 20-25th, 2012 (oral).
10. Evgenya I. Simakov, Randall L. Edwards, *Design of a Wakefield Experiment in a Traveling-wave Photonic Band Gap Accelerating Structure*, the 2012 International Particle Accelerator Conference, New Orleans, LA, May 20-25th, 2012 (poster).
11. Evgenya I. Simakov, W. Brian Haynes, Michael A. Madrid, Frank P. Romero, Tsuyoshi Tajima, and Walter M. Tuzel, *An Update on the DOE Early Career Project on Photonic Band Gap Accelerator Structure*, the 15th Advanced Accelerator Concepts Workshop, Austin, TX, June 10-15, 2012 (oral).
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1. Evgenya I. Simakov, Sergey A. Arsenyev, Cynthia E. Buechler, Randall Edwards, William Romero, Manoel Conde, Gwanhui Ha, John Power, Eric Wisniewski, and Chunguan Jing, *Experimental Study of Wakefields in an X-band Photonic Band Gap Accelerating Structure,* Proceedings of 2015 International Particle Accelerator Conference, Richmond, VA, May 3-8, 2015, p. WEPJE008.
2. S. Arsenyev, W.B. Haynes. D. Shchegolkov, E. Simakov, T. Tajima, C.H. Boulware, T.L. Grimm, and A.R. Rogacki, *High Gradient Testing of the Five-Cell Superconducting RF Module with a PBG Coupling Cell,* Proceedings of 2015 International Particle Accelerator Conference, Richmond, VA, May 3-8, 2015, p. WEPTY082.
3. S. Arsenyev, D. Shchegolkov, E. Simakov, C.H. Boulware, T.L. Grimm, and A.R. Rogacki, *Five-Cell Superconducting RF Module with a PBG Coupling Cell: Design and Cold Testing of the Copper Prototype,* Proceedings of 2015 International Particle Accelerator Conference, Richmond, VA, May 3-8, 2015, p. WEPTY083.
4. Evgenya I. Simakov, Sergey A. Arsenyev, Cynthia E. Buechler, Randall Edwards, and William Romero, *Experimental Study of Wakefields in an X-band Photonic Band Gap Accelerating Structure,* to appear in AIP Conference Proceedings, 2015.
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6. Sergey Arsenyev and Evgenya I. Simakov, *Update on the Design of a Five-Cell Superconducting RF Module with a PBG Coupler Cell*, Proceedings of 2013 North American Particle Accelerator Conference, Pasadena, CA, September 29 – October 4th, 2013, p. WEPAC34.

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8. Evgenya I. Simakov, Sergey A. Arsenyev, W. Brian Haynes, Sergey S. Kurennoy, Dmitry Yu. Shchegolkov, Natalya A. Suvorova, Tsuyoshi Tajima, Chase H. Boulware, and Terry L. Grimm, *Superconducting photonic band gap structures for high current applications,* Proceedings of the 16th International Conference on RF superconductivity, Paris, France, September 22-27, 2013, p. THIOC03.
9. E.I. Simakov, W.B. Haynes, M.A. Madrid, F.P. Romero, T.Tajima, W.M. Tuzel, C.H. Boulware, and T.L. Grimm, Phys. Rev. Lett. 109, 164801 (2012).
10. Evgenya I. Simakov, W. Brian Haynes, Mike A. Madrid, Frank P. Romero, Tsuyoshi Tajima, Walter Tuzel, Charles H. Boulware, Terry Grimm, *An Update on a Superconducting Photonic Band Gap Structure Resonator Experiment*, Proceedings of 2012 International Particle Accelerator Conference, New Orleans, LA, May 20-25th, WEOAB03 (2012).
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13. Evgenya I. Simakov, Chase H. Boulware, Terry L. Grimm, *Design of a Superconducting Photonic Band Gap Structure Cell,* Proceedings of the 2011 Particle Accelerator Conference, New York, NY, March 28th – April 1st, MOP042 (2011).

Cost and schedule information

The project was completed on cost and on schedule. The single-cell SRF PBG resonators were tested ahead of schedule. The AWA test was completed on-schedule. The five cell SRF PBG resonator was tested on schedule, however the test was unsuccessful. The PI spent 60 per cent of her time and effort on the project, which is in agreement with the revised budget, submitted to DOE in April of 2010. Most of the cost charged to the project was the direct time and effort of the PI with a little money spent for the time and effort of a mechanical engineer and technologists who are helping with tuning of the 11.7 GHz cells, and an R&D scientist who helped with SRF tests. About $100K was spent to order a cryostat to upgrade the cryogenic laboratory; $98K were spent to procure two SRF PBG cavities from Niowave; $30K was spent for other materials and supplies in preparation for the high gradient testing of SRF cavities (mostly sent to local machine shops); $30K was spent for cryogens during SRF testing in Year 2 and $50K in Year 5; $80K was spent for fabrication of 11.7 GHz cells and other hardware for the wakefield experiment; $290K was sent to MIT to support the graduate student for three years and 7 months; approximately $100K was paid in maintenance fees for the CST Microwave Studio and HFSS for 5 years; $38K total was sent to Euclid Techlabs for several contracts to pay for fabrication of the loads and diagnostics for the wakefield experiment at AWA; $92K was sent to Niowave for fabrication of the copper prototype of the 2.1 GHz 5-cell accelerating structure.

List of people who worked on the project

Evgenya Simakov, the PI (0.60 FTE).

Sergey Arsenyev, graduate student, MIT (1.00 FTE).
Cynthia Heath, mechanical engineer (0.10 FTE in FY13-FY14).
Samuel Elson, undergraduate student (full time during summer break).
Randall Edwards, mechanical technologist (occasional help).
Brian Haynes, electrical engineer (occasional help).
William Romero, mechanical technologist (occasional help).
Dmitry Shchegolkov, physicist II (0.10 FTE in FY 15).
Tsuyoshi Tajima, physicist IV (occasional help in FY15).