SUPERCONDUCTING PHOTONIC BAND GAP STRUCTURES FOR HIGH-CURRENT APPLICATIONS*

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Abstract

We report the results of recent design and testing of several 2.1 GHz superconducting radio-frequency (SRF) photonic band gap (PBG) resonators. PBG cells have great potential for outcoupling long-range wakefields in SRF accelerator structures without affecting the fundamental accelerating mode. Here we describe the results of our efforts to fabricate 2.1 GHz PBG cells with round and elliptical rods and to test them with high power at liquid helium temperatures. Two PBG cells with round rods were tested in spring of 2012 and achieved accelerating gradients of 15 MV/m at 2 Kelvin. Two PBG cells with elliptical rods were tested in summer of 2013 and achieved higher accelerating gradients of 18.3 MV/m at 2 Kelvin.

INTRODUCTION

Superconducting radio frequency (SRF) cavities are the natural choice for the future generation of high-duty-factor accelerators for the high power free-electron lasers (FELs) where the heat produced in the accelerating structure cannot be effectively extracted [1]. Going to higher frequencies in SRF accelerators will save on RF and cooling power as well as provide a more compact and lower cost accelerating structure. Operating at high frequency and low bunch charge reduces the risks of brightness degradation in electron beam transport. However, extremely low RF losses in SRF cavities become a disadvantage with respect to excitation of higher order mode (HOM) wakefields in the linac which oscillate almost indefinitely and interact with the accelerated beam causing instabilities, energy spread and additional cryogenic losses.

Photonic Band Gap [2] (PBG) cavities have the unique potential to filter out all HOM power and reduce the wakefields. A PBG structure or simply, photonic crystal, represents a periodic lattice of macroscopic components (e.g., rods), metallic, dielectric or both. For accelerator applications, two-dimensional PBG resonators made as an array of metal rods are frequently employed. For certain dimensions of the array, a defect in the structure (a missing rod) forms a mode-selective PBG resonator cavity [3]. This resonator is capable of supporting the accelerating mode and not supporting any higher order modes which then propagate towards the peripheries of the cavity and get filtered out with waveguides.

The first ever demonstration of acceleration in a PBG resonator was conducted at Massachusetts Institute of Technology (MIT) in 2005 [4]. Since then, the importance of PBG structures for accelerators has been recognized by many research institutions worldwide. In the experiment reported in [4], the 6-cell open copper PBG structure was employed to construct a room-temperature travelling-wave accelerator at 17.137 GHz with inherit ability to filter out wakefields.

The idea that PBG cells will greatly benefit higher-frequency superconducting electron accelerators by greatly reducing the wakefields was first expressed by the authors of [5], who fabricated and cold-tested the first ever superconducting PBG cell at 11 GHz. We are also aware of another successful attempt to fabricate superconducting PBG resonators at 6 GHz and 16 GHz [6]. However, the authors of [5,6] have only completed the low power tests, and therefore never proved that their designs and fabrication procedures were able to withstand high power. In addition, those first superconducting PBG resonators still represented open structures with removed outer wall and liquid helium flowing through the pipes connected to hollow rods of the PBG structure. The number of PBG hollow rods was limited to 3 rows of rods in [5] and four rows of rods in [6]. As a result, the unloaded Q-values of the cavities were dominated by diffraction losses and ohmic losses could not be measured accurately.

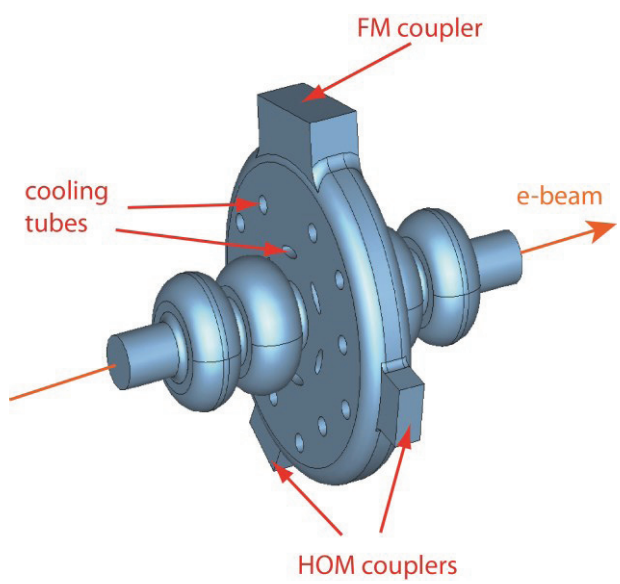

Figure 1: Conceptual drawing of an SRF accelerator section incorporating a PBG cell with HOM couplers.

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We realized that SRF PBG resonators should not be employed as open single-mode accelerating structures but rather serve as an effective way to incorporate HOM couplers, and also, the fundamental mode coupler as a part of the accelerating structure [7] (Figure 1). One PBG resonator with waveguide couplers attached to its outside wall may replace one of the regular elliptical accelerating cells in an accelerating module. Since substantial accelerating gradients could be maintained inside of a PBG resonator incorporating HOM waveguides, placing HOM waveguides in a PBG cell may greatly increase the overall real estate gradient as compared to the real estate gradient in a module with HOM couplers located in the beam pipes.

We have initiated a project at Los Alamos National Laboratory (LANL) to evaluate the high gradient performance of the SRF PBG resonators and demonstrate the applicability of the PBG resonator technology to SRF accelerators.

2.1 GHz SRF PBG RESONATORS: DESIGN AND FABRICATION

Several 2.1 GHz SRF PBG resonators were designed at LANL. The structures were designed with the 18 straight niobium rods sandwiched in between two niobium plates and enclosed by a niobium outside wall. The beam pipe had the inner diameter of 1.25 inches and blended edges. The design was performed with the CST Microwave Studio [8] and later verified with the HFSS [9]. First two cells were designed with 18 round cylindrical rods. The dimensions of those cells are listed in Table 1. The table also lists other characteristics of the designed cell. It can be seen from the table that the breakdown due to high maximum magnetic fields is going to be the most critical limit to the high gradient performance of the designed cell. The maximum surface electric field in the PBG cell is reached on the blended edge of the beam pipe, as expected. However, the maximum surface magnetic field does not occur on the side wall of the cavity as in the case of a simple elliptical cavity. Instead, the maximum is reached on the rods of the PBG structure [7].

Table 1: Dimensions and Accelerator Characteristics of the 2.1 GHz SRF PBG Accelerator Cell with Round Rods

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	71.43 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)

We then tried to improve the performance of the resonator with regular cylindrical rods and push its gradient limitations by investigating different strategies for reducing the peak surface magnetic field. The initial idea was to bend the inner rods of the PBG resonator in a manner mimicking an elliptical SRF cavity, where the high magnetic field is pushed away from the surface. However, bending the rods of the PBG structure did not produce the same effect. Next, we followed the idea of [10] and changed the shapes of the 6 inner rods of the PBG resonator from cylindrical to elliptical (Figure 2). This produced the desirable effect reducing the surface fields up to 40 per cent depending on the major radius of the elliptical rods (Figure 3). We varied the dimension for the minor radii of elliptical rods until the peak magnetic fields were minimized for each major radius.

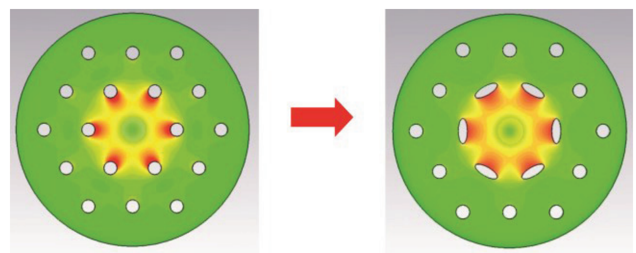

Figure 2: In order to reduce the surface magnetic field the shape of the inner row of rods in the PBG structure was changed from the round cylinders to elliptical cylinders.

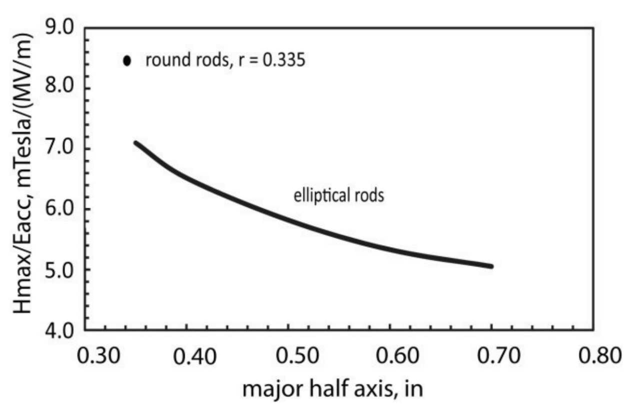

Figure 3: Peak magnetic fields on the surface of the 2.1 GHz PBG resonator as a function of the major half-axis of the elliptical rods.

Using the time domain solver we analyzed the confinement of HOMs and the fundamental mode in a PBG resonator with elliptical rods. We discovered that if the periodicity of the PBG structure is broken and the elliptical rods are moved slightly toward the center of the resonator, then the fundamental mode in this structure becomes better confined than in the structure with round rods. At the same time HOMs in this structure are confined worse and can be extracted more efficiently than in the structure with round rods [11]. The

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dimensions and the accelerator characteristics of the structure with the shifted elliptical rods are summarized in Table 2.

Table 2: Dimensions and Accelerator Characteristics of the 2.1 GHz SRF PBG Accelerator Cell with Elliptical Rods

Spacing between the rods, p	56.57 mm
OD of the rods, d	17.04 mm = 0.3*p
Shift of elliptical rods, Δp	0.89 mm
Major OD of the elliptical rod, a	24.94 mm = 0.5*p
Minor OD of the elliptical rod, b	9.80 mm
ID of the equator, D0	300 mm
Length of the cell, L	71.43 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)	$1.8*10^8$
Q_0 (2K)	$6.2*10^9$
R/Q	150.7 Ohm
E_{peak}/E_{acc}	2.37
B_{peak}/E_{acc}	5.66 mT/(MV/m)

Figure 4: Photograph of the 2.1 GHz PBG cell with round rods during manufacturing stage.

The resonators with round rods and with elliptical rods were fabricated by Niowave, Inc from a combination of stamped sheet metal niobium with the residual resistance ratio RRR>250 and machined ingot niobium components with RRR>220. After the electron beam welding, a buffered chemical polish etch was performed to prepare the RF surface for testing. The temperature of the acid was carefully monitored during the etching. A photograph of a resonator with round rods during the fabrication stage is shown in Figure 4. The photograph of resonators with elliptical rods right after fabrication is shown in Figure 5.

HIGH GRADIENT TESTING OF THE 2.1 GHz SRF PBG RESONATORS

Figure 5: Photograph of the 2.1 GHz PBG cavities with elliptical rods ready to be tested.

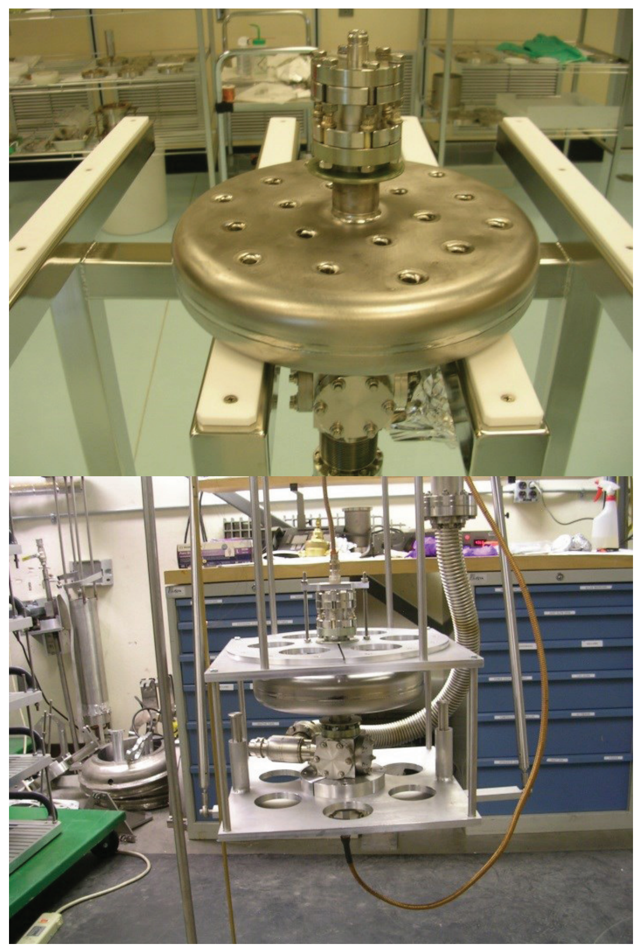


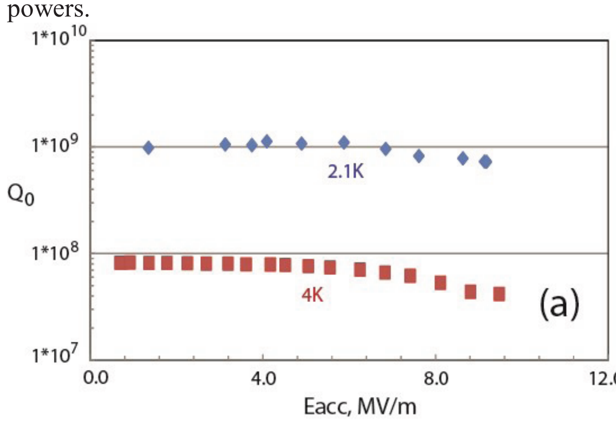
Figure 6: The 2.1 GHz PBG cell with round rods assembled with the couplers in the clean room (top) and installed on the vertical test stand before lowering into the cryostat (bottom).

The resonators underwent high gradient testing at LANL. Resonators with round rods were tested in Spring of 2012, and resonators with elliptical rods were tested in

Summer of 2013. Each cavity delivered from Niowave was opened in a class 100 clean room and a pickup coupler flange and a movable bellow with a matched input power coupler were attached at the ends of the beam pipes. The cavity was then sealed and taken out of the clean room, set on the vertical cryostat insert, pumped down and leak checked (Figure 6).

The cavity was then moved into a vertical cryostat of 965 mm in diameter and 3048 mm in depth. The cavity was actively pumped down all the time with a 30 L/s ion pump attached on the cryostat lid. The atmospheric pressure at Los Alamos is about 600 Torr which corresponds to ~4 K LHe boiling temperature. A 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.

At the start of each test we adjusted the moveable coupler to a slightly over-coupled position, the decay time of the reflected power was measured in a pulsed mode at a low field. The unloaded Q (Q_0) and coupling Q's of input and pickup couplers were calculated from this pulsed-mode measurements. Next, the $Q_0 - E_{acc}$ sweep data was obtained in a CW regime for different drive powers and the gradient and the external Q-factors were computed from measured drive, reflected and transmitted powers.



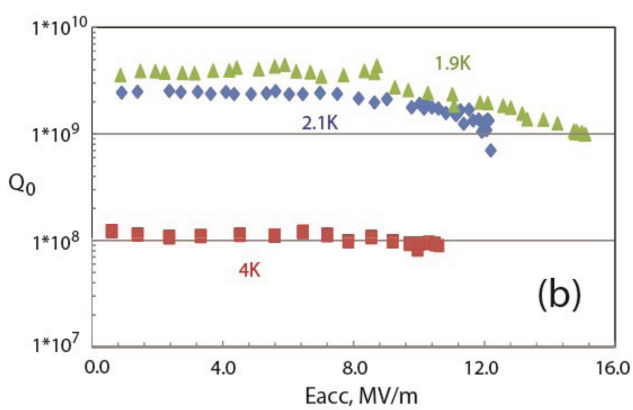


Figure 7: Unloaded Q (Q_0) as a function of accelerating gradient (E_{acc}) of the 2.1 GHz SRF PBG cavities with round rods: (a) cavity #1 tested in March of 2012, and (b) cavity #2 tested in April of 2012.

Table 3: Measured Performance of two 2.1 GHz SRF PBG Resonators with Round Rods 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

Figure 7 shows the $Q_0 - E_{acc}$ curves at 4 K and 2 K for the two cavities with round rods. Table 3 summarizes the test results including frequencies, Q-factors, and maximum achieved gradients. 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.

Figure 8 shows the $Q_0 - E_{acc}$ curves at 4 K and 2 K for the two cavities with elliptical rods. Table 4 summarizes the test results. The cavities had somewhat longer beam pipes than the cavities with round rods, and therefore Cavity #3 turned out to be undercoupled at 4 K even when the co-axial coupler was moved fully inwards. As a result, the 4 K measurements of this cavity were quite inaccurate. In addition, the magnetic field compensating coil was not turned on before the cool down, which explains the lower Q-values measured during the 2 K test. The cavity, however, performed excellent at 2 K and withstood a high 18.3 MV/m accelerating gradient. Cavity #4 was tested with a longer co-axial coupler probe. It performed excellent at 4 Kelvin and went up to 18.2 MV/m accelerating gradient and demonstrated high unloaded Qs. However, we observed a significant frequency shift in this cavity (300 kHz up vs. 30 kHz up in other three PBG cavities) when going from 4 Kelvin down to 2 Kelvin. Then during the testing at 2 K we observed a very strong Q-slope which was possibly due to field emission from a defect. The cavity quenched at 15.3 MV/m at 2 K.

Overall, the measurements totally confirmed the predicted improvement in the gradient performance of the cavities with elliptical rods as compared to the cavities with round rods.

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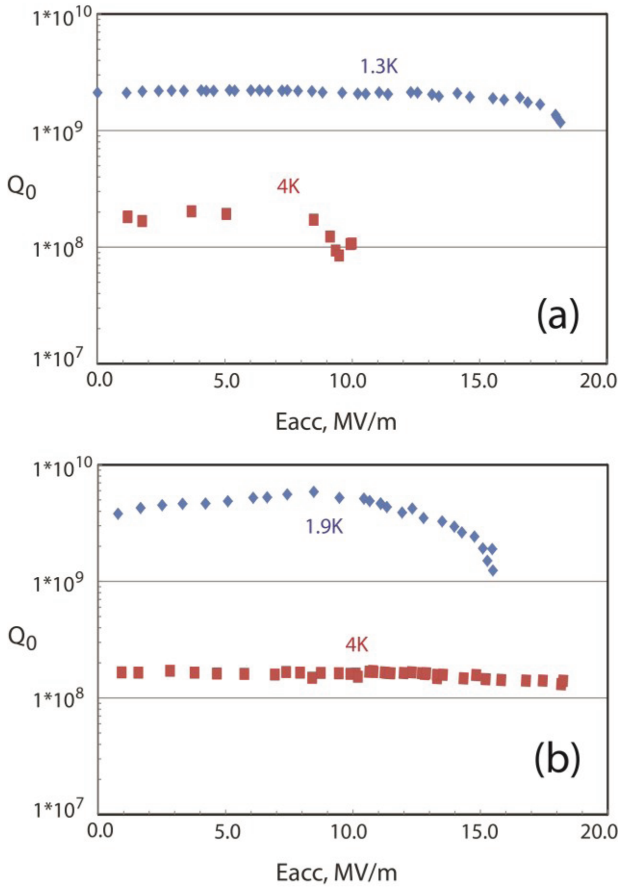

Figure 8: Unloaded Q (Q_0) as a function of accelerating gradient (E_{acc}) of the 2.1 GHz SRF PBG cavities with elliptical rods: (a) cavity #3 tested in July of 2013, and (b) cavity #4 tested in August of 2013.

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

	Theory	Cavity #3	Cavity #4
Frequency	2.100 GHz	2.11524 GHz	2.11292 GHz
Q_0 (4K)	$1.8*10^8$	$1.6*10^8$	$1.6*10^8$
Q_0 (2K)	$6.2*10^9$	$2.2*10^9$	$3.9*10^9$
Maximum E_{acc} (4K)		10.0 MV/m	18.2 MV/m
Maximum E_{acc} (2K)		18.3 MV/m	15.3 MV/m
B_{peak} (4K)		57 mT	103 mT
B_{peak} (2K)		104 mT	87 mT

CONCLUSION AND FUTURE PLANS

We have demonstrated the proof-of-principle fabrication and high gradient operation of superconducting photonic band gap cavities at 2.1 GHz. Four cavities were tested at both 4 K and 2 K and performed quite well, demonstrating accelerating gradients as high as 18.3 MV/m. The two cavities with elliptical rods on average have performed 30 per cent better than the cavities with round rods. This is in perfect agreement with theoretical predictions.

To continue research on applications of PBG cavities for reducing wakefields in SRF accelerators, we designed a five-cell PBG accelerator section which includes a PBG cell with a fundamental and higher order mode couplers attached to its outside wall [12]. The copper prototype will be fabricated and tested in the near future. We expect the Q-factors of all major HOMs not to exceed 10^3 in a five-cell structure with three waveguide couplers attached to the PBG cell.

We believe that the PBG technology will provide means for SRF accelerators to move to higher frequencies, significantly reduce the size of SRF accelerators and allow increasing the brightness of the electron beam transport.

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