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Evgenya I. Simakov, W. Brian Haynes, Michael A. Madrid, Frank P. Romero, Tsuyoshi Tajima, Walter M. Tuzel, Chase H. Boulware, and Terry L. Grimm

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First High Power Test Results for 2.1 GHz Superconducting Photonic Band Gap Accelerator Cavities

Evgenya I. Simakov,* W. Brian Haynes, Michael A. Madrid, Frank P. Romero, Tsuyoshi Tajima, and Walter M. Tuzel
Los Alamos National Labroatory,
PO Box 1663, Los Alamos, NM 87545, USA

Chase H. Boulware and Terry L. Grimm
Niowave, Inc.,
1012 North Walnut Street, Lansing, MI 48906, USA

We report the results of the recent high power testing of superconducting radio frequency photonic band gap (SRF PBG) accelerator cells. Tests of the two single-cell 2.1 GHz cavities were performed at both 4 Kelvin and 2 Kelvin. An accelerating gradient of 15 MV/m and an unloaded quality factor Q_0 of $4 * 10^9$ were achieved. It has been long realized that PBG structures have great potential in reducing long-range wakefields in accelerators. A photonic band gap structure confines the fundamental TM_{01}-like accelerating mode, but does not support higher order modes (HOMs). Employing PBG cavities to filter out HOMs in superconducting particle accelerators will allow suppression of dangerous beam instabilities caused by wakefields and thus operation at higher frequencies and significantly higher beam luminosities. This may lead towards a completely new generation of colliders for high energy physics and energy recovery linacs for the free-electron lasers.

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Future high energy accelerators are destined to give physicists a new doorway to explore energy regimes into the TeV range and deliver the missing pieces of the puzzle of the origin of mass and probe the theory of extra dimensions [1, 2]. Challenging, sometimes revolutionary technologies are required. The International Technology Recommendation Panel (ITRP) chose the superconducting radio frequency (SRF) cavities for construction of the main linac for the International Linear Collider [2, 3]. SRF cavities are also the natural choice for the future generation of high average current or high duty factor machines (such as energy recovery linacs for future free-electron lasers (FELs)) where the heat produced in the accelerating structure cannot be effectively extracted. Going to higher frequencies in SRF accelerators might be able to save on power as well as provide a more compact and lower cost accelerating structure. However, the beam breakup threshold due to higher order mode (HOM) wakefields in the main linac scales inversely proportional to frequency squared [4]. The HOMs can greatly reduce luminosity, increase emittance and strongly affect interaction of the beams at the collision point [5]. Studies of the beam breakup mechanisms and the efficient methods for the higher order mode suppression have become a critical area of research for the future high duty factor and high current SRF accelerators (including energy recovery linacs) for linear colliders [6] and free-electron lasers [7, 8]. Photonic Band Gap (PBG) [9] cavities have the unique potential to absorb all HOM power and greatly reduce the wakefields. The research that is reported here demonstrates the high power operation of a novel, superconducting rf acceleration structure which can mitigate the problem of dangerous wakefield radiation. Until now, the gradient limitations of SRF PBG cavities have not been experimentally tested. We report the successful fabrication, cleaning and operation up to an accelerating gradient of 15 MV/m of two single-cell 2.1 GHz SRF PBG cavities.

The first fabrication and testing of PBG resonators for accelerator applications dates back to more than a decade ago [10, 11]. The first ever demonstration of acceleration in a PBG resonator was conducted at Massachusetts Institute of Technology (MIT) in 2005 [12, 13]. Since then, the importance of PBG structures for accelerators has been recognized by many research institutions worldwide [14–18]. The idea that PBG cells will benefit higher-frequency superconducting electron accelerators by greatly reducing the wakefields was first expressed by the authors of [11], who fabricated and cold-tested the superconducting PBG cell at 11 GHz. Another successful attempt to fabricate superconducting PBG cells was reported at 6 GHz and 16 GHz [14]. However, the resonators described in [11, 14] were only tested at low power, and were never subject to high power testing which revealed the gradient limitations. In addition, these resonators were designed as open structures resulting in diffraction losses being dominant over the ohmic loss and reducing the overall Q-factors of the resonators by orders of magnitude.

We realized that the fundamental difference must exist between the designs of an SRF PBG resonator and a room-temperature resonator [19]. Unlike its copper predecessor, the SRF resonator cannot be designed as an open structure for two reasons. First, the SRF resonator must be lowered into a cryostat or incorporated in a cryomodule 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-factor, which is determined by the losses due to the accelerating mode leaking out of the periodic structure. In resonators which were previously designed for the experiment at MIT [12, 13], the Q-factor which is due to diffraction was of the order of 10^5, which was almost two orders of magnitude larger than the ohmic Q-factor of the structure, determined by the ohmic losses in copper. However, since the ohmic losses in superconducting niobium are very low, the diffraction Q-factor of the superconducting PBG resonator must be orders of magnitude larger than 10^{10}, which is a typical ohmic Q of the superconducting resonators. The diffraction Q-factors 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. Having said above, 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 also, the fundamental mode (FM) coupler as a part of the accelerating structure. Placing the fundamental mode coupler in a PBG structure may also become an effective way to mitigate the so-called coupler-kick [8, 20], since the PBG structure shields the field asymmetries which are introduced by the couplers [21].

A conceptual drawing of a PBG cell incorporated as a part of an SRF accelerator section is shown in Figure 1. The accelerator section consists of four regular high-gradient accelerating elliptical cells and one PBG cell with the two rows of small diameter niobium tubes (different from the room-temperature case when the tubes are replaced with solid rods). The PBG cell also accelerates electrons similar to the elliptical cells, although at somewhat lower gradient and in addition, it includes the FM coupler and HOM couplers. Two HOM couplers in the form WR-229 waveguides are located at the enclosing wall of the PBG cell and reduce the Q-factors of the lowest HOMs (including the dipole mode). The cut-off frequency of the WR-229 waveguides is above 2.1 GHz, so the Q-factor of the fundamental mode is not affected by those couplers. The shape and the symmetry of the fundamental mode is preserved in the presence of HOM couplers because it is well screened by the PBG structure. One bigger WR-430 waveguide connected to the PBG cell represents the fundamental mode coupler and may also serve as an additional HOM coupler. This coupler setup

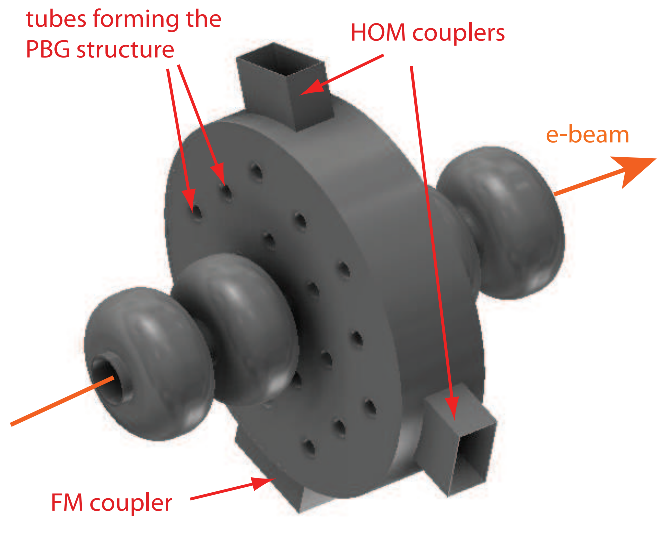

FIG. 1. A conceptual drawing of an SRF accelerator section incorporating a PBG cell that has fundamental mode and higher order mode couplers with elliptical higher-gradient accelerating cells.

TABLE I. The 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 rods (cooling channel), d_{in}	8.8 mm
ID of the equator, $D0$	300 mm
Thickness of Nb end walls, t_{wall}	2.8 mm
Length of the cell, L	71.43 mm $= \lambda/2$
ID of the beam pipe, R_b	31.75 mm = 1.25 inches
Radius of the beam pipe blend, r_b	6.4 mm = 0.25 inches
Frequency (TM_{01} mode)	2.100 GHz
Geometry factor, G	179.3 Ohm
Ohmic Q-factor at 4K, $Q_0(4K)$	$1.5 * 10^8$
Ohmic Q-factor at 2K, $Q_0(2K)$	$5.8 * 10^9$
Shunt impedance, R/Q_0	145.77 Ohm
E_{peak}/E_{acc}	2.22
B_{peak}/E_{acc}	8.55 mT/(MV/m)

closely resembles the setups of couplers conventionally placed in beam pipes (so-called "end groups") [22, 23]. However, unlike the end groups, the new PBG-based couplers are located within the accelerating structure and by these means greatly increase the real estate gradient, resulting in the decreased length and cost of the future accelerators based on SRF technology.

The design of a single-cell 2.1 GHz SRF PBG resonator was performed with a CST Microwave Studio [24] and verified with HFSS [25]. The structure was designed with 18 straight niobium tubes 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 dimensions of the cell are sum-

TABLE II. Comparison between the frequencies and peak surface fields in the 2.1 GHz SRF PBG resonator derived from different electromagnetic solvers.

Solver	Frequency, GHz	E_{peak}/E_{acc}	B_{peak}/E_{acc}, mT/(MV/m)
CST studio, hexahedral mesh	2.100	2.32	8.65
CST studio, tetrahedral mesh	2.100	2.16	8.44
HFSS	2.099	2.22	8.55

marized in Table I. The table also lists the other characteristics of the designed cell. It can be seen from the table that the breakdown due to high maximum magnetic fields (quench) 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 inner side of the first row of tubes of the PBG structure. Accurate computation of the peak surface magnetic field is important for predicting the high gradient performance of the resonator. Table II lists the ratios of E_{peak}/E_{acc} and B_{peak}/E_{acc} computed with two different solvers of the CST Microwave Studio and the HFSS, which employed different meshes resulting in different surface approximation of the structure. Great care was taken to ensure the best agreement between the solvers. It can be seen from the table that with the densest meshes the three solvers agree within 7 per cent in peak electric fields and within 2 per cent in the estimates of peak magnetic field, which is the most crucial for the resonator's performance.

The resonators 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 one resonator during the fabrication stage and after fabrication is shown in Figure 2. The matched coaxial couplers were designed to be placed in the beam pipe for the high power tests.

The resonators underwent high power testing at LANL. Each cavity delivered from Niowave was opened in a class 100 clean room and a pickup coupler flange and a flange with a matched moveable power coupler were attached at the ends of the beam pipes. No high-pressure rinsing using ultra-pure water was carried out due to facility maintenance. The cavity was sealed and taken out

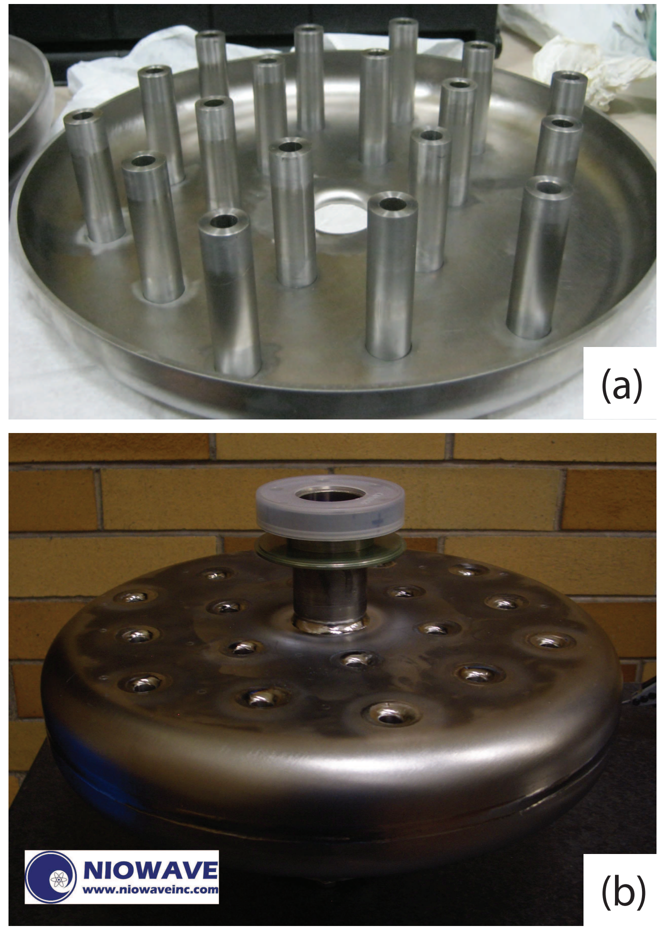

FIG. 2. (a) Photograph of the components for the 2.1 GHz PBG cell fit prior to the electron beam welding. (b) Photograph of the final fabricated 2.1 GHz SRF PBG cell.

of the clean room, set on the vertical cryostat insert, pumped down and leak checked. 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 as 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.

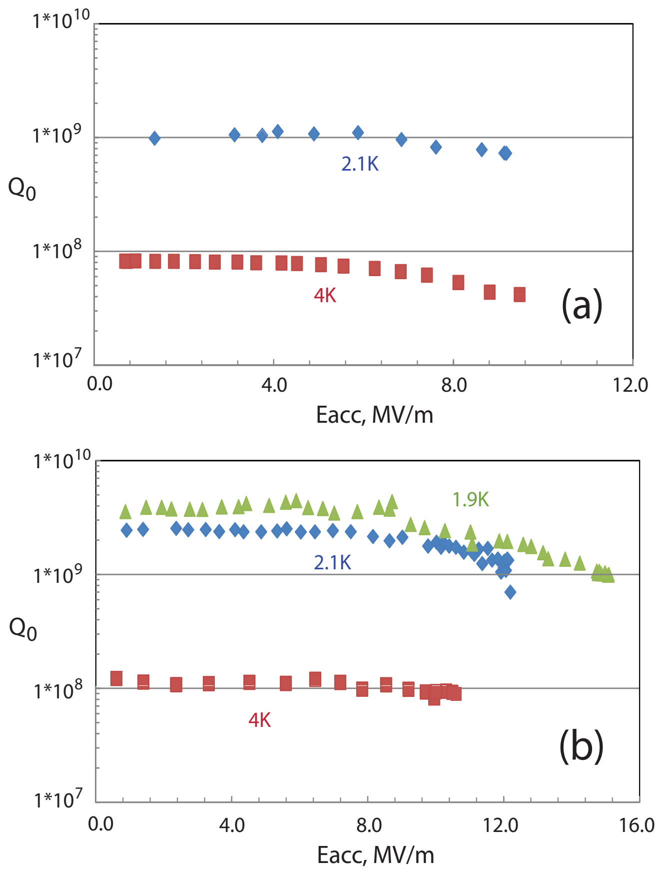

FIG. 3. Unloaded Q (Q_0) as a function of accelerating gradient E_{acc} for the 2.1 GHz SRF PBG cavities: (a) Cavity 1 tested on 03/30/12; and (b) Cavity 2 tested on 4/27/12.

Figure 3 shows the $Q_0 - E_{acc}$ curves at 4 K and 2 K for the two cavities. Table III summarizes the test results including frequencies, Q-factors, and maximum achieved gradients and peak surface magnetic fields. 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 4 K. Also, during the 2 K 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 cavity underwent testing and some RF processing at 2.1 K on the first day and then was pumped overnight. The achieved accelerating gradients on the second day at 1.9 K were as high as 15 MV/m, limited by the magnetic quench at the peak magnetic field of about 130 mTesla. This result confirms the design of the resonators and the expected quench limit of 10-20 MV/m depending on the quality of the Niobium surface of the rods. During the tests of both cavities, no multipacting was observed which was confirmed by a biased probe.

In conclusion, we have demonstrated the proof-of-principle fabrication and high power operation of superconducting photonic band gap accelerator cavities at 2.1 GHz and tested them for achievable gradients. Two cavities were tested at both 4 K and 2 K and performed well demonstrating accelerating gradients as high as 15 MV/m which corresponds to the peak surface magnetic fields of approximately 130 mT. The the maximum achieved gradients and measured Q-factors were well in agreement with theoretical predictions. SRF PBG cavities may become a promising concept for placing efficient higher order mode couplers in future high duty factor and high current SRF accelerators (including energy recovery linacs) for linear colliders and FELs. The next step of this project is the design and testing of a 2.1 GHz SRF PBG accelerator section which includes a PBG cell with the fundamental coupler and higher order mode couplers. We also consider improvements to the design of the PBG resonator which may reduce the peak surface magnetic fields in the structure and increase the maximum achievable accelerating gradients [26].

TABLE III. Measured performance of two 2.1 GHz SRF PBG resonators and comparison with theory.

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

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* smirnova@lanl.gov

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