RESULTS OF THE NEW HIGH POWER TESTS OF SUPERCONDUCTING PHOTONIC BAND GAP STRUCTURE CELLS*

Evgenya I. Simakov#, Sergey A. Arsenyev, W. Brian Haynes, Sergey S. Kurennoy, David Lizon, James F. O'Hara, Eric F. Olivas, Dmitry Yu. Shchegolkov, Natalya A. Suvorova, and Tsuyoshi Tajima, Los Alamos National Laboratory, Los Alamos, NM 87545, U.S.A.
Chase H. Boulware, Terry L. Grimm, Niowave, Inc., Lansing, MI, 48906, U.S.A.

Abstract

We report the results of the recent 2.1 GHz superconducting rf (SRF) photonic band gap (PBG) resonator experiment in Los Alamos. The new SRF PBG cell was designed with the particular emphasis on changing the shape of PBG rods to reduce the peak magnetic fields and at the same time to preserve its effectiveness for suppression of the higher order modes (HOMs). The new PBG cells have great potential for outcoupling long-range wakefields in SRF accelerator structures without affecting the fundamental accelerating mode. Two 2.1 GHz PBG cells with elliptical rods were fabricated and tested with high power in a liquid helium bath at the temperature of 4 K and 2 K. The cells performed in accordance with simulation and the maximum achieved accelerating gradient was 18.3 MV/m.

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 must be effectively extracted [1]. Operating the accelerator at high frequency and low bunch charge reduces the risks of brightness degradation in electron beam transport. However, high frequencies become a disadvantage with respect to excitation of higher order mode (HOM) wakefields in the linac which get excited more easily and interact with the accelerated beam causing instabilities, energy spread and ultimately the beam breakup.

Photonic Band Gap [2] (PBG) cavities have the unique potential to filter out much of the HOM power and reduce the wakefields. A PBG resonator is capable of supporting the accelerating mode and not supporting any higher order modes which 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 [3]. Since then, the importance of PBG structures for accelerators has been recognized by many research institutions worldwide. In the experiment reported in [3], 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.

A project funded by the U.S. Department of Energy (DOE) Office of Science Early Career Research Program at Los Alamos National Laboratory has recently demonstrated fabrication and high power operation of single-cell SRF PBG resonators at 2.1 GHz [4]. Two resonators were fabricated in 2012 and demonstrated solid high gradient performance with the maximum achieved gradient of 15 MV/m limited by the magnetic quench.

We have initiated a project at LANL to push the high gradient limitations of the SRF PBG resonators and demonstrate the possibility of a resonator with significantly reduced peak surface magnetic field and still excellent performance with respect to filtering out higher order modes.

2.1 GHz SRF PBG RESONATORS WITH REDUCED SURFACE FIELDS

We have followed the idea of [5] and changed the shapes of the 6 inner rods of the PBG resonator from cylindrical to elliptical. This produced the desirable effect reducing the surface fields up to 40 per cent depending on the major radius of the elliptical rods [6]. The question however was if the new resonators with elliptical rods were as effective with respect to filtering out wakefields as resonators with round rods. To answer this question we used the time-domain solver of the CST Microwave Studio [7] and 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 [6].

The final dimensions and the accelerator characteristics of the structure with the shifted elliptical rods are summarized in Table 1. The cells were designed with 18 hollow cylindrical rods: 6 elliptical and 12 round. The maximum surface electric field in the PBG cell is reached on the blended edge of the beam pipe, as was in the case of the cavity with round cylindrical rods [4]. The maximum surface magnetic field is again reached on the rods of the PBG structure; however it is 40% lower than the maximum surface magnetic field in the cavity with round cylindrical rods operating at the same gradient.

* Work is supported by the Department of Defense High Energy Laser Joint Technology Office through the Office of Naval Research.
#smirnova@lanl.gov

Table 1: 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 round 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)

Two 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. The photograph of resonators right after fabrication is shown in Figure 1.

Figure 1: Photograph of the 2.1 GHz PBG cavities with elliptical rods ready to be tested.

HIGH GRADIENT TESTING OF THE 2.1 GHz SRF PBG RESONATORS

The resonators underwent high gradient testing at LANL 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 power input 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. The testing procedure was the same as described in [4].

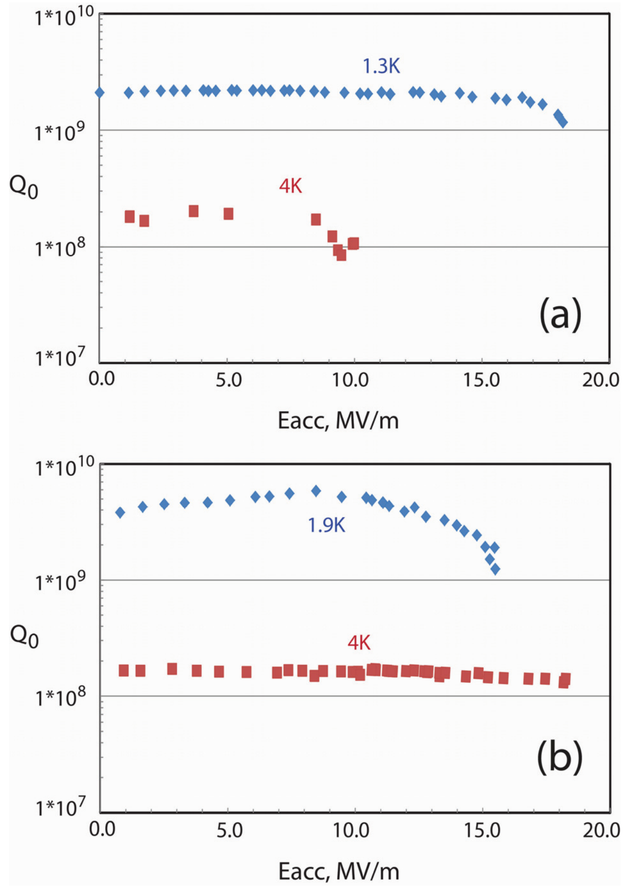

Figure 2: Unloaded Q (Q_0) as a function of accelerating gradient (E_{acc}) of the 2.1 GHz SRF PBG cavities with elliptical rods: (a) cavity #3 tested on 7/15/13, and (b) cavity #4 tested on 8/19/13.

Figure 2 shows the Q_0 – E_{acc} curves at 4 K and 2 K for the two cavities with elliptical rods. Table 2 summarizes the test results. The cavities had somewhat longer beam pipes than the cavities with round rods, and 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

ISBN 978-3-95450-138-0

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.

Table 2: 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

OBSERVATIONS OF THE FIRST SOUND GENERATED BY QUENCH

We have also attempted to put together a simplified quench diagnostics and installed 6 Buzzer Elements Piezo Benders 20 mm in diameter sensors, one next to each cooling hole of elliptical rods as shown in Figure 3. We observed ~10 kHz sound waves generated by quench at each road with the hope that the amplitude of the sound at each location could give us an indication of which of the six elliptical rods was experiencing quench.

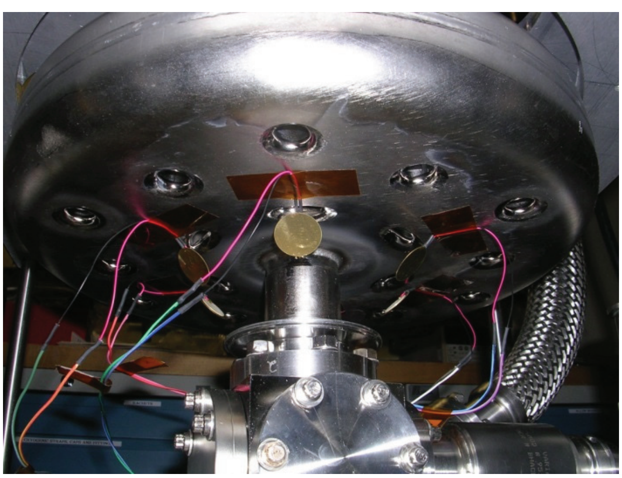

Figure 3: Piezoelectric sensors installed next to 6 hollow elliptical rods of the PBG structure.

The observed sound was similar in amplitude and timing at all six locations (Figure 4). This may suggest that quench occurred on the surface of the cavity outside of the rods, or that the sound mostly propagated through the metal body of the cavity instead of propagating through liquid helium. The detected sound traces looked very similar at both 4 K and 2 K.

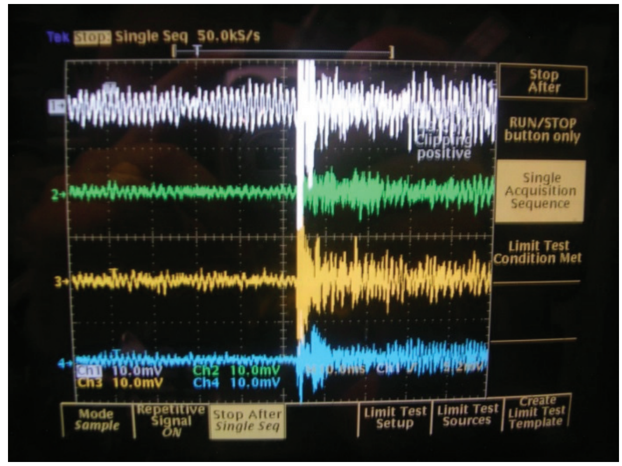

Figure 4: Sound traces from the piezoelectric sensors on an oscilloscope.

CONCLUSION

In summary, we have demonstrated the proof-of-principle fabrication and high gradient operation of superconducting photonic band gap cavities with elliptical rods. The cavities were tested at both 4K and 2K 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 tested earlier [4]. This is in perfect agreement with theoretical predictions. We believe that PBG technology will be successfully applied to design novel effective HOM couplers for high current SRF accelerators. As a result, it may significantly reduce the size the accelerators and allow increasing the brightness of the electron beam transport.

REFERENCES

[1] S. Belomestnykh, Reviews of Accelerator Science and Technology 5, p. 147 (2012).
[2] E. Yablonovitch. Phys. Rev. Lett., 258, p.2059 (1987).
[3] E.I. Smirnova, A.S. Kesar, I. Mastovsky, M.A. Shapiro, and R.J. Temkin, Phys. Rev. Lett. 95(7), p. 074801 (2005).
[4] 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, p.164801 (2012).
[5] B.J. Munroe, A.M. Cook, M.A. Shapiro, R.J. Temkin, V.A. Dolgashev, L.L. Laurent, J.R. Lewandowski, A.D. Yeremian, S.G. Tantawi, and R.A. Marsh, Phys. Rev. ST-AB 16, p. 012005 (2013).
[6] Evgenya I. Simakov, W. Brian Haynes, Sergey S. Kurennoy, James F. O'Hara, Eric F. Olivas, Dmitry Yu. Shchegolkov, Proceedings of the IPAC 2012, p. WEPPP035 (2012).
[7] CST Microwave Studio, Computer Simulation Technology, www.cst.com