PUSHING THE GRADIENT LIMITATIONS OF SUPERCONDUCTING PHOTONIC BAND GAP STRUCTURE CELLS *

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Abstract

We present a design of a superconducting rf photonic band gap (SRF PBG) accelerator cell with specially shaped rods which reduces the peak surface magnetic fields and preserves the effectiveness of the PBG structure for suppression of the higher order modes. The ability of PBG structures to suppress long-range wakefields is especially beneficial for superconducting electron accelerators for high power free-electron lasers (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. As a result, there would be possibilities for increasing the frequency of SRF accelerators and for the development of novel compact high-current accelerator modules for the FELs.

INTRODUCTION

It has been realized long ago that photonic band gap (PBG) structures have great potential in reducing long-range wakefields in accelerators. The first ever demonstration of acceleration in room-temperature PBG structures was conducted at MIT in 2005 [1]. Since then, the importance of that device has been recognized by many research institutions. The effectiveness of PBG structure for suppression of long-range higher order mode (HOM) wakefields is especially beneficial for superconducting rf (SRF) electron accelerators for high power free-electron lasers (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.

Photonic Band Gap [2] cavities have the unique potential to absorb all HOM power and greatly 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, it is relatively easy to employ two-dimensional PBG resonators based on arrays of metal rods [1]. In the experiment reported in [1], the 6-cell open PBG structure was employed to construct a travelling-wave 2pi/3 accelerator with inherit ability to filter out wakefields. However, for the SRF accelerators, the SRF PBG resonators rather serve as a novel, elegant, and very effective way to incorporate HOM couplers, and also, the fundamental mode coupler as a part of the accelerating structure [3] (Figure 1). Since substantial accelerating gradients could be maintained inside of a PBG resonator incorporating HOM waveguides, placing those in the PBG structure instead of the beam pipes may greatly increase the overall real estate gradient. We have initiated a project at Los Alamos National Laboratory (LANL) to demonstrate the applicability of the PBG resonator technology to SRF accelerators [4].

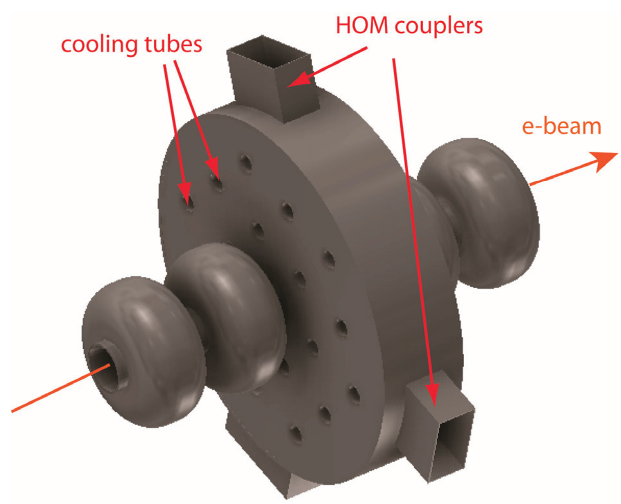

Figure 1: Conceptual drawing of an SRF accelerator section incorporating a PBG cell with HOM couplers.

2.1 GHZ SRF PBG RESONATOR

Two 2.1 GHz SRF PBG resonators were fabricated and tested at LANL in the framework of the DOE Early Career project. The resonators were fabricated by Niowave, Inc. with the dimensions reported in [4]. A photograph of one resonator is shown in Figure 2. The resonators underwent high gradient testing at the beginning of 2012. The achieved accelerating gradients were as high as 15 MV/m, limited by the magnetic quench.

The goal of this project is to adjust the parameters and dimensions of the SRF PBG resonator in order to reduce the peak surface magnetic fields and increase the maximum achievable gradients, while at the same time preserving the effectiveness of the PBG structure for suppression of the higher order modes.

At the start of the project, 2.1 GHz SRF PBG resonators were modelled by 3 different electromagnetic solvers: the HFSS [5] and the CST Microwave Studio [6] time domain (with hexagonal mesh) and frequency

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domain (with tetrahedral mesh). Great care was taken to ensure the agreement between the solvers. The frequencies and the peak surface fields derived from each simulation are summarized in Table 1.

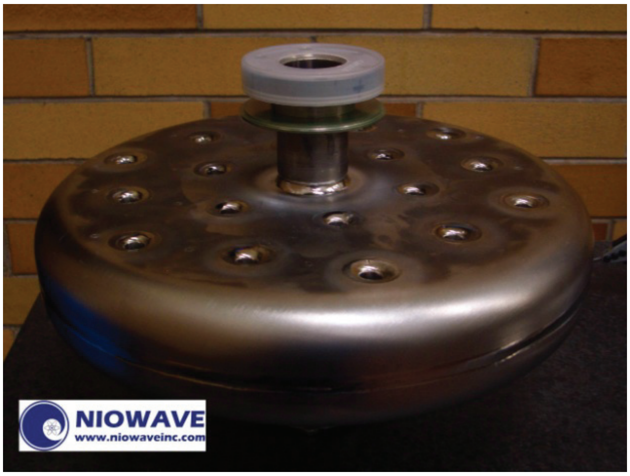

Figure 2: Photograph of the 2.1 GHz PBG cell (courtesy to Niowave, Inc.).

Table 1: Comparison of the Frequencies and Peak Surface Fields Derived from Different Solvers for the 2.1 GHz SRF PBG Resonator with Cylindrical Rods

	Frequency, GHz	Emax/Eacc	Hmax/Eacc (mTesla/(MV/m))
CST studio, hexahedral mesh	2.100	2.32	8.63
CST studio, tetrahedral mesh	2.100	2.16	8.44
HFSS	2.099	2.22	8.55

MINIMIZATION OF THE SURFACE MAGNETIC FIELDS

We investigated different strategies for reducing the peak surface magnetic fields in a PBG resonator trying to improve upon the performance of the resonator with regular cylindrical rods and push its gradient limitations. 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 [7] and changed the shapes of the 6 inner rods of the PBG resonator from cylindrical to elliptical (Figure 3). This produced the desirable effect reducing the surface fields by 40 per cent (Figure 4). We varied the dimension for the minor radii of elliptical rods until the peak magnetic fields were minimized for each major radius. Also, the dimensions of the whole structure had to be adjusted to tune the cell with elliptical rods for the frequency of 2.1 GHz. This could be achieved by either putting a rectangular insert into the elliptical rod, or by shifting the elliptical rods towards the center or by changing the period of the whole structure.

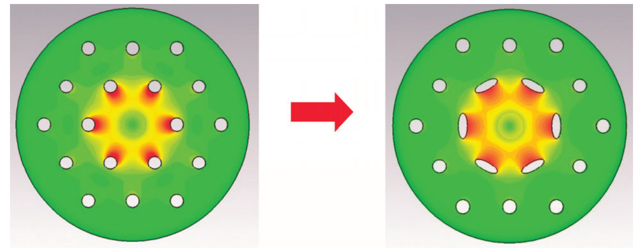

Figure 3: In order to reduce the surface magnetic field the shape of the inner row of rods in the PBG structure was changed from the round cylinders to elliptical cylinders.

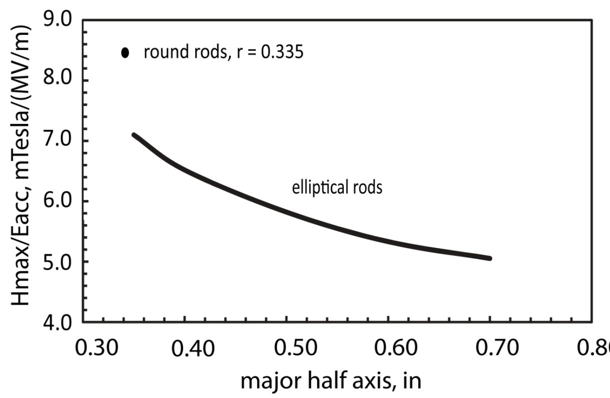

Figure 4: Peak magnetic fields on the surface of the 2.1 GHz PBG resonator as a function of the major half-axis of the elliptical rods.

OPTIMIZATION OF THE HOM SUPPRESSION

We determined that changing the inner row of PBG rods from the round shape to elliptical shape reduces the peak magnetic field. However, a question arises if the PBG resonator with elliptical rods would still be as effective as the one with round rods with respect to the confinement of the fundamental mode and suppression of wakefields. We modeled the HOMs in a PBG geometry with opened side walls in two ways:

- First, we excited the cavity with an electron beam in the Particle Studio and looked at decays of wakefields.
- Second, we excited the cavity with a current pulse containing the frequency spectrum of interest in a time-domain solver of the Microwave Studio and looked at decays of stored microwave energy.

The second method ran faster and was easier to converge. To confirm the applicability of the transient method for characterization of the wakefield suppression in a PBG cell, we first modeled the case of a cell with round rods of different diameters. The results are shown in Figure 5 (a), demonstrating the increasing confinement of both, the fundamental mode and the HOMs with increasing the diameter of PBG rods.

Using the time-domain solver we analyzed the confinement of HOMs and the fundamental mode in all

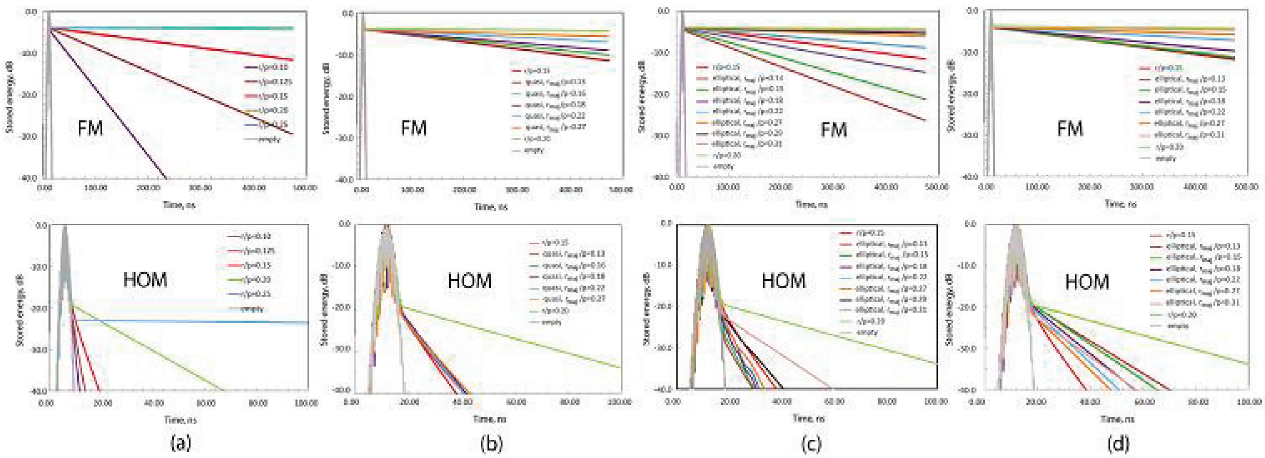

Figure 5: The decay of the fundamental mode and the higher order modes in a PBG resonator when excited by a current in a Microwave Studio time-domain solver for (a) structure of rounds rods, (b) structure with 6 elliptical rods with rectangular inserts, (c) structure with 6 elliptical rods shifted to the center, and (d) structure of elliptical rods with reduced period.

three cases of PBG structure with elliptical rods: rods with inserts, elliptical rods with shifted period and elliptical rods with the shifted first row. The results are summarized in Figure 5 (b), (c) and (d). The structure with elliptical rods and the shifted first row performed the best for filtering out HOMs and appropriately confined the fundamental mode for $0.2 \leq r_{maj} / p \leq 0.3$.

To complete the higher order mode analysis we plan to design the exact configuration of the waveguide HOM couplers which minimizes the quality factors of the few lowest confined HOMs. thermal analysis

Thermal analysis was conducted to rule out the possibility of thermal quench due to inadequate cooling of niobium by liquid helium inside of the rods. Thermal analysis was performed with ANSYS software [8]. Analysis was performed first at 2 Kelvin with liquid Helium in a superfluid state and also at 4 Kelvin when both conduction and the free convection mechanisms of the heat transfer had to be taken into account. No thermal issues were discovered at 2 Kelvin for gradients up to 30 MV/m. At 4 Kelvin we still need to conduct the full computational fluid dynamics analysis to understand the coupling of the two heat transfer mechanisms. No thermal issues were observed during the tests of 2.1 GHz SRF PBG resonators with round rods for accelerating gradients up to 10 MV/m [4].

CONCLUSION AND FUTURE PLANS

We have reported the results of our theoretical investigations of the high gradient limitations and HOM suppression for the superconducting photonic band gap resonators. The PBG technology can significantly reduce the size of SRF accelerators and allow increasing the brightness of the electron beam transport. The proof-of-principle operation of SRF PBG cavities is already demonstrated in the framework of the DOE Early Career project [4]. In the framework of this project we plan to fabricate a 2.1 GHz SRF PBG cavity with 6 elliptical rods shifted to the center (Figure 6) and experimentally demonstrate its high gradient operation and limitations. We expect to confirm experimentally the 40% increase in achievable gradients.

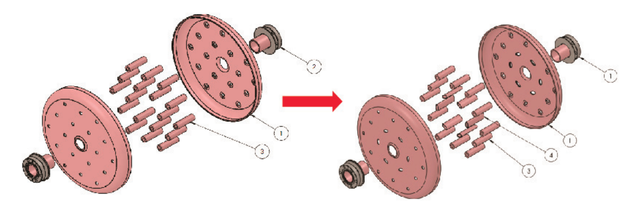

Figure 6: Engineering drawings of the current design of the PBG resonator with round rods and the resonator with 6 elliptical rods to be fabricated in the near future.

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