DESIGN OF A SUPERCONDUCTING PHOTONIC BAND GAP STRUCTURE CELL*

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Abstract

We present a design of a superconducting photonic band gap (PBG) accelerator cell operating at 700 MHz. It has been long recognized that PBG structures have great potential in reducing long-range wakefields in accelerators. Using PBG structures in superconducting particle accelerators will allow moving forward to significantly higher beam luminosities and lead towards a completely new generation of colliders for high energy physics. We designed the superconducting PBG cell which incorporates higher order mode (HOM) couplers to conduct the HOMs filtered by the PBG structure out of the cryostat. The accelerator characteristics of the cell were evaluated numerically. A scaled prototype cell was fabricated out of copper at the higher frequency of 2.8 GHz and cold-tested. The 700 MHz niobium cell will be fabricated at Niowave, Inc. and tested for high gradient at Los Alamos in the near future.

INTRODUCTION

Superconducting radio frequency (SRF) cavities are the natural choice for the future generation of high energy linacs, especially for high-duty-factor machines where the heat produced in the accelerating structure cannot be effectively extracted. Going to higher frequencies in SRF accelerators will save on RF power as well as provide a more compact and lower cost accelerating structure. However, with the current technology, higher order mode (HOM) wakefields in the main linac scale as frequency cubed and can greatly reduce luminosity and strongly affect interaction of the beams at the collision point [1]. Photonic Band Gap [2] (PBG) 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. The first ever demonstration of acceleration in a PBG resonator was conducted at Massachusetts Institute of Technology (MIT) in 2005 (the 17 GHz MIT PBG accelerator is shown in Figure 1) [3]. Since then, the importance of PBG structures for accelerators has been recognized by many research institutions worldwide.

700 MHZ SRF PBG ACCELERATOR

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

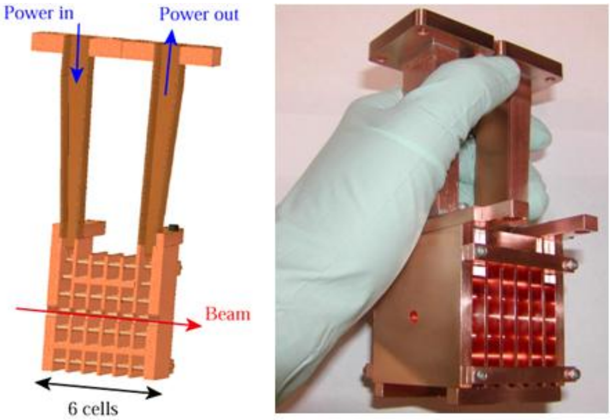

Figure 1: The 17 GHz MIT PBG accelerator structure [3].

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 designing a 700 MHz SRF PBG resonator. At the very start we realized that the fundamental difference must exist between the designs of an SRF PBG resonator and a room-temperature resonator. 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, which is determined by the losses that the accelerating mode experiences by leaking out of the periodic structure. In resonators which were previously designed for the 17 GHz PBG experiment at MIT the diffraction Q was of the order of 10^5, which was almost two 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 larger than 10^{10}, 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

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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 also, the fundamental mode coupler as a part of the accelerating structure.

A conceptual drawing of a PBG cell incorporated as a part of an SRF accelerator section is shown in Figure 2. Three HOM couplers in form of the WR-770 waveguides are located at the enclosing wall of the PBG cell and reduce the Q-factors of the lowest HOMs (including the dipole mode) to below 100. The cut-off frequency of the WR-770 waveguides is above 700 MHz, 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 presence of the HOM couplers because it is well screened by the PBG structure. We also considered a possibility 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. However, for a higher-frequency SRF accelerator the PBG cell also represents a convenient location for a waveguide fundamental mode coupler. Unlike the conventional couplers and ferrite HOM dampers that are located in beam pipes, 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 superconducting facilities.

DESIGN OF THE 700 MHZ CELL

The design of a single SRF PBG cell operating at 700 MHz was performed with the CST Microwave Studio [4].

Table 1: Dimensions and AcPecelerator Characteristics of the 700 MHz SRF PBG Accelerator Cell

Spacing between the rods, p	6.74 inches
Diameter of the rods, r	2.022 inches = 0.3*p
Outside diameter, R0	35 inches
Length of the cell, L	8.436 inches (λ/2)
Diameter of the beam pipe, Rb	4 inches
Radius of the beam pipe blend, rb	1 inch
Ohmic Q (2K)	$1.1*10^{10}$
R/Q	140 Ohm
Emax/Eacc	1.82
Hmax/Eacc	84 Oe/(MV/m)

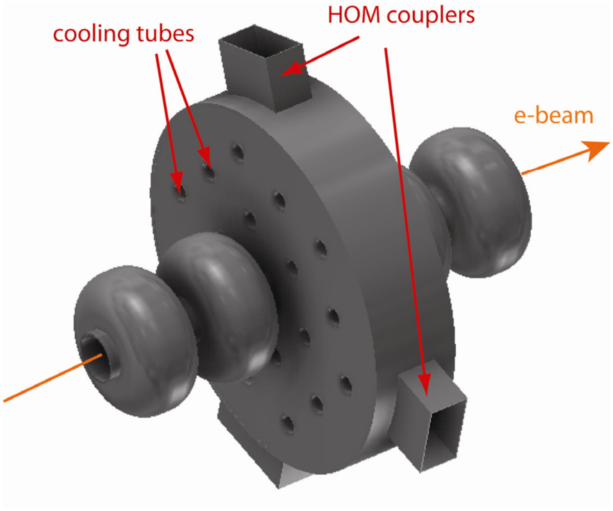

Figure 2: Conceptual drawing of an SRF accelerator section incorporating a PBG cell with HOM couplers.

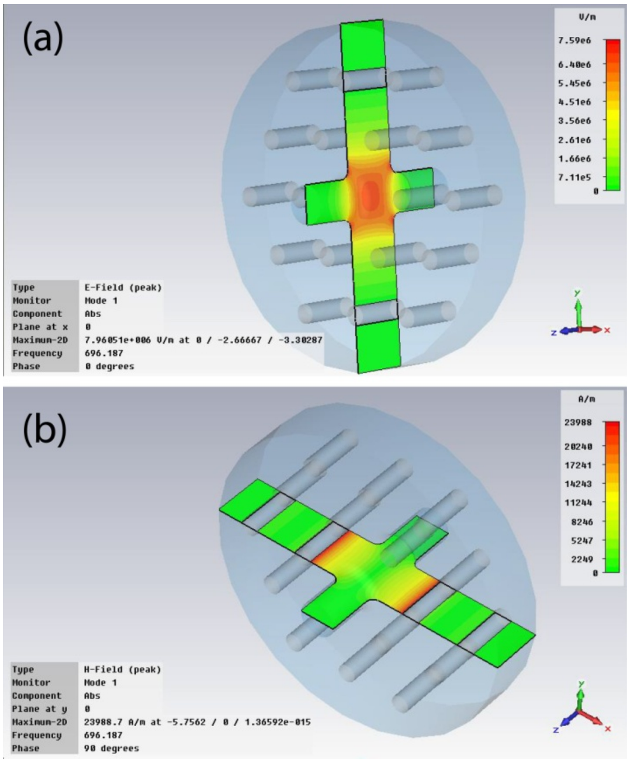

Figure 3: Distribution of the magnitude of electric (a) and magnetic (b) fields in an SRF PBG cell at 700 MHz.

The structure was 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 diameter of 4 inches and blended edges. The dimensions of the cell are listed in Table 1. The table also lists the accelerator characteristics of the designed cell. It can be seen from the table that heating up due to high maximum magnetic fields is going to be the most critical limit to the high gradient performance of the designed cell. The distribution of the magnitudes of the electric and magnetic fields in the cell is shown in Figure 3. The maximum surface electric field in the PBG cell is reached

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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 pillbox cavity. Instead, the maximum magnetic field is reached on the rods of the PBG structure. It suggests that in order to minimize the surface magnetic fields, the shape of the rods had to be varied. We now consider elliptical rods and the rods with blended ends as the means of reducing the surface magnetic fields.

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 this PBG resonator. The resonator will next be fabricated at Niowave, Inc., lowered into a cryostat at LANL's SRF laboratory and tested for high gradients.

FABRICATION AND TESTING OF THE SCALED PROTOTYPE CELL

A copper prototype photonic band gap cavity was constructed at Niowave to serve as a test bed for comparison with simulation, and determine the sensitivity of the photonic band gap array performance to the details of the fabrication design. The prototype was constructed with reduced-diameter beam portes 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 the array. The prototype was scaled to a higher frequency of 2.7 GHz. The dimensions of the prototype cavity are listed in Table 2. The photograph of the cavity is shown in Figure 4.

Table 2: Dimensions of the Copper Prototype Cavity

Spacing between the rods, p	1.693 inches
Diameter of the rods, r	0.508 inches = 0.3*p
Outside diameter, R0	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

We measured room-temperature cavity Q of 3400 with the sleeve removed, compared with 11500 with the sleeve clamped on. The measurement suggests that the impact of the enclosure is significant. In the prototype model, the enclosure also supports antennas (electrically or magnetically coupled) to analyze HOM behavior and coupling at the outer diameter of the structure. The computed and measured frequencies and Q-factors of the structure are summarized in Table 3.

The prototype test was also of interest from the manufacturing point of view. This experience with the prototype was drawn on to predict the tolerances and types of electron beam welds which will be appropriate for the niobium cavity.

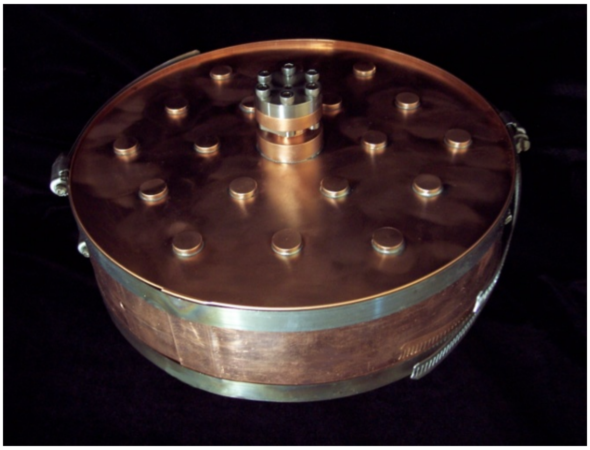

Figure 4: Copper prototype at 2.7 GHz.

Table 3: 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

CONCLUSION AND PLANS

We presented the design of an SRF PBG cell operating at 700 MHz and the cold test measurement results of its higher-frequency scaled prototype. The results of the cold test were found to be in reasonable agreement with simulations and will be used to predict tolerances for fabrication of the 700 MHz niobium cavity. The 700 MHz cavity will be fabricated and tested for high gradient in the near future. We believe that superconducting PBG cells have the potential of greatly increasing the real estate gradient while at the same time improving the beam quality for the future high-energy colliders. This research is also valuable for modern radiation sources, such as free electron lasers (FELs), to reduce the very prominent beam breakup phenomena due to the high electron beam current.

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