UPDATE ON THE DESIGN OF A FIVE-CELL SUPERCONDUCTING RF MODULE WITH A PBG COUPLER CELL*

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Abstract

We present a complete design of the 5-cell superconducting accelerating module incorporating a Photonic Band Gap (PBG) cell with couplers. The purpose of the PBG cell is to achieve better Higher Order Mode (HOM) damping which is vital for preserving the quality of high-current electron beams in novel linear accelerators used, for example, for free electron lasers. We first discuss the aspects of incorporating a PBG cell in a superconducting PBG module. The main goal is to ensure the equal probability of quench in each of the five cells, which can be achieved with significant geometry modifications. We then present the simulation data on HOM damping. Particularly, we calculate the external quality factors for the 10 most dangerous HOMs for this particular structure. HOM coupler configurations and modifications to the PBG geometry are discussed.

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 [1]. Going to higher frequencies in SRF cavities is desirable because of the lower cost and higher achievable luminosity of an electron beam. However, higher order mode (HOM) wakefields excited by a beam scale as frequency cubed and can easily destroy the beam in a high-frequency machine. If we want to go to the frequencies as high as 2.1 GHz, we have to find an effective way to suppress or outcouple HOMs.

PBG cavities are of interest to the particle accelerator community because they have reduced higher-order modes that can degrade beam quality [2, 3].

Waveguide couplers are commonly used as an HOM suppression mechanism (see, for example, [4]). Usually the couplers are attached to the beam pipe. In contrast with a room-temperature PBG cell, the superconducting cell is made closed in the transverse plane and utilizes waveguide couplers to extract the HOMs. Low field at the periphery of the PBG cell allows us to attach the waveguide couplers directly to the outside wall of the cell. This is beneficial to HOM damping because the HOMs are extracted at the point where their field is higher than at the beampipe. We also use less waveguides and increase real estate gradient.

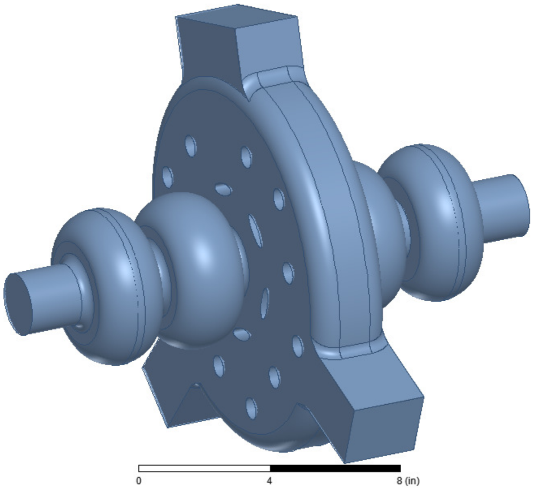

Figure 1: The 5-cell accelerating module with the central PBG cell.

Table 1: Dimensions and Accelerating Characteristics of the 5-cell Module

Frequency	2.1 GHz
Length of the module	14.05 in (35.69 cm)
Diameter of elliptical cells	4.95 in (12.57 cm)
Diameter of the PBG cell	12.32 in (31.3 cm)
Spacing of PBG rods	2.34 in (5.94 cm)
Radii of PBG rods	0.35 in (0.89 cm)
Beam pipe diameter	1.96 in (4.99 cm)
Angular position of the HOM couplers relative to the FM coupler	125°
r/Q	$1.44*10^3$ Ohm/m
E_{peak}/E_{acc}	2.65
B_{peak}/E_{acc}	4.48 mT/(MV/m)
Q_0 (4K)	$2.3*10^8$
Q_0 (2K)	$8.9*10^9$
Max theoretical gradient (for B_{peak}=200 mT)	45 MV/m

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FIVE CELL MODULE DESIGN

We incorporate a PBG cell into a module of five accelerator cells by using it instead of one of the conventional cells. As an example of a conventional accelerating module we take a high-current FEL accelerating module from [4]. The middle cell of the module [4] was replaced with a PBG cell (Fig. 1). A module with an incorporated PBG cell should be designed with lower accelerating gradient in the PBG cell than in other cells [5]. This is due to the fact that for the same accelerating gradient, the surface magnetic field in a PBG cell is higher than in a conventional cell because of the more sophisticated geometry [6]. If the module was designed to have a flat field profile, performance of the entire accelerator would be limited by a single PBG cell due to the higher probability of quench. To make the non-flat gradient profile, we introduce small differences in the eigenfrequencies of the cells. Like in a system of connected pendulums, this leads to different amplitudes of the fields in different cells [5].

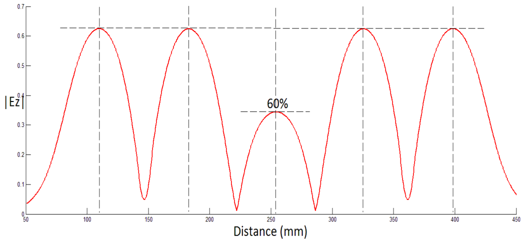

Figure 2: Electric field magnitude (accelerating gradient) along the central axis.

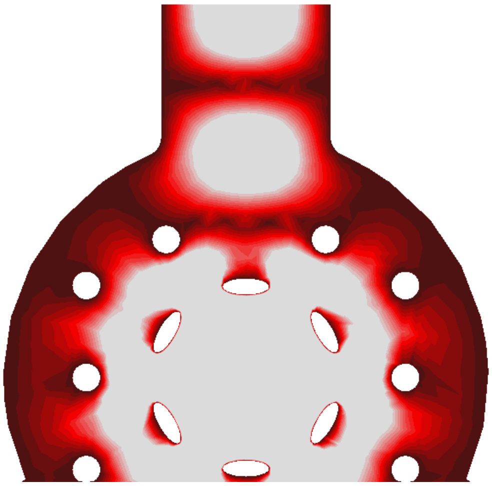

Figure 3: Magnitude of E-field in the fundamental mode coupled into the PBG structure thru the waveguide.

A conventional 2D PBG lattice has only rods with circular cross-section. The corresponding 5-cell module design was presented in [5]. However, it is beneficial to alter the shape of some rods to get better accelerating properties. In particular, the inner row of rods in the designed module is "squeezed" in radial direction and stretched in angular direction (Fig. 3) in order to produce lower ratio of the peak surface magnetic field to the accelerating gradient [7, 8]. Using elliptical rods allows us to push the gradient in the PBG cell higher, up to 60% of the gradient in the four conventional cells (Fig. 2). This is significantly better than we can do with a PBG cell which has only round rods (about 40%) [5]. Properties and dimensions of the accelerating module are listed in Table 1.

We are planning to use the Navy FEL beamline at LANL for the testing of the structure. The parameters of the experiment are listed in Table 2. The electron beam will be synchronous with the accelerating mode (beam on crest). Due to the negligible Ohmic losses almost all the power coupled to the module will go to the beam.

The fundamental mode coupler was designed to provide near critical coupling for the experiment with the electron beam (Fig. 3). Standard WR430 waveguide was used. One of the PBG rods was removed for coupling. The existing design can also be used for tests with the copper prototype and no beam – in that case Ohmic dissipation is approximately equal to the beam loading in the hot test and the coupling would still be close to critical. The beam tests will be conducted at much lower accelerating gradient (5 MV/m) than the cavity is capable to sustain. This ensures reliability of the structure.

Table 2: Parameters for the Planned Test

Charge per bunch	1 nC
Bunch repetition rate	100 MHz
Klystron power	200 kW
Average gradient	5.6 MV/m

HOM DAMPING

In order to understand what HOMs affect the beam the most, we performed a CST Particle Studio simulation with the beam displaced in either of the two transverse directions (X and Y). The computed wake impedance reflects the spectrum of the HOMs (Fig. 4). We used the areas underneath each peak as a criterion of whether or not the mode is dangerous. The area is related to a more commonly used quantity R/Q, which can be generalized for non-monopole modes. Each mode has two orthogonal polarizations, which are listed separately in Table 3. Generally we only have to look at the frequencies up to the beampipe cut-off, but one significant peak beyond the cut-off was examined as well (Table 3, modes 9 and 10). We then tried to minimize the quality factors for the most dangerous 10 HOMs. It was also verified that the frequencies of the monopole HOMs don't lie close enough to multiples of the beam frequency to allow the so-called "build-up" to happen.

There are dangerous HOMs with both the TE and the TM polarizations in the center cell. The HOM couplers should have cutoff below the frequencies of the modes with either polarization and therefore have customized dimensions (2.2in × 2.4in). The couplers and the PBG

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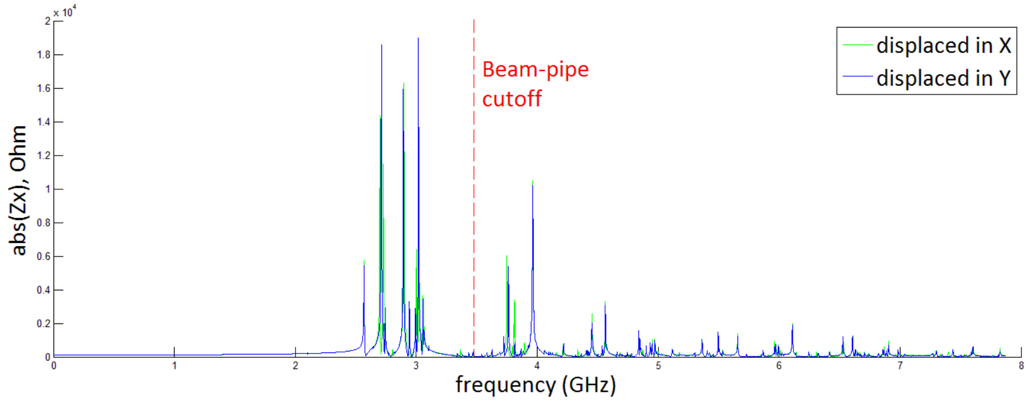

Figure 4: Transverse wake impedance profile for both X and Y beam displacements.

cell were optimized to provide sufficient dumping for all HOMs (Q less or about 1000). The final optimized Qs are listed in Table 3. The design also has advantage over the traditional solution of placing HOM couplers on the beam pipe because it utilizes only 3 couplers instead of 6.

Table 3: Quality Factors of the HOMs

Mode #	Peak area, Ohm/m*Hz	R/Q, Ohm	Frequency, GHz	Quality factor
1	27.1	32.4	2.556	1070
2	26.6	32.3	2.562	560
3	51.9	120.0	2.712	480
4	87.2	120.8	2.715	420
5	85.4	107.8	2.949	430
6	71.8	107.7	2.952	500
7	46.3	84.8	3.013	240
8	67.9	85.3	3.025	690
9*	73.9	79.0	3.943	200
10*	76.3	79.1	3.943	200

CONCLUSIONS

We designed a 5-cell SRF module with incorporated PBG cell and HOM couplers attached to the PBG cell. Using elliptical rods in the PBG structure enhanced the performance of the cavity (flatter gradient profile) relative to the round rods [5]. Fundamental mode coupler was designed to provide coupling close to critical for both hot-test and cold-test experiments. HOM couplers were designed to provide sufficient damping (Q less or about 1000) for the 10 most dangerous HOMs. We are planning to fabricate the copper prototype of the 5 cell structure first. It would let us measure quality factors of the HOMs and conduct a bead-pull test to determine the field profile. We then will fabricate the real superconducting module and mount it on the LANL Navy FEL beamline.

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REFERENCES

[1] Hasan Padamsee, Jens Knobloch and Tom Hays, "RF Superconductivity for Accelerators," Second Edition, Wiley-VCH (2011).
[2] John D. Joannopoulos, Steven G. Johnson, Joshua N. Winn, Robert D. Meade, "Photonic crystals. Molding the Flow of Light," Second Edition, Princeton University Press (2008).
[3] Evgenya I. Smirnova, "Novel Photonic Band Gap Structures for Accelerator Applications," PhD Thesis, Massachusetts Institute of Technology, June 2005.
[4] Haipeng Wang et al., Proc. of PAC2007, p. 2496 (2007).
[5] Sergey A. Arsenyev, Evgenya I. Simakov, AIP Conf. Proc. 1507, pp. 425-430 (2012).
[6] Roark A. Marsh, "Experimental Study of Photonic Band Gap Accelerator Structures," PhD Thesis, Massachusetts Institute of Technology, June 2009.
[7] Evgenya I. Simakov et al., Proc. of IPAC 2012, WEPPP035, (2012).
[8] Brian J. Munroe et al., Proc. of IPAC 2012, TUPRO71 (2012).

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*above the beampipe cut-off