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The Design of a Five-Cell Superconducting RF Module with a PBG Coupler Cell

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Abstract. We discuss the problem of incorporating a Photonic Band Gap (PBG) cell into a superconducting accelerating module of 5 cells designed for the operational frequency of 2.1 GHz. The reason for using a PBG cell is to provide a good accelerating mode confinement and good Higher Order Mode (HOM) suppression. PBG cell can potentially be used for placing HOM and fundamental mode couplers. However, because of the naturally higher ratio of the peak magnetic field to the accelerating field in the PBG cell, it should be designed to operate at a lower accelerating gradient than the other cells of the module. This ensures that the probability of quench in the PBG cell would be no higher than in other elliptical cells of the structure.

Keywords: Photonic Band Gap, Photonic crystal, Linear accelerator, Superconducting RF.

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I. INTRODUCTION

Superconducting radio frequency 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 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 [1]. 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 [2, 3] are of interest to the particle accelerator community because they lack the higher-order modes (HOMs) found in conventional cavities that can degrade beam quality. Unlike a room-temperature PBG cell, a superconducting PBG cell cannot be made open in the transverse plane; otherwise diffraction losses of the accelerating mode would be higher than dissipative losses [4]. Instead, we attach HOM waveguide couplers, overcritical for the fundamental mode, to the sides of the PBG cell (see Fig. 1, a).

Along with ferrite absorbers, waveguide couplers are commonly used as an HOM suppression mechanism (see, for example, [5]). The couplers are usually attached to a beam pipe in order to avoid high fundamental mode field at the junction. Replacing one of conventional cells with a PBG cell allows us to attach the waveguide couplers directly to the cell, which is hoped to provide better HOM suppression [6]. In this paper, however, we do not discuss coupling modes in or out of the module, but only focus on making the desired field profile.

Similar to the conventional accelerating cell, a PBG cell is also used to accelerate particles. However, for the same accelerating gradient, surface magnetic field in a PBG cell is significantly higher than in a conventional cell due to the more sophisticated geometry [7]. This leads to a higher probability of breakdown (for room-temperature accelerators) or quench (for superconducting accelerators).

This paper is focused on superconducting linear accelerators, where a single PBG cell is used to damp HOMs in a module of five accelerating cells. 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. The goal of this paper is

to design a module with equal probability of quench in every cell. This can be achieved by lowering the accelerating gradient (and so the surface magnetic field) in the PBG cell in such a way that the maximum values of the surface magnetic field are equal in each of five cells.

II. BACKGROUND

PBG cell consists of a photonic crystal -- 2-dimensional triangular lattice of rods (either metallic or dielectric), surrounding the defect (missing rod) where accelerating mode is excited. Fig 1, b shows the transverse section of a room-temperature PBG cell consisting of three layers of metal rods and the fundamental mode field profile which resembles TM_{01} -mode if close enough to the central axis.

In an infinite 2-dimensional photonic crystal of metallic rods the dispersion diagram has so-called band gaps. Frequencies in those gaps do not correspond to any wavelength number and therefore wave propagation at those frequencies is forbidden [8]. The cavity formed by a defect in a PBG structure is therefore selective with respect to the frequency. One can choose parameters of the crystal in such a way that the fundamental (accelerating) mode frequency lies in a band gap (and so is confined), but the HOMs have frequencies outside the gap (and so allowed to leak out) [9].

FIGURE 1. a) PBG cell incorporated into an accelerating module. b) Transverse section of a three-layer PBG structure and accelerating TM_{01} -like mode in excited in the cell.

In this work we incorporate a PBG cell into a module of five conventional cells. As an example of conventional accelerating module we take a high-current FEL accelerating module [5]. The module is designed for accelerating ultra-relativistic ($\beta \approx 1$) electrons. It has elliptically shaped cells in order to get minimum dissipative losses. The length of the end is reduced by 2.1% of the fundamental wavelength in order to get a flat field profile (in the absence of detuning which we describe further).

III. CIRCUIT MODEL

An accelerating module could be considered as a system of five connected oscillators with amplitude of oscillations dependent on resonant frequencies of the oscillators. By mismatching the frequencies of the cells we can get the desired field profile with the amplitude of the electric field oscillations lowered in the PBG cell.

Achieving the desired accelerating gradient profile by randomly detuning different cavities turns up to be an irrational way to solve the problem. In fact, it means that we have to explore all values of 3-dimensional detuning vector $\Delta \mathbf{f} = (\Delta f_1, \Delta f_2, \Delta f_3)$, where Δf_i is a frequency shift of the i -th cell (symmetry condition reduces 5-dimensional detuning vector to 3 dimensions). While exploring different values of $\Delta \mathbf{f}$, we have to make sure that the module of 5 cavities still matches the boundary conditions imposed by the beam pipe.

To simplify the process of tuning the cells to achieve the desired field profile, we used a circuit model for the accelerating module [10]. It is commonly used to make the gradient profile flat by deforming cavities after

fabrication. In this paper, however, we will use it for a different reason – to make the gradient profile intentionally not flat, with the field amplitude in the PBG cell lowered.

In the circuit model a set of cavities is represented by coupled LC-circuits. The model is only valid for the π -mode which is usually used for superconducting accelerators. Each circuit includes capacitance C_i and inductance L . For this type of cells the circuits are capacitively-coupled and the coupling strength is related to capacitances C_k . The chain ends by capacitances C_b on both sides which represent the beam-pipe boundary condition. A current in each circuit represents the voltage (or accelerating gradient) in a corresponding cavity [10].

We let the initial (or unperturbed) cell have capacitance C_0 and inductance L and assumed that its π -mode frequency $f_{\pi 0}$ is equal to the desired frequency (2.1 GHz). The frequency can be easily adjusted by varying the radius of the cell and computed by running an eigenmode simulation with periodic boundaries. Then, assume that the frequencies of different cells are different from the desired frequency ($f_{\pi i} \neq f_{\pi 0}$) and correspond to different capacitances in the circuit model ($C_i \neq C_0$).

FIGURE 2. A circuit model representing the 5-cell accelerating cavity.

Using expressions for impedances of a capacitor and an inductor $1/(i\omega C)$ and $i\omega L$ respectively, we write out Kirchhoff's equations for each circuit

$$\begin{aligned} \left(\frac{1}{i\omega C_b} + i\omega L \right) I_1 + \frac{1}{i\omega C_1} I_1 + \frac{1}{i\omega C_k} (I_1 - I_2) &= 0 \\ \frac{1}{i\omega C_k} (I_i - I_{i-1}) + \left(\frac{1}{i\omega C_i} + i\omega L \right) I_i + \frac{1}{i\omega C_k} (I_i - I_{i+1}) &= 0, \text{ for } i = 2 \dots 4 \\ \frac{1}{i\omega C_k} (I_5 - I_4) + \left(\frac{1}{i\omega C_5} + i\omega L \right) I_5 + \frac{1}{i\omega C_b} I_5 &= 0 \end{aligned} \quad (1)$$

Defining a cell-to-cell coupling coefficient $k = C_0/C_k$ and a beam-pipe coefficient $\gamma = C_0/C_b$ and using the cell voltages V_i instead of the currents I_i , we rewrite the equations (1) as a 5-dimensional eigenvector problem

$$\begin{pmatrix} C_0/C_1 + k + \gamma & -k & 0 & 0 & 0 \\ 0 & -k & C_0/C_i + 2k & -k & 0 \\ 0 & 0 & 0 & -k & C_0/C_5 + k + \gamma \end{pmatrix} \begin{pmatrix} V_1 \\ \dots \\ V_i \\ \dots \\ V_5 \end{pmatrix} = \left(\frac{f}{1/2\pi\sqrt{LC_0}} \right)^2 \begin{pmatrix} V_1 \\ \dots \\ V_i \\ \dots \\ V_5 \end{pmatrix} \quad (2)$$

where $i = 2 \dots 4$ and $f = \omega/2\pi$.

This equation is valid for the unperturbed case as well. If we plug in values $C_i = C_0$ and $V_i = (-1)^{i+1}$ for the flat field profile of the π -mode, we will get $\gamma = 2k$ and

$$f_{\pi 0} = \left(\frac{1}{2\pi\sqrt{LC_0}} \right) \sqrt{1 + 4k}.$$

Analogously,

$$f_{\pi i} = \left(\frac{1}{2\pi\sqrt{LC_i}} \right) \sqrt{1 + 4k}. \quad (3)$$

Using the relation (3) between a circuit frequency $f_{\pi i}$ and its capacitance C_i we can substitute C_0/C_i by values that we can easily compute: $(f_{\pi i}/f_{\pi 0})^2$.

Next, we reverse the eigenvector problem, i.e. we want to find the matrix elements for a given eigenvector $\mathbf{V}$. We also require that the frequency of the oscillations f has to be equal to the designed value $f_{\pi 0}$. The solution that we get is

$$\begin{pmatrix} x_1 \\ \dots \\ x_i \\ \dots \\ x_5 \end{pmatrix} = \begin{pmatrix} V_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & V_i & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & 0 & V_5 \end{pmatrix}^{-1} \begin{pmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 2 & 1 & 0 \\ 0 & 0 & \dots & 1 & 1 \end{pmatrix} \begin{pmatrix} V_1 \\ \dots \\ V_i \\ \dots \\ V_5 \end{pmatrix} \quad (4)$$

where $i = 2 \dots 4$ and values $x_i = [(f_{\pi i}/f_{\pi 0})^2 - 1]/k$ say how much the i -th cavity should be detuned.

Cell-to-cell coupling coefficient k depends on a particular geometry of the cells. We compute it by running an auxiliary simulation with two coupled cells only. We slightly change the radius of one of the cells and observe the ratio V_1/V_2 . For the geometry of [5] the CST Microwave Studio simulation gives $k = 0.0157$.

Due to the higher ratio of the peak surface magnetic field to the accelerating gradient, we have to make the gradient in the center cell equal to 37% of the gradient in the other cells. We plug the desired voltages $V_{1,5} = 1, V_{2,4} = -1, V_3 = 0.37$ into the matrix equation (4) and find the necessary values for the frequencies $f_{\pi i}$ of the cell.

However, the circuit model does not describe the system perfectly due to the simplifying assumptions we made (for example, that varying a radius of a cell doesn't change the capacitance C_k). So we have to adjust the input numbers for the voltages. We also compensate slightly enhanced gradient in the end cells by lowering the input voltages V_1 and V_5 . Finally, for the input voltages $V_{1,5} = 0.9867, V_{2,4} = -1, V_3 = 0.4301$, we get the desired field profile by running the CST Microwave Studio simulation (Fig. 3, a). It gives us equal maximum values of the surface magnetic field in each of five cells (Fig. 3, b).

The final adjustments in frequency and dimensions are summarized in Table 1. In the PBG cell, we adjust the spacing between the rods instead. Presence of the fundamental mode coupler would not affect the field profile significantly because of its high Q-factor – about 40000.

FIGURE 3. a) Accelerating gradient profile along the central axis of the 5-cell module. b) Absolute value of the magnetic field in the mode – peak surface field is equal in all five cells.

TABLE (1). Changes in π -mode frequencies and radii of the cells compare to the unperturbed cell.					
Cell #	1	2	3	4	5
$\Delta f_{\pi i}$	-0.2 MHz	9.6 MHz	-44.3 MHz	9.6 MHz	-0.2 MHz
Δr_i	0.2 mil	-9.6 mil	45.8 mil – equivalent to a PBG cell with $a = 2.375$ in		-9.6 mil
				0.2 mil	

IV. CHARACTERISTICS OF THE 5-CELL CAVITY

Geometrical sizes of the designed 5-cell module with incorporated PBG cell are listed in Table 2. Accelerating characteristics of the module are listed in Table 3. We also compare the results with properties of the module consisting of elliptical cells only [5] and the module consisting of PBG cells only. We also compare it with the experimental results for a single PBG SRF cavity tested at LANL [6].

Quality factor values for the designed module are about the same as for the module consisting of elliptical cells. The ratios of E_{peak}/E_{acc} and B_{peak}/E_{acc} are slightly higher and ratio R/Q is slightly lower since the average gradient in the designed module is lower. These disadvantages, however, could be significantly reduced by the fact that the input coupler can be attached directly to the center cell without occupying any extra space in the beam pipe and reducing the real-estate gradient. More than that, incorporating a PBG cell into an accelerating module will provide good HOM damping and better quality of electron beam.

TABLE (2). Dimensions of the designed 5-cell module.	
Frequency	2.1 GHz
Length of the middle cells	2.81 in (7.14 cm)
Length of the end cells	2.69 in (6.83 cm)
Diameter of elliptical cells	4.95 in (12.75 cm)
Diameter of the PBG cell	12.52 in (31.79 cm)
Distance between rods in the PBG cell, a	2.38 in (6.03 cm)
Radius of the rods, r_{cyl}	$0.15 \cdot a = 0.36$ in (0.91 cm)

TABLE (3). Comparison between different accelerating cavity designs.				
	Elliptical “low loss” shape cells	PBG single cell tested at LANL	PBG cells in this project	Module of four elliptical cells and one PBG cell
Q_0 (4K)	$2.4 \cdot 10^8$	$1.5 \cdot 10^8$	$1.5 \cdot 10^8$	$2.3 \cdot 10^8$
Q_0 (2K)	$9.1 \cdot 10^9$	$5.8 \cdot 10^9$	$5.6 \cdot 10^9$	$8.7 \cdot 10^9$
R/Q	105 <i>Ohm/cell</i>	146 <i>Ohm</i>	97 <i>Ohm/cell</i>	98 <i>Ohm/cell</i>
E_{peak}/E_{acc}	2.48	2.22	2.53	2.63
B_{peak}/E_{acc}	4.18 <i>mT/(MW/m)</i>	8.55 <i>mT/(MW/m)</i>	10.61 <i>mT/(MW/m)</i>	4.84 <i>mT/(MW/m)</i>

V. CONCLUSIONS

We designed a 5-cell SRF module with incorporated PBG cell which has no surface magnetic field enhancement in the PBG cell and therefore has equal probability of quench in all 5 cells. The method based on the circuit model theory agrees with the eigenmode simulations done with CST Microwave Studio. Characteristics of the designed cavity are calculated and compared with the initial design without the PBG cell. The comparison shows that the accelerating properties of the module are a little worse than that of a module consisting of conventional cells only. This is the price we have pay for effective HOM suppression provided by the PBG cavity.

In future we plan to design the input coupler and the HOM couplers for the module and compare their effectiveness with existing HOM outcoupling mechanisms. A prototype of the structure will be made of copper and

cold tested at LANL. Finally, real superconducting structure will be fabricated by Niowave and hot tested in the FEL beam line at LANL.

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