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# FIVE-CELL SUPERCONDUCTING RF MODULE WITH A PBG COUPLER CELL: DESIGN AND COLD TESTING OF THE COPPER PROTOTYPE*

S. Arsenyev†, Massachusetts Institute of Technology, Cambridge, MA 02139, USA
D. Shchegolkov, E. Simakov,
Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM 87545, USA
C.H. Boulware, T.L. Grimm, A.R. Rogacki, Niowave, Inc.,
1012 North Walnut Street, Lansing, MI 48906, USA

*Abstract*

We report the design and experimental data for a copper prototype of a superconducting radio-frequency (SRF) accelerator module. The five-cell module has an incorporated 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. Better HOM damping raises the current threshold for beam instabilities in novel SRF accelerators. The PBG design also increases the real-estate gradient of the linac because both HOM damping and the fundamental power coupling can be done through the PBG cell instead of on the beam pipe via complicated end assemblies.

First, we will discuss the design and accelerating properties of the structure. The five-cell module was optimized to provide good HOM damping while maintaining the same accelerating properties as conventional elliptical-cell modules. We will then discuss the process of tuning the structure to obtain the desired accelerating gradient profile. Finally, we will list measured quality factors for the accelerating mode and the most dangerous HOMs.

## INTRODUCTION

Superconducting radio frequency (SRF) cavities are the natural choice for future generations 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 in some applications for various reasons. First, it allows us to lower cost and increase achievable luminosity of an electron beam. Second, it is necessary for harmonic cavities operating at multiples of accelerator frequency. However, higher-order-mode (HOM) wakefields excited by a beam scale as the frequency cubed and can easily destroy the beam in a high-frequency machine. One high-current linac of relatively high frequency is the proposed SRF harmonic linac for eRHIC [2], which would be used to undo nonlinear distortion of the beam's longitudinal phase space induced by the main linac waveform.

Photonic band-gap (PBG) cavities are of interest to the particle accelerator community because they have reduced higher-order modes that can degrade beam quality [3, 4]. Unlike a room temperature PBG cell, the superconducting cell is closed in the transverse plane and utilizes waveguide couplers to extract the HOMs. Waveguide couplers are commonly used as an HOM suppression mechanism but are usually attached to the beam pipe (see, for example, [5]). In contrast, low field at the periphery of the PBG cell lets the waveguide couplers be connected directly to the outside wall of the cell. This is beneficial to HOM damping and increases real estate gradient by saving space on the beampipes [6].

Figure 1: Copper prototype of the 5-cell accelerating module.

A niobium cavity was fabricated to test the maximum achievable accelerating gradient at superconducting temperature [7]. It was decided, however, that a much cheaper copper prototype (Fig. 1) would be fabricated prior to the niobium cavity for two reasons. This prototype serves to demonstrate the novel tuning required for the multi-cell structure with the PBG coupling cell, applied later to the niobium cavity. Also, HOM damping can be analyzed in the copper cavity by measuring external quality factors $Q_e$ for the most dangerous HOMs. At room temperature, the $Q_e$ can be calculated more accurately in the copper prototype because the conductivity of copper is about 10 times higher than that of niobium at room temperature. Mode overlapping, which is an issue for measurements in the niobium cavity at room temperature, is less of a problem. Unloaded Q factors for the copper prototype are in the order of $1.5 \times 10^4$ which is

* Work supported by the U.S. Department of Energy (DOE) Office of Science Early Career Research Program
† arsenyev@mit.edu

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much higher than $Q_e$ estimated to be a few thousands for the dangerous HOMs, therefore a superconducting experiment to measure HOM damping is not necessary.

## DESIGN AND SIMULATIONS

### *Fundamental Mode*

If the module was designed to have a flat field profile, performance of the entire accelerator module would be limited by a single PBG cell due to the higher peak magnetic field on the surface of the inner rods. To flatten the peak magnetic field profile instead of the gradient profile, we introduce small differences in the eigenfrequencies of the cells. Similar to a system of connected pendulums, this leads to different amplitudes of the fields in different cells [6]. The inner PBG rods are specifically shaped to minimize $B_{peak}$, which allows us to achieve gradient as high as 60% of that in elliptical "low-loss" shaped cells. The penalty in accelerating gradient incurred to implement the coupling through the PBG cell is minimal, as shown by accelerator parameters listed in Table 1.

Table 1: Accelerating Properties of the Module Compared to a Design with 5 Elliptical "low loss" Cells

| | PBG | 5 elliptical cells |
|---|---|---|
| Frequency $f_0$ | 2.1 GHz | |
| Shunt impedance $\frac{R}{Q}$ | 515 Ω | 525 Ω |
| Geometrical factor $G$ | 265 | 276 |
| Peak surface electric field ratio $E_{peak}/E_{acc}$ | 2.65 | 2.50 |
| Peak surface magnetic field ratio $B_{peak}/E_{acc}$ | 4.48 $\frac{mT}{\frac{MV}{m}}$ | 4.27 $\frac{mT}{\frac{MV}{m}}$ |

The cavity was originally designed for the Los Alamos National Laboratory Navy Free-Electron Laser beamline with beam current 100 mA and RF power of 200 kW. These parameters require the fundamental power coupler (FPC) to have $Q_e = 3.8 \times 10^4$ to be perfectly matched with the beam. Since the accelerating mode is strongly confined in the PBG lattice, one of the rods was removed which resulted in $Q_e = 2 \times 10^4$. This rather strong coupling gives us flexibility to adjust to particular beam current and RF power values as $Q_e$ can be increased by means of a waveguide stub.

### *Higher Order Modes*

The structure possesses two mirror-flip symmetry planes: XZ and XY, where the origin is defined in the center of the structure, the Z axis is parallel to the beam path and the X axis is parallel to the FPC. Each HOM has either strictly parallel or strictly perpendicular electric field in either symmetry plane and can be classified based on that. We will call modes that have **E** in the XZ plane $X - modes$, and modes that have **E** perpendicular to the XZ plane $Y - modes$. For every X mode there is a Y mode with slightly different frequency but sometimes with very different $Q_e$.

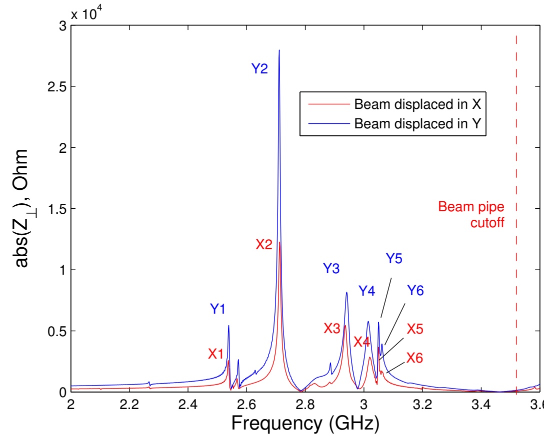


Figure 2: Transverse impedance calculated by CST Particle Studio. 12 most dangerous modes correspond to the biggest peaks in impedance.

Table 2: Most Dangerous HOMs

| HOM | Field in PBG cell | Freq, GHz | Area under $Z_\perp$ peak, $10^9\Omega/s$ | $R/Q_0$, Ohm |
|---|---|---|---|---|
| X1 | TE | 2.531 | 16.4 | 11.1 |
| X2 | TM | 2.704 | 144.4 | 113.4 |
| X3 | TE | 2.932 | 111.7 | 89.6 |
| X4 | TM | 3.015 | 74.3 | 55.9 |
| X5 | TE | 3.045 | 24.2 | 14.1 |
| X6 | TM | 3.057 | 29.9 | 6.9 |
| Y1 | TE | 2.531 | 18.1 | 13.5 |
| Y2 | TM | 2.705 | 144.4 | 111.8 |
| Y3 | TE | 2.937 | 113.3 | 80.2 |
| Y4 | TM | 3.012 | 75.1 | 59.5 |
| Y5 | TE | 3.049 | 24.2 | 13.8 |
| Y6 | TM | 3.059 | 29.9 | 8.8 |

The structure does not have a translational symmetry along the z-axis and TE-TM classification is not applicable. A mode can have TE-like field in one cell and TM-like field in another. We can, however, classify the modes that have E in the XY plane as "TE in PBG" and the modes that have E perpendicular to the XY plane as "TM in PBG".

We focused on HOMs with frequencies below the beam pipe cutoff (3.525 GHz for $TE_{11}$ waveguide mode) that are longitudinally confined in the cavity and can only decay due to external damping or Ohmic losses.

CST Particle Studio simulations were performed with electron beam offset from the central axis by quarter beam pipe radius in X direction and in Y direction. PML boundaries were defined on all waveguide couplers. Transverse wake impedance $Z_\perp$ was calculated for both cases (Fig. 2). Transverse impedance is measured in Ohms in agreement with its definition from [8]. Based on integrated areas under each peak, 12 most dangerous HOMs were chosen (Table 2). A peak area associated with an HOM is proportional to the transverse deflecting voltage a bunch sees due to the that

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HOM excited by the previous bunch. For dipole modes it is also proportional to shunt impedance $R_d/Q_0$ and frequency squared.

## EXPERIMENTAL DATA

### *Fundamental Mode*

In the setup we used (Fig. 1) each cell consisted of two half cells, clamped together at the equator. Each elliptical half cell was machined with extra 0.1" of material at the equator and then trimmed to get the necessary gradient profile. Tuning was done in multiple steps starting with the cells closest to the center and finishing with the end cells. Each step involved a bead pull measurement with results plugged into the circuit model of the cavity to estimate how much the half cells should be trimmed on the next step. The procedure continued until the desired gradient profile was achieved within 5% accuracy as shown in Fig. 3.

A coaxial-to-waveguide adapter was used to excite the mode through the FPC. A coaxial probe inserted in the beam pipe was used to measure transmission $S_{21}(f)$ and loaded quality factor $Q_L$ was obtained. By comparing it with unloaded quality factor $Q_0$, the external quality factor for the FPC was found to be $2.2 \times 10^4$ in good agreement with the design.

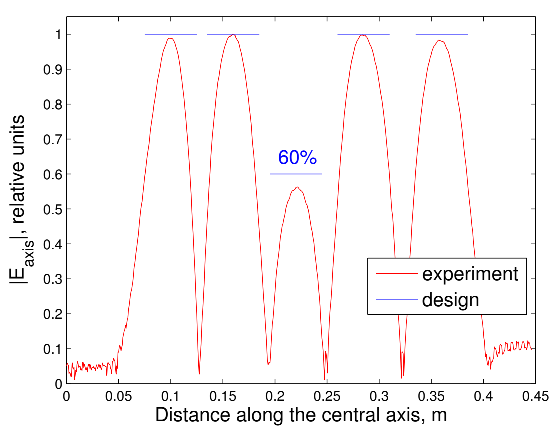


Figure 3: Gradient profile of the tuned cavity obtained from bead-pull measurements.

### *Higher Order Modes*

Magnetic probes with a loop at the end were inserted in the beam pipe along the central axis to excite the HOMs. If a probe was oriented so that the loop was in XZ plane, only the X modes were excited. Similarly, a probe oriented in YZ plane only excited the Y modes.

External quality factors were calculated from measured loaded quality factors $Q_L$ and unloaded quality factors $Q_0$. To measure $Q_0$, the waveguides were blanked off with metal plates. To measure $Q_L$, RF loads were connected to the FPC and the HOM waveguides to absorb HOM power extracted by the waveguides. We used loads of standard waveguide sizes WR430 and WR510, therefore specifically designed taper sections were used to taper out the HOM waveguides. The $S_{21}$ profiles agreed very well with HFSS simulation of the actual geometry which made it easy to identify the modes $S_{21}$ peaks corresponded to. To address the issue of mode overlapping, a different measurement was done where one of the antennas was replaced with an waveguide-to-coaxial adapter attached to the FPC. This way only the TM-like modes were excited which allowed accurate measurement of their Q factors without interference with the neighboring modes.

Table 3 summarizes the measured data on HOM damping. The difference between originally planned and measured Q factors (first and third columns) is explained by HFSS simulations with the actual geometry after tuning (second column). It was found that some HOMs are very sensitive to small geometry changes introduced by the way the cavity was tuned. It was also found that the shape of the tapered sections can significantly affect $Q_e$ for some modes. For the modes X2 and Y2, tapers of different shape were used to correctly estimate $Q_e$.

Table 3: Comparison between Measured and Simulated $Q_e$ for the most Dangerous HOMs

| HOM | Planned $Q_e$ (HFSS) | $Q_e$ (as fabricated, HFSS) | Measured $Q_e$ |
|---|---|---|---|
| X1 | $1.2 \times 10^3$ | $3.7 \times 10^3$ | $4.2 \times 10^3$ |
| X2 | $7.3 \times 10^2$ | $1.3 \times 10^3$ | $1.4 \times 10^3$ |
| X3 | $3.3 \times 10^2$ | $2.9 \times 10^2$ | $1.8 \times 10^2$ |
| X4 | $1.9 \times 10^2$ | $2.0 \times 10^2$ | $1.6 \times 10^2$ |
| X5 | $1.3 \times 10^4$ | $1.0 \times 10^4$ | $7.8 \times 10^3$ |
| X6 | $4.7 \times 10^2$ | $4.4 \times 10^2$ | $4.8 \times 10^2$ |
| Y1 | $1.0 \times 10^3$ | $4.4 \times 10^3$ | $7.4 \times 10^3$ |
| Y2 | $8.6 \times 10^2$ | $1.9 \times 10^3$ | $1.7 \times 10^3$ |
| Y3 | $2.5 \times 10^2$ | $2.6 \times 10^2$ | $1.8 \times 10^2$ |
| Y4 | $2.7 \times 10^2$ | $1.7 \times 10^2$ | $3.0 \times 10^2$ |
| Y5 | $1.8 \times 10^3$ | $1.5 \times 10^3$ | $8.9 \times 10^2$ |
| Y6 | $7.8 \times 10^2$ | $6.3 \times 10^2$ | $3.7 \times 10^2$ |

## CONCLUSIONS

Fabrication and tuning mechanisms for a multi-cell accelerating cavity with a PBG coupling cell were successfully tested on a copper prototype. External quality factor for the accelerating mode was found in good agreement with simulations, and for the HOMs with reasonable agreement with simulations. Measured external Q factors for the most of the dangerous HOMs were below $10^3$.

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