Tuning of Photonic Band Gap Accelerating Structures

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July 18, 2019

Abstract

The use of photonic band gap structures(PBGs) in superconducting RF cavities promises improved damping of higher order modes in accelerator applications. The tuning of PBG cavities differs from the tuning of traditional RF cavities due to their different geometry, but remains a vital part of smooth operation. This tuning must be accomplished through predictable deformation of the PBG cavity by mechanical means, altering its electromagnetic properties. A possible tuning system for PBG structures is discussed, accompanied by results of both mechanical and electromagnetic simulations using ANSYS. An approximate sensitivity for tuning using the given force configuration is presented.

1 Introduction

Modern research applications require particle accelerators capable of bringing particles to ever higher energies. A crucial component of new particles accelerators is the use of superconducting radio frequency(SRF) cavities.

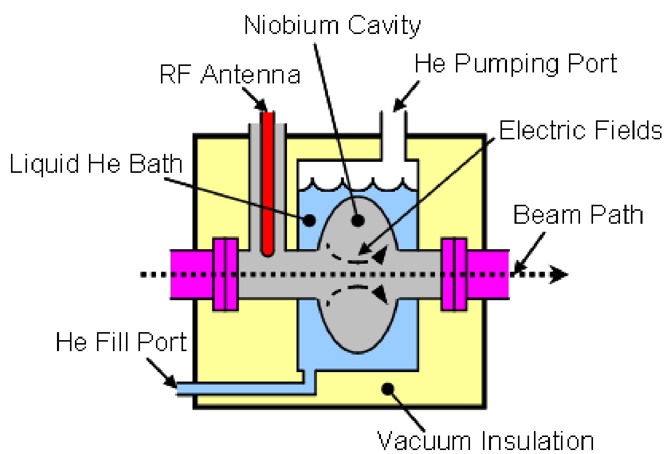

Figure 1: A single cell SRF cavity[1]

The main advantage of superconducting cavities made from materials like niobium over their room temperature copper counterparts is the extremely low dissipation of power in their walls. This leads to a quality factors on the order of 10^9-10^{11}, allowing for the build of up high energies in a cavity's resonant modes, which leads to high accelerating gradient and therefore higher energy gain for particles passing through an SRF cavity.

Some resonant modes are better for acceleration than others. Most cavities operate in the TM_{010} monopole mode, shown in Fig. 2, in which the electric field is parallel to the direction of the beam's path and is radially uniform.

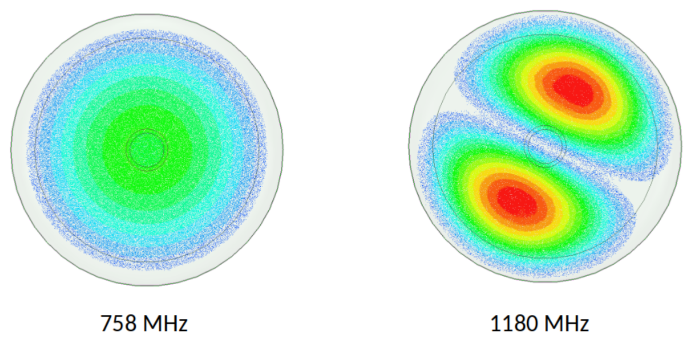

Figure 2: Left: the monopole accelerating mode for an SRF cavity along with its frequency. Right: the dipole mode for the same cavity.

The accelerating mode is not the only mode that can be excited. The right of Fig. 2 shows a dipole mode, which not only fails to accelerate a beam of particles in the center, but can even lead to the break up of the beam. Dangerous, higher frequency modes like this dipole mode are referred to as higher order modes(HOMs). Normally, the cavity is excited by coupling to an RF power source at the frequency of the accelerating mode, but there is still a risk of exciting HOMs. As particles are accelerated through the cavity, they produce radiation, known as wakefields. These wakefields are appear as a Fourier sum of the cavity's resonant modes, so due to the high quality factors of SRF cavities, it is possible for energy to be built up in HOMs. This effect must be mitigated for smooth operation of an SRF cavity.

Some current research is being done on the use of photonic band gap structures(PBGs)[1] for mode isolation. A PBG is a periodic array of dielectric of metal material that blocks propagation of fields inside a certain band of frequencies while allowing others. This property can be exploited to make PBG SRF cavities, as shown in Fig. 3. A PGB is inserted into an SRF cavity with one lattice site in the center removed, which creates a subcavity that traps a monopole mode with a frequency inside the structure's band gap while allowing dangerous HOMs to propagate outwards.

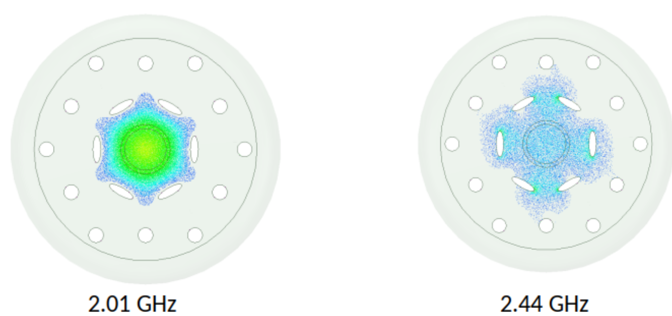

Figure 3: Left: the accelerating mode confined to the center of a PBG cavity. Right: the dipole mode, spread out in the PBG lattice.

Due to the high quality factors of SRF cavities, their bandwidths are very small - generally on the order of a few Hz. During operation, an SRF cavity is subject to a variety of forces, including radiation pressure and microphonic effects from the He refrigeration system. These effects can slightly deform a cavity, which causes a shift in its resonant frequencies. Because of the narrow bandwidth, this can disrupt coupling between the cavity and the power source.

[1] PBGs are sometimes referred to also as "photonic crystals".

This sensitivity necessitates a tuning system of some kind. A cavity tuner generally operates by deforming the cavity in a predictable way in order to shift the frequency of the accelerating mode to compensate for detuning effects, maintaining smooth and stable operation. Tuning systems for standard SRF cavities have been thoroughly studied, but little work has been done on the tuning of PBG cavities. This work seeks to characterize the tuning properties of one proposed force application configuration.

2 Methods

2.1 Cavity Modelling

The niobium PBG cavity used in this project was based on a design by Sergey Arsenyev[2].

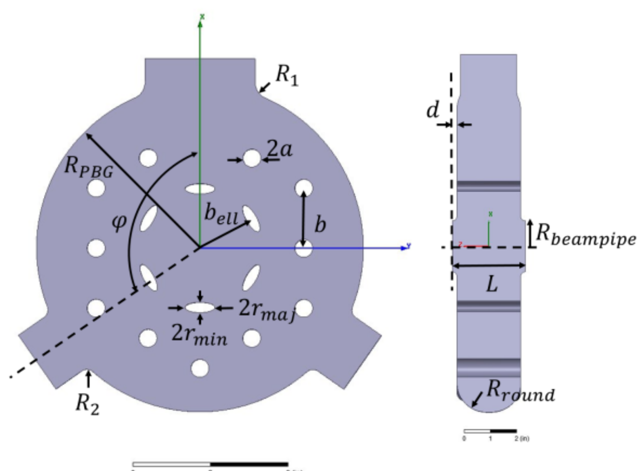

Figure 4: Parametrized PBG cavity design[2]

The cavity used here(see Fig. 3) used the same geometric parameters but omitted the couplers shown in Fig. 4. These couplers, although critical for a functional cavity, do not significantly change the fundamental properties of an ideal cavity. Omitting them allows us to focus on the behavior of the PBG cavity in isolation. Some Python code was written in order to automatically generate new geometries for different parameters in order to enable easier data collection and analysis. This process is documented for a simpler elliptical cavity in [3].

2.2 Correlation of Parameters with Frequency

In order to develop a system to tune the frequency, it was necessary to quantify the relationship between the geometry and the accelerating mode frequency. This was done by calculating the resonant frequency for a large number of geometries using Ansoft HFSS. The basic process for finding resonant modes of an elliptical cavity using HFSS is documented in [4].

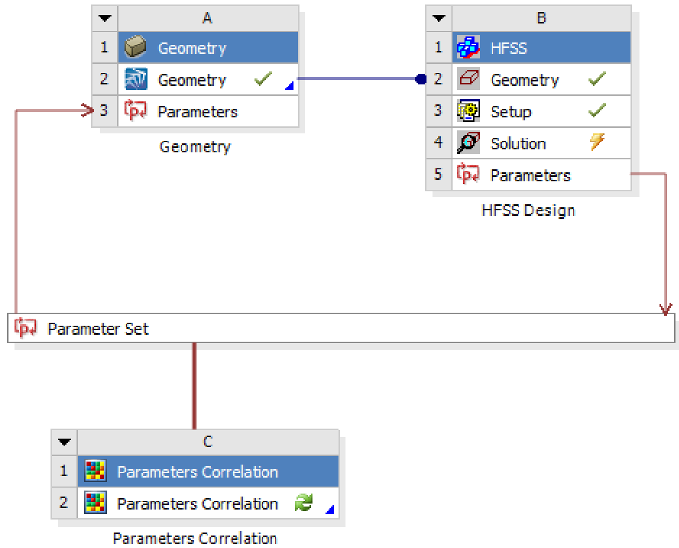

Figure 5: The loop of data collection in ANSYS Workbench

Once about 1400 data points were collected(a process that took a total of nearly 60 hours of run time), the generated data were analysed using Python. First, a simple PCA process was applied to find which parameters explained the greatest variance in the data.

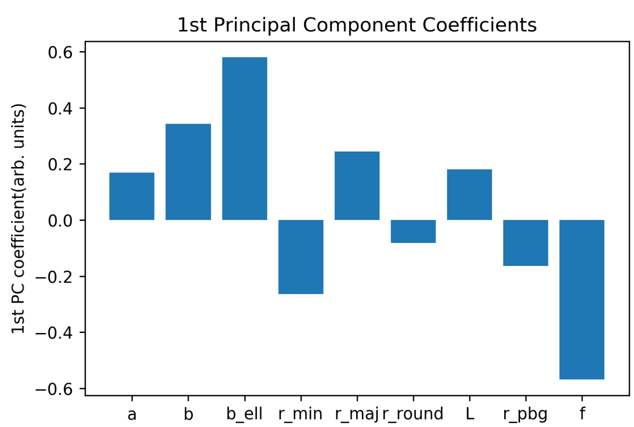

Figure 6: The coefficients of parameters in the first principal component

PCA suggests that the frequency can be decreased by increasing b_{ell} and decreasing r_{min}. This fits well with intuition about the problem; the subcavity inside the PBG should be somewhat analogous to an ideal cylindrical pillbox cavity with radius $R = b_{ell} - r_{min}$, in which the monopole mode frequency would scale as $1/R$.

A neural network was also trained on the data in order to assess the feasibility of predicting resonant frequency directly from geometric parameters, bypassing the long HFSS simulation process. The results of this neural network when applied to a set of test data are shown in Fig. 7.

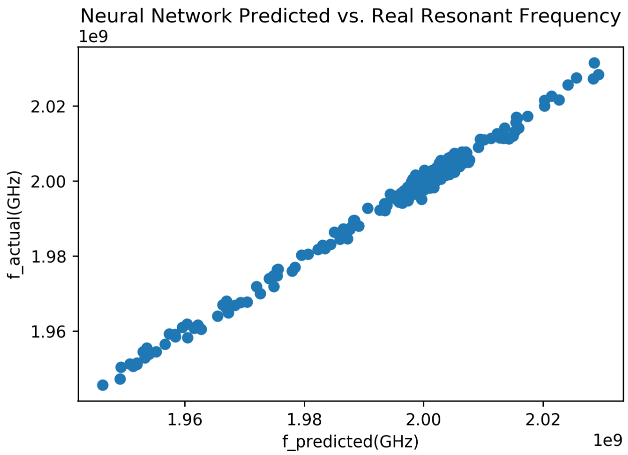

Figure 7: Neural network predictions compared with HFSS calculated results. Each point represents a different set of geometric parameters.

The neural network's performance is quite poor. Although the data in Fig. 7 appear to be fairly linear, the deviations are on the scale of several MHz, which is not suitable for tuning applications, where frequency must be stable to within a few Hz. Because of this, we chose to pursue different methods.

2.3 Tuner Concept

We turn now to the mechanical aspect of tuning. One way to increase b_{ell}, which should correspond to a decrease in monopole frequency, is to squeeze the cavity near the beam pipe. Figure 8 shows the system we investigated. An equal amount of force is applied on both sides of the cavity, causing the ellipses to be pressed outwards when force is applied, increasing b_{ell}.

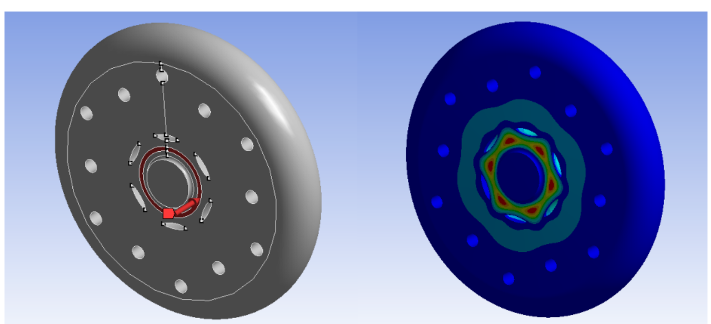

Figure 8: Left: force is applied to the cavity on the red area. Right: the deformation pattern, calculated by ANSYS, when force is applied. Red indicates high deformation, blue indicates little or no deformation.

With a system in place to find the deformation of the cavity model when forces are applied, we can start to analyse some of these results.

2.4 Extracting Parameter Changes

For forces on the order of 10^3 or 10^4 N, the deformation is relatively small(typically a few micrometers), so the overall geometry of the cavity remains the same. By tracking specific vertices during the deformation process, we are able to approximate how each of the geometric parameters change when different magnitudes of force are applied.

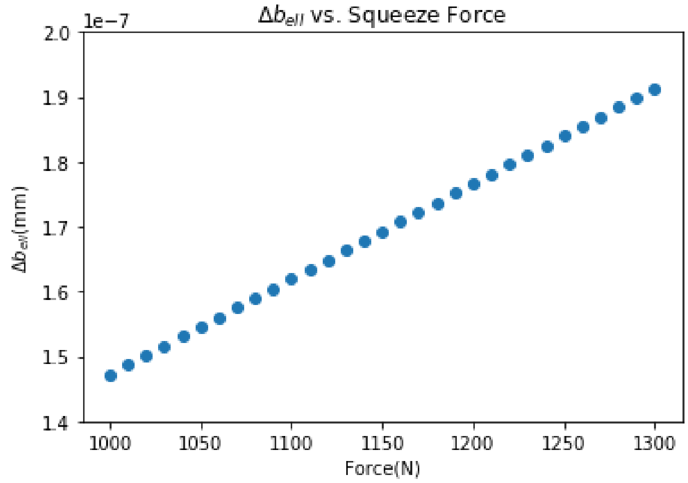

Figure 9: Approximate change in b_{bell} for varying force

The data shown in Fig. 9 are almost perfectly linear, telling us that b_{ell} varies with applied force at a rate of 1.47×10^{-10} mm/N. The remarkably regular predictability of parameter changes suggested that we might be able to observe a similarly regular shift in accelerating mode frequency when forces were applied.

2.5 b_{ell} and Freqency Correlation

Since the neural network did not show much promise for predicting resonant frequency, we investigated using a small number of parameters - perhaps just b_{ell} and r_{min} - to get a bound on frequency shift for applied force. Unfortunately, frequency simulations became increasingly unstable as the range of parameter values shrank. When all other parameters are held constant and b_{ell} is varied over a relatively large range, the data shows some, albeit weak, correlation.

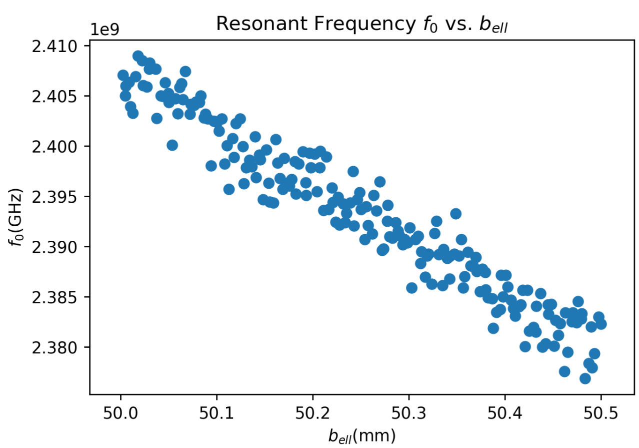

Figure 10: Monopole mode frequency when only b_{ell} is varied over a 0.5 mm range

Since the changes in b_{ell} that we're interested in are on the order of 10^{-7} mm(see Fig. 9), we need to observe correlation on a much smaller scale. Running very high resolution simulations on a smaller range of b_{ell}, we obtain the data shown in Fig. 11.

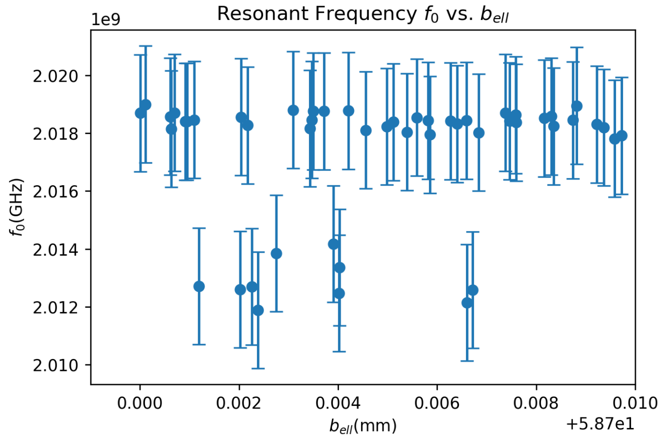

Figure 11: Monopole mode frequency when only b_{ell} is varied over a 0.01 mm range

The error bars on these data points come from the maximum change in frequency allowed for convergence set in HFSS[2]. No useful relationship was observed, so we will shift our focus now to simulating deformed geometries directly in HFSS.

2.6 Simulating Deformed Meshes

A system was developed to transfer a deformed mesh from ANSYS Mechanical to HFSS for simulation. This process is far from ideal, requiring nearly an hour to obtain a resonant frequency with reasonable accuracy for a given amount of force. Nonetheless, we were successful in obtaining data for two values of force showing that the monopole frequency *does* decrease when force is increased:

Force(N)	Frequency(GHz)
1000	2.4087 ± 0.0007
10000	2.4060 ± 0.0012

Table 1: Two values of force and corresponding frequencies

Using these two data points we obtain a tuning sensitivity of 290 ± 50 Hz/N. The uncertainty of this number is quite high, but it serves to show that a tuning system applying force in the way described here is potentially viable.

3 Future Work and Conclusions

Much improvement could be made on the accuracy of electromagnetic simulations. HFSS is a powerful tool but is ultimately limited by how well it is integrated with the rest of the project. Ideally, an improved system would use the same mesh for both mechanical and electromagnetic simulations, but careful convergence testing would be required to verify the accuracy of any results obtained this way. Additionally, implementation of a tuning system for a PBG cavity would require much work in mechanical design beyond the simple simulations tested here. No design of a full tuning system was attempted here, but this work has shown that tuning of PBG cavities is feasible.

[2]Convergence critera are explained in more detail in Appendix A.

4 Acknowledgements

I would like to thank my advisor, Thomas Oseroff, for his help and guidance in this project. I would also like to thank Cornell for giving me this research opportunity. This work was funded through NSF Grant No. DMR-1332208.

References

[1] H.Padamsee, J.Knobloch and T.Hays, "RF Superconductivity for Accelerators", WILEY-VCH, Second Edition.

[2] Sergey A. Arsenyev. Photonic Band Gap Structures for Superconducting Radio-frequency Particle Accelerators. PhD thesis, MIT, 2016.

[3] "Cavity Modelling Tutorial". Mattias McMullin, accessible for CLASSE users at `\\samba\user\mwm239\Ansys Docs\Cavity_Modelling_Tutorial.pdf`

[4] "Cavity Analysis with HFSS". Mattias McMullin, accessible for CLASSE users at `\\samba\user\mwm239\Ansys Docs\Cavity_Analysis_with_HFSS.pdf`

Appendix A

Meshing and Solution Convergence

HFSS uses an adaptive pass method to solve eigenmode problems such as the one described here. An initial mesh is generated from the geometry, and then HFSS finds a solution for that mesh. The mesh is then refined and another solution is generated. This process is repeated until the user-defined convergence criteria are met.

There are two important convergence criteria in HFSS. First, the maximum change in frequency between passes for a pass to be considered "converged". This was usually set to be somewhere between .01% and .05%, although a higher value was used to speed up the already long collection process described in section 2.2. The second important criterion is the number of converged passes. Instead of just accepting the first pass with a change in frequency less than the specified value, there is an option to require that multiple passes consecutively satisfy that condition. This was set to be three passes in all simulations used here.

As the mesh is refined, the change in frequency usually, but not always, decreases.

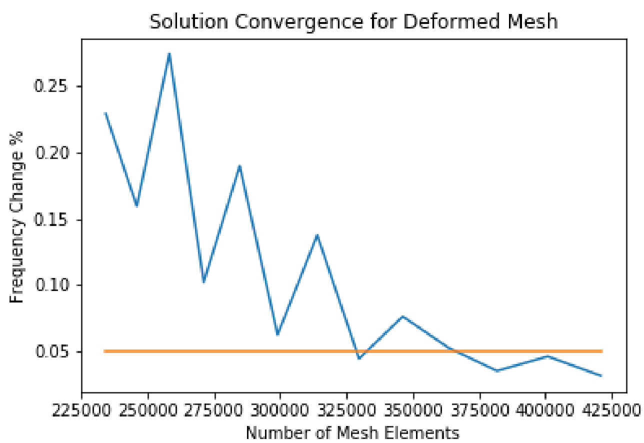

Figure 12: Convergence of a solution for a PBG deformed by a force of 10000 N. The orange line represents the .05% maximum frequency change setting

Figure 12 shows convergence for a mesh imported from ANSYS Mechanical into HFSS. This process is highly inefficient. The geometry is meshed first in Mechanical for deformation calculations, and then brought to HFSS, where it is meshed again several times. The frequency change setting can of course be set to be lower than .05%, but ultimately the accuracy of the solutions is limited by the initial mesh created in Mechanical. Because of this, we were careful to use a fine mesh in Mechanical and to use the same mesh for the two data points shown in section 2.6. Even so, values obtained using this method are probably not reliable for anything coarser than those data points presented.

The ability to alter the convergence criterion might suggest that the data used in parameter correlations, like that in Fig. 11, could have been made more precise. This might be possible, but performance limitations catch up quite quickly.

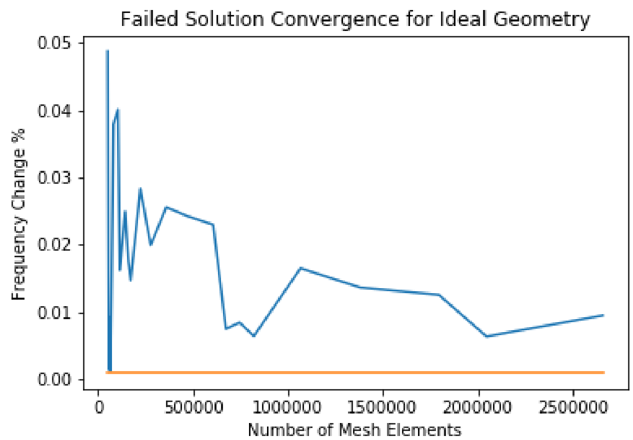

Figure 13: A failed, RAM-limited, solution for an ideal, non-deformed geometry. The orange line represents the .001% maximum frequency change setting.

Fig. 13 shows an attempt at increasing the precision of parameter correlations. Here, the model used was the ideal PBG cell geometry. This model is geometrically far simpler than the deformed meshes, but even so, HFSS was not able to find a solution with the specified criteria. The simulation shown here ran for approximately two hours before crashing due to RAM limitations[3]. Even if this RAM limitation could be solved by some optimization, the solution time still makes high precision solutions impractical for applications that require many data points.

[3]The PC in use has 32GB of RAM.