Examination of Microphonic Effects in SRF Cavities

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Superconducting RF cavities in Cornell's proposed Energy Recovery Linac contain the electric field essential for acceleration of electron bunches. However, these cavities are susceptible to mechanical vibrations which, due to their thin walls and the narrow bandwidth of their resonance curves, can shift the resonant frequencies of the cavities and severely deform the electric field, thus reducing the overall efficiency of the ERL. In-depth studies of these frequency shifts are imperative in order to discern under what conditions they will occur, to what extent, and how to compensate for them. Such investigations began this summer. First I used a modeling software package called ANSYS to simulate various cavities and find their natural mechanical resonant frequencies. I then tested corresponding real cavities for confirmation of modeling accuracy, using piezos to both drive and detect the vibrations. Results show that ANSYS can predict with reasonable accuracy many of the resonances of the SRF cavities, and will be a valuable tool in determining which stabilizing configurations are most effective.

I. INTRODUCTION

Upon the expiration of CESR's use as an electron storage ring, it will be used primarily as a source of x-rays. Unfortunately, multiple passes around the ring make it very difficult to maintain small emittance. The key to feasible operation while achieving consistently small beam size will be the proposed energy-recovery linear accelerator (ERL) [1]. The basic scheme of the ERL is shown in Fig. 1. Electron bunches are injected into the linac where they encounter a series of superconducting RF cavities. These cavities are shaped such that the electric field inside is as shown in Fig. 2. Each cell is half a period long, so when the bunch enters the next cell, the electric field has alternated its direction so the bunch sees the same field orientation as the previous cell and is again accelerated. By the end of the last cavity, the bunches will have increased their energy by a factor of 500. They continue on the recirculation path, radiating x-rays until they return to the linac for deceleration. The path is chosen to be half of a period offset, so that when the bunches re-enter the cavities, they see the opposite orientation of the electric field and decelerate accordingly, thereby giving their energy back to the field so the cycle may continue.

For this process to work effectively, the bunches must experience the highest field amplitude possible. This occurs when the driving frequency of the bunches coincides with the natural resonant frequency of the cavities. The 7-cell niobium cavities [2] have a natural frequency of 1.3 GHz, so the bunches are constantly driven at that frequency. However, mechanical vibrations from traffic, pumps, and ground motion can disturb the cavities and shift this frequency, causing mismatch between the frequencies of the cavities and the bunches, and possibly distorting the electric field mode. It would require significant amounts of energy to re-stabilize a cavity field. Therefore, it is important to determine several aspects of the vibrational qualities of these cavities: the resonant frequencies of the cavities must be identified, because if they lie near the frequency of surrounding equipment, they will be

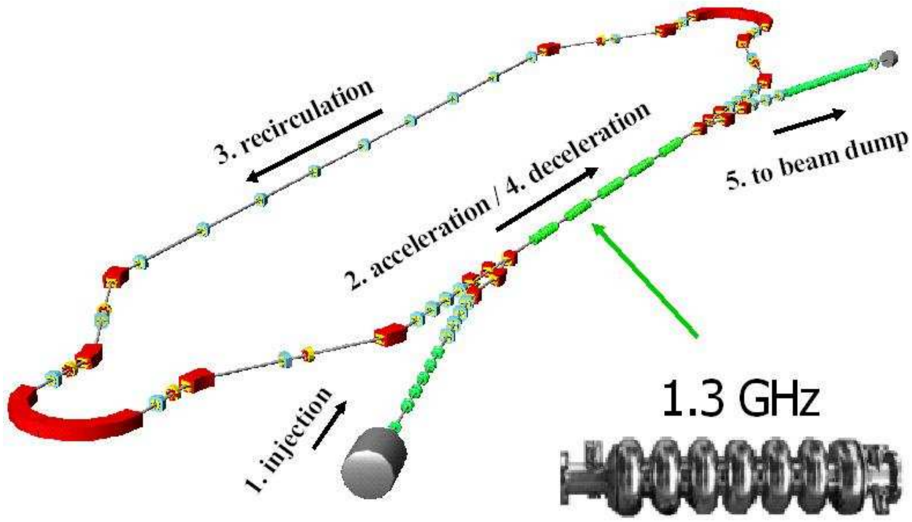

FIG. 1: Basic proposed ERL configuration

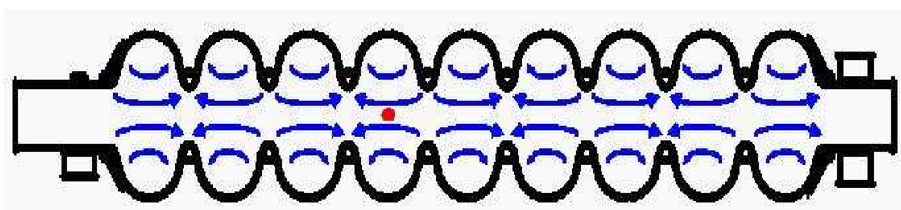

FIG. 2: Cavity cross-section indicating direction of electric field (arrows) as an electron bunch (dot) traverses the cells. When the bunch enters the next cell, the field orientation will be reversed.

amplified and cause greater distortion to the field; various stabilizing precautions must be tested, such as the addition of support structures and their optimal locations; active compensation schemes must be investigated, including the strategic placement of piezos on the cavities. The exploration of these questions was the basis of my research.

II. SIMULATION AND VERIFICATION

To gain a knowledge of the natural resonances of the SRF cavities, I imported their exact geometries into ANSYS [3] and performed modal analysis on single-cell and 7-cell structures. These simulations were performed with varying parameters, depending on which cavity each model was intended to represent. For example, copper properties were chosen to model a certain single-cell Cu cavity (Fig.3) that was tested later. For all theoretical modeling, niobium properties were used. This theoretical modeling was done to examine how a cavity would behave under conditions that could not yet be realized in the lab. One such model was used to compare resonances of a regular 7-cell cavity (Fig. 4) to those of a cavity with additional supports between each cell (Fig. 5). Another simulation showed how a 7-cell cavity would vibrate if the middle of the center cell was fixed. Yet another explored the effect of changing the cavity's wall thickness. These "hypothetical" simulations can provide insight as to what kinds of arrangements may be helpful in reducing microphonics.

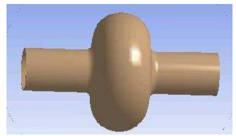

FIG. 3: Model of single cell cavity

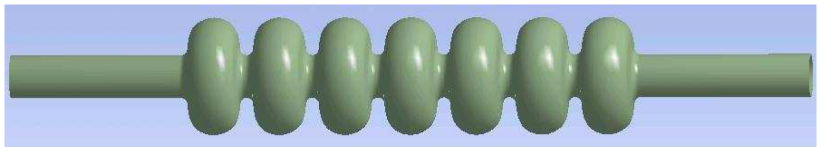

FIG. 4: Model of 7 cell cavity

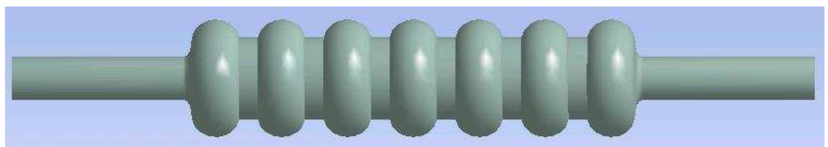

FIG. 5: Model of 7 cell cavity with additional cylindrical supports between each cell

The ANSYS models are also useful in showing which vibrational modes are most detrimental to the stability of the electric field. Transverse modes are not likely to change the field by an unacceptable amount, whereas longitudinal modes have very strong effects. Breathing modes, where all or part of the cavity expands radially from the major axis of symmetry, will also cause major distortions to the electric field. The models display at which frequencies these longitudinal and breathing modes occur, and consequently the SRF group can then try to avoid exciting them. Examples of various types of vibrational modes are illustrated in Fig. 6.

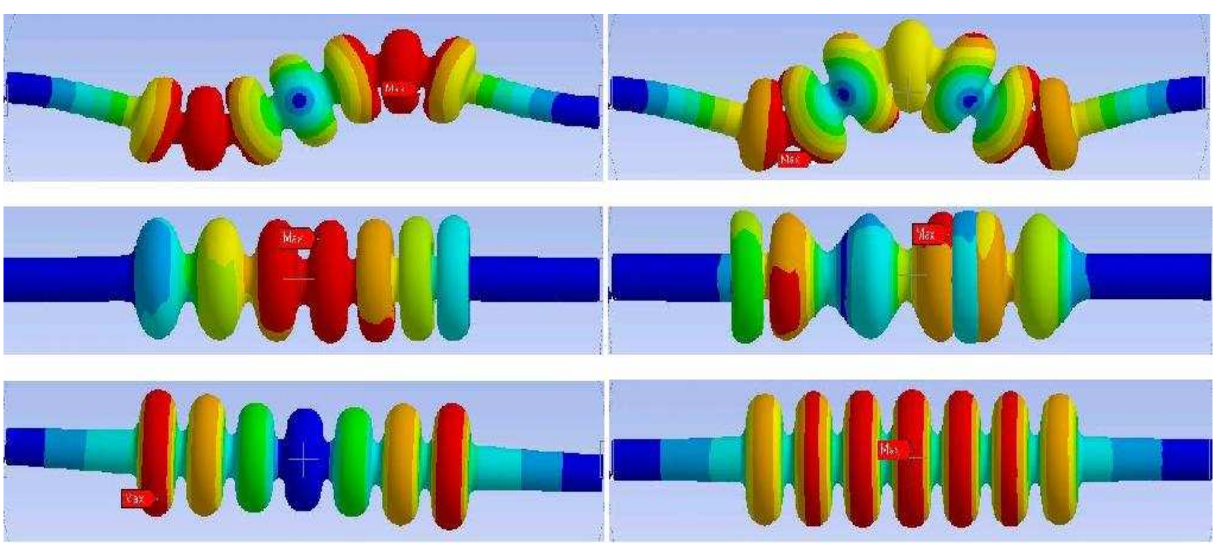

FIG. 6: Some vibrational modes of a regular 7-cell SRF cavity. First row: transverse modes. Middle row: longitudinal modes. Bottom row: breathing modes.

I attempted to verify the validity of these models by comparing their results to readings from actual cavities. First I scanned for resonances on a copper 1-cell cavity, and then on a copper 7-cell cavity by means of the setup shown in Fig. 7. A voltage is applied to the driving piezo underneath the cavity, causing it to vibrate. The reading piezo at the top of the cavity detects these vibrations. This piezo is connected to the oscilloscope which displays the change in amplitude as a function of frequency of the vibrations. When the signal reaches a peak amplitude, this is a resonance of the cavity. The lock-in amplifier scans over a specified range of frequencies, and a Lab View program records the magnitude of the vibrations. The data is written to a file which I plot in Excel. One such plot is shown in Fig. 8. This scan was performed with both the driving piezo and the reading piezo underneath the cavity. A prior scan was done with one piezo on top and one underneath, but this setup proved to be less sensitive. The vertical bars indicate where the modeled frequencies lie with respect to the scanned resonances.

FIG. 7: Experimental Setup: scanning for resonances of a Cu 7-cell cavity. The cavity is shown lower left, with the data acquisition equipment on the table on the right.

III. RESULTS AND CONCLUSIONS

This research brings many interesting findings that will be taken into consideration as the ERL project continues. As can be seen in Fig. 8, there is good agreement between the ANSYS simulations and actual data, verifying the validity of simulated results. All of the modeled resonant frequencies fall within 10 Hz of a measured frequency. There was an undetermined problem with the scan in the range of 530-700 Hz, which is where the only inaccuracies occur. The presence of many other measured resonances can be attributed to vibrations of the plates that hold the piezos, and of the frame that holds the cavity. The ANSYS models show how the undesirable longitudinal and breathing modes vibrate and at which frequencies they occur. Since these resonances can be excited by the presence of surrounding equipment vibrating at the same frequency, the SRF group will want to locate and minimize any of these vibrations and find means of decoupling them with the cavities.

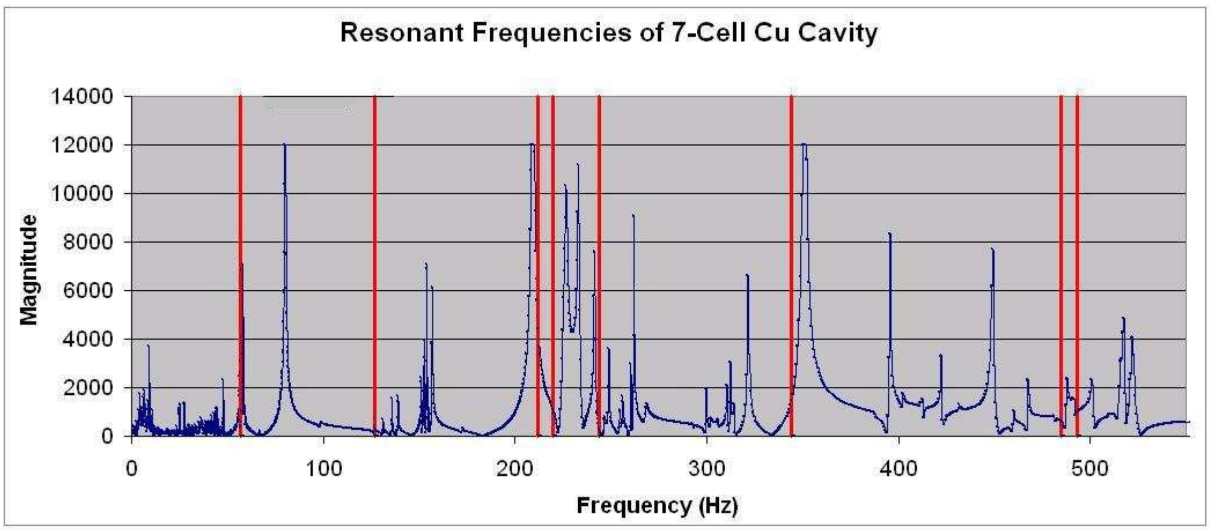

FIG. 8: Modeled and experimental data

The theoretical models show that in principle, varying the wall thickness of the cavities will not change their resonant frequencies very much (Table I). I modeled a regular 7-cell Nb cavity with the standard width of 3mm, and then a 7-cell Nb cavity with a width of 4mm. Changing the width by 30% only increased the frequencies by a few Hz at most. It is expected that the magnitude of the vibrations decreases with increasing wall thickness, but this will be verified later.

TABLE I: Resonant frequencies (Hz) for 7-cell Nb cavities of varied thickness.

3mm thick	4mm thick
53	52
119	117
195	193
207	204
229	210
322	318

Ground vibration amplitudes decay as $1/f^4$, so there is much lower driving ground vibration at higher frequencies. Also, mahcinery vibrates mostly at frequencies below 200 Hz. Therefore, we see less driving of cavity vibration modes at higher frequencies. In addition, the control bandwidth of a piezo is limited by the lowest frequncy, meaning that it can compensate only up to a portion of the ground vibration frequency of the cavity, so higher frequencies yield broader control bandwidths. For all these reasons, it is important to be able to shift the cavity's resonances upward as much as possible.

According to the simulation, incorporating cylindrical supports into the cavity design (Fig. 5) would increase its resonant frequencies, while the same number of problematic longitudinal and breathing modes still remain within the concerned range ($< 1000Hz$). This can be useful in that the result is simply to shift the location of the harmful modes.

Fixing the center of the middle cell (so the cavity may still be tuned from the sides) significantly increases the resonant frequencies. I also modeled a cavity with both inter-cell supports and a fixed center. Comparisons of these hypothetical simulations are shown in Table II. The addition of both of these modifications results in the greatest frequency increase of the modes, which is the optimal case.

TABLE II: Modeled resonant frequencies (Hz) of a 7-cell Nb cavity with various structural modifications. * indicates longitudinal or breathing modes

Regular	Supports between cells	Fixed center	Supports and fixed center
53	75	172	275
119	185	419	280
195*	192*	475*	648*
207	272*	522*	655*
229*	335	630	746
323	340	910 *	761
456	580	915*	930*
464*	634*	1180*	1450
522*	905	1182*	1520*
566	930*	out	out
637	1055*	of	of
668	1245	range	range

The SRF group will continue to use ANSYS to simulate various configurations and determine which setups could be useful in minimizing the effects of microphonics. Future work will involve the investigation of piezos as a means of active compensation for frequency mismatch between the cavity and the electron bunches. Piezos expand and/or contract when a voltage is applied to them. They may be attached to areas of the cavity where vibration amplitude becomes large, and the appropriate voltage can be applied so as to stiffen or slightly change the shape of the cavity and shift its resonance to the desired frequency. An optimistic endeavor is the hopeful creation of a program that will measure the incurred frequency shift of a cavity due to microphonics and apply the necessary voltage to any attached piezos to minimize the shift. Now with a greater understanding of the vibrational nature of the SRF cavities, the door is wide open for more promising movements toward the ERL.

IV. ACKNOWLEDGMENTS

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[1] Study for a proposed Phase I ERL Synchrotron Light Source at Cornell University, ed. by S. Gruner and M. Tigner, CHESS Tech. Memo 01-003, JLAB-ACT-01-04 (July 2001).

[2] Conceptual Layout of the Cavity String of the Cornell ERL Main Linac Cryomodule, Proceedings of the 11th Workshop on RF Superconductivity, Travenmunde, Germany, September 8-12, (2003).

[3] www.ansys.com