Ground Vibration and Siting of the Cryogenics Facility for Cornell ERL Prototype

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1 INTRODUCTION

A prototype Energy Recovery Linac (ERL) has been proposed and schematic design of the facility is underway. Such a facility necessarily involves the juxtaposition of extremely sensitive superconducting RF cavities and the noisy and powerful motors and compressors used to make the liquid helium the cavity needs. In this paper we give preliminary consideration to the possible deleterious effects on the performance of the superconducting cavities due to microphonics generated by the helium compressors. The compressors are singled out because by far they are the highest power mechanical system in the facility driven by a total of approximately 1100 hp. The cavities for the ERL are expected be especially sensitive to microphonics due to the relatively high Q_{ext} of 2.6×10^7, corresponding to a half width half maximum bandwidth of 25 Hz.

At some distance from the cryoplant the local cultural noise sources will dominate over those produced by the cryogenic compressors. Siting further away than this distance yields no realizable benefit if the local sources cannot be removed. If at least 300-400 ft were kept between the compressors and the cavities there would be little concern about their influence via ground vibration as other facilities have operated in this mode and either microphonics have not played a role or microphonics are dominated by sources other than ground vibration. [1] However there are strong economic reasons to site the cryogenics facility close to the cavities: to minimize the capital cost of transfer lines, and more importantly to reduce the cryogenic losses in the transfer lines which in turn reduces the size and operating cost of the cryoplant.

For the proposed ERL prototype [2] a detuning tolerance also of ± 25 Hz was assumed which then determined the optimal Q_{ext} and the required klystron power capability of 13 kW per cavity. If instead, 15 Hz were the detuning tolerance the required power would be reduced by about 3 - 4 kW per cavity. For reference, measurements at the TTF (Tesla Test Facility) on cavities very similar to those to be used in the ERL prototype showed peak to peak detuning range of ± 10 Hz. The TTF cavities have a much larger bandwidth of 260 Hz half width at half maximum and a Q_{ext} of 2.5×10^6[3]. The higher detuning tolerance for the prototype was chosen to be conservative because very little was known about the actual microphonic levels that will be present.

One can obtain an estimate of the minimum siting distance of the compressors by breaking the problem into three pieces:

1. Determine the amount of vibration caused by the cryogenics plant at a given distance.
2. Determine the correspondence between the ground vibration levels at the cavities and the detuning it causes.
3. Determine the maximum detuning tolerance such that klystron power remains reasonable.

By measuring the vibration levels produced by a similar cryoplant at various distances and locations and studying the physics of the vibrations of soils and foundations which are expected to be present at the prototype facility we can arrive at an estimate for the amount of ground vibration levels at the cavity location. The effect of these ground vibration on the cavity length can be roughly estimated from some theoretical calculations of the structures and some measurements of intentionally excited cavities.

1.1 Measurements at Other Facilities

Many ground vibration measurements have been made of accelerator tunnel areas and seismically quiet areas. These were done to study the effects of vibration on beam quality for linear colliders where the motion of quadrupoles is the most critical phenomena. The measurements show that cultural noise at an accelerator site (generated at or near the site by man-made phenomena) is typically four orders of magnitude greater than measurements in culturally quiet sites in the frequency band of interest — a few Hz to a few hundred Hz [4] p347, [6]. Only one instance of measured ground motion near superconducting cavities has been previously documented as far as this author can find out. It shows the presence of strong vibrational peaks which are ascribed to the compressors. [7]

The largest narrow band sources of microphonics measured in a test cryostat at the TTF are identified [8], page 10, as due to the helium compressors and vacuum pumps. It is not known exactly how the vibrations produced by these devices couple to the cavities. Possibilities include through the cryogenic lines including acoustic signals through the helium, through the beam tubes, and through the ground via the cryostat supports [5] p427. What is observed is that the resonant frequency of the cavity is modulated strongly at the compressor frequency. The largest line in the measured CW microphonics spectrum was at 287 Hz and was associated with a mechanical resonance in the cavity. It varied from cavity to cavity. The source of the exciting vibration was not identified.

There have been theoretical studies of the mechanical resonances of superconducting RF cavities of the TESLA structure. [9] Calculations of the resonant frequencies of the lowest transverse and longitudinal modes were made. The lowest frequency longitudinal mode with the 'constrained' structure (the end plates are held rigidly) was calculated to be 234 HZ, which is not that far from the large mechanical resonance frequency observed by Liepe at 287 Hz on the TTF cavities. The next calculated longitudinal mode is at 465 Hz. The mechanical Q factors for these modes are expected to be the in the range of 60 to 200 [10] based on measurements on other cavities in liquid helium.

2 VIBRATION MEASUREMENTS NEAR THE CESR CRYOGENICS FACILITY

A series of Geophone measurements were made at various locations and distances from the CESR cryogenics compressors. The compressor motors consist of three large electric motors with a total power of 925 hp. The motors are firmly mounted to the foundation and located within about 20 ft of each other. Figure 1 shows the locations of the center of the motor distribution and the measurement points. The compressors and three of the measurements were all on a common foundation slab nominally at the third floor level. The slab is actually on grade as the building is built into the side of a hill. The remaining measurements are at the ground floor level approximately 20 feet lower.

Power spectrum measurements of vertical motion were taken using velocity sensitive Geophone detector with a resonant frequency of 1 Hz and an HP 35665A dynamic signal analyzer. Measurements of third floor locations plotted in Figure 3. The measurement taken closest to the motors (28 ft) shows very violent motion over a wide frequency range. The floor could be felt to vibrate especially at lower frequency. At this location the acoustical level of noise was painful and ear protection was necessary. One can see the trend that the higher frequencies tend to get damped preferentially with distance from the noise source. This is a significant result in that it means that the high frequency demands on the piezo tuner are lessened.

The other third floor measurement locations were not so obviously unsuitable. However the spectrum taken at 67 ft has a very large peak near 60 Hz. In fact when the power spectrum is integrated over the frequency range of 1 to 400 Hz, the integrated rms vertical displacement at 67 ft is almost the same as at 28 ft as shown in Figure 2. The point at 106 ft has a similar overall power spectrum to that at 67 but with substantially less 60 Hz peak.

The other four measurement plotted in Figure 2 were taken at ground level (i.e., Level 0). The East Flare location (54 ft) was actually quite close to the compressors but 20 ft below. The East SRF Cavity location (118 ft) might have had some significant noise source locally present in the form of water pumps. The points at L0 and Metal Rack were general access areas with no special equipment nearby that would generate large vibrations. The power spectrum from these data are shown in Figure 4. At frequencies above 100 Hz the data is very similar for all locations though there are noticeably stronger harmonics of 60 Hz at the Metal Rack location. There is a large peak at 90 Hz in the horizontal spectrum taken at the East RF cavity. The largest excitation peak of any of the four ground floor measurements is at 60 Hz which is especially large in the L0 location.

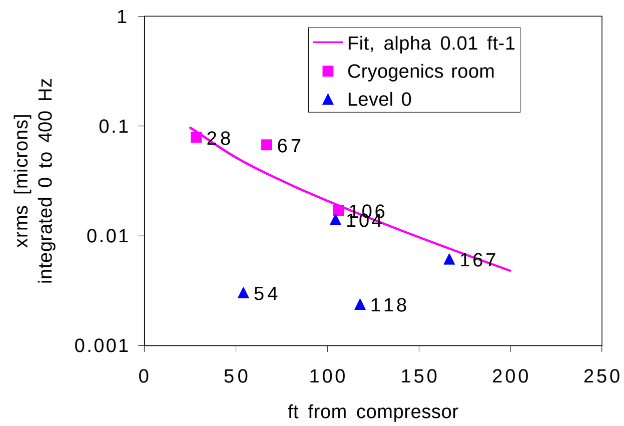

Figure 2: RMS vertical motion integrated from 1 to 400 Hz at various locations.

The integrated rms displacement is calculated from the power spectrum and the result for all measurement points is shown in Figure 2. There is a clear correlation of the integrated motion with distance, but also more than an order of magnitude spread in rms motion at a given distance which indicates that distance is not the only relevant factor.

3 ESTIMATED GROUND MOTION

Given all the uncertainties and complications only the simplest model of the expected level of ground motion and its attenuation with distance is worth considering. Present plans assume the cryogenics equipment in separate building on a separate foundation located at grade level with the SRF cavity in a 'bunker' some 20 ft below grade and a distance to be determined. The fact that there is a separate foundation and that the cavity is well below the surface both contribute to isolate the vibrational energy from the cavities. We should therefore expect the situation in the prototype to be most like that observed for the level 0 measurement points.

At larger distances vibrational motion decreases due to material damping and geometrical scaling. There are three kinds of waves that transport the vibrational energy: R (Rayleigh) waves are surface waves and transport about 2/3 of the energy. S (shear) waves are full three dimensional waves and transmit about 1/3 the energy and P (longitudinal) can be neglected as far as vibration excitation is concerned. Since a Rayleigh wave is bound to the surface, from geometry one can see that the amplitude is reduced with distance as $1/\sqrt{d}$, where d is the distance from the source. For simplicity we assume the Rayleigh waves

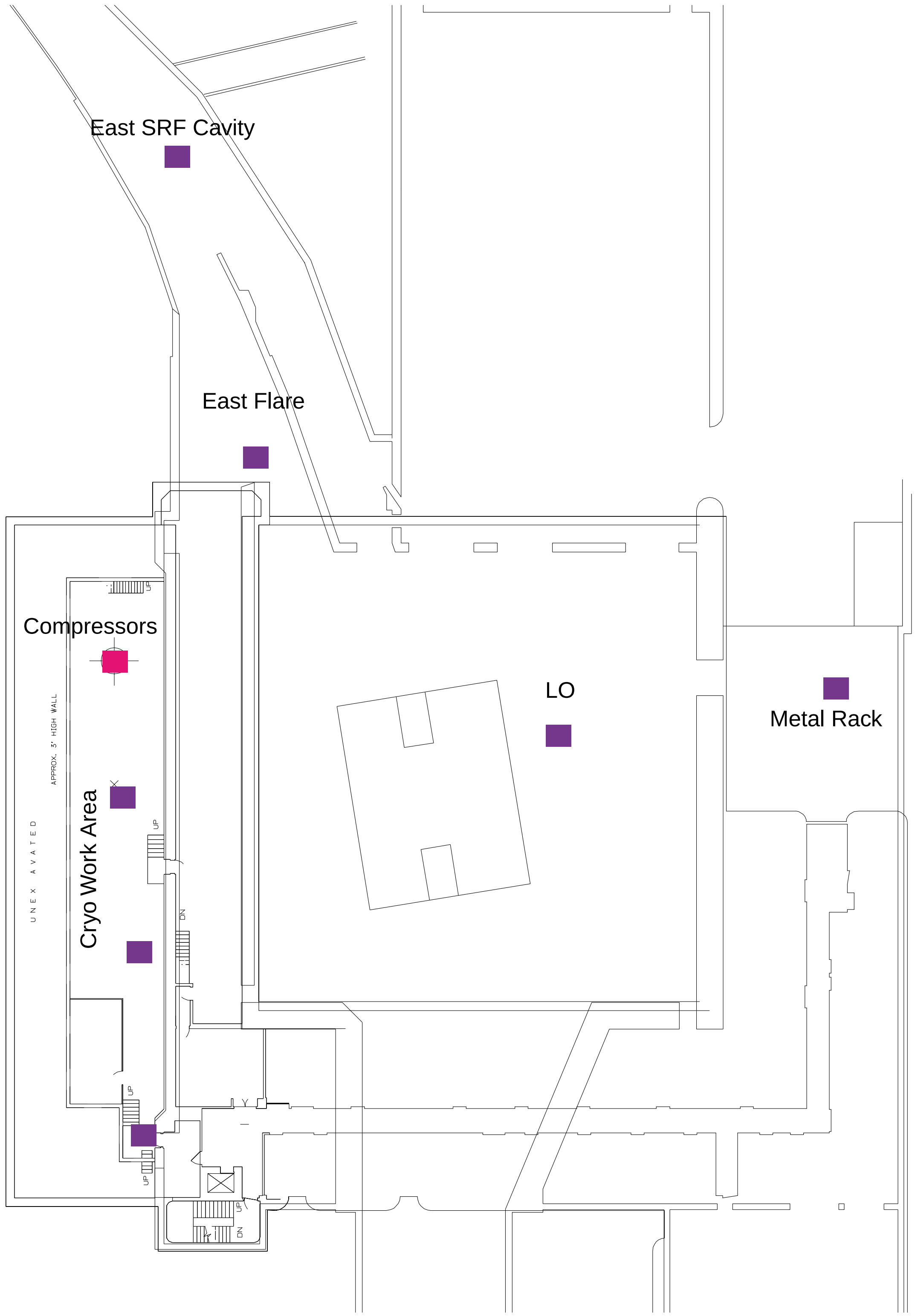

Figure 1: Points where vibration measurements were taken are marked as is the location of the cryogenic compressor motors.

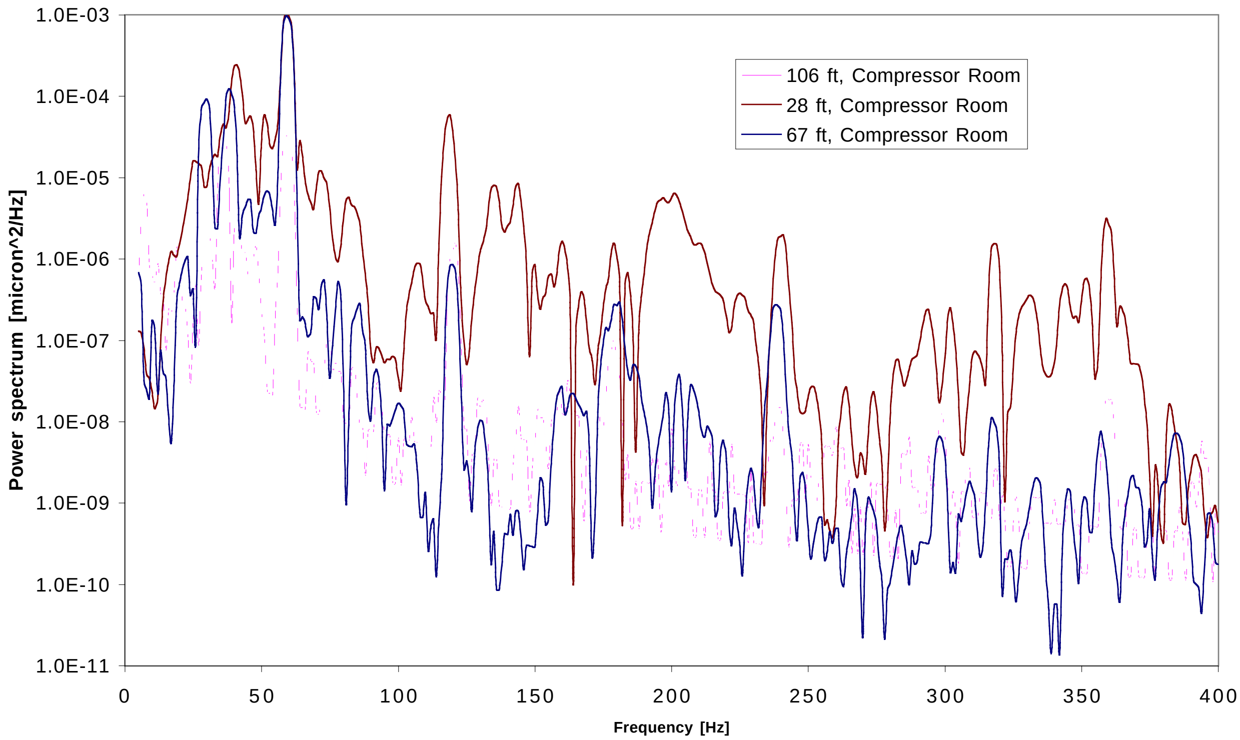

Figure 3: Power spectrum measurements on common slab with compressor motors.

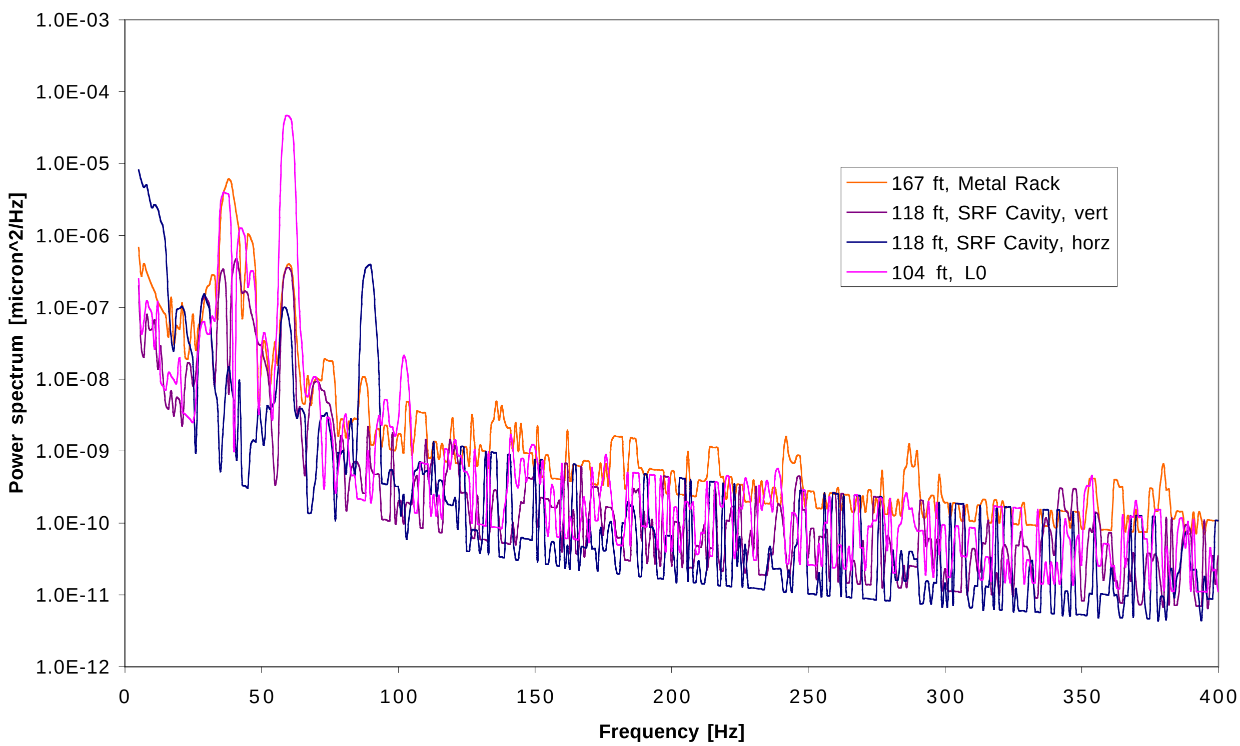

Figure 4: Power spectrum at ground level, two floors below the compressors and at grade.

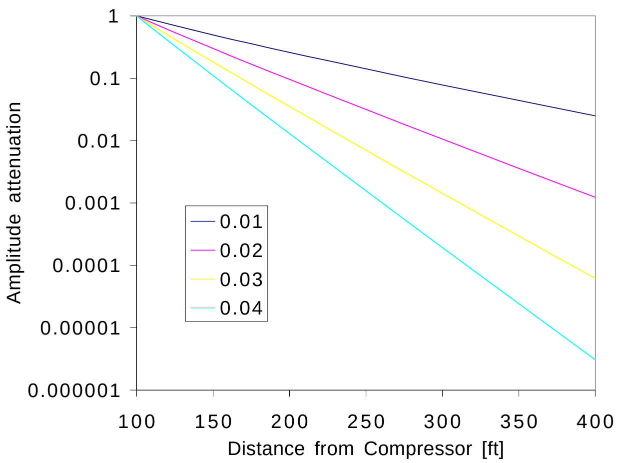

Figure 5: Attenuation of the vertical component of Rayleigh with distance including geometrical and material damping normalized to a source distance of 100 ft. Curves for four different values of the attenuation coefficient are shown.

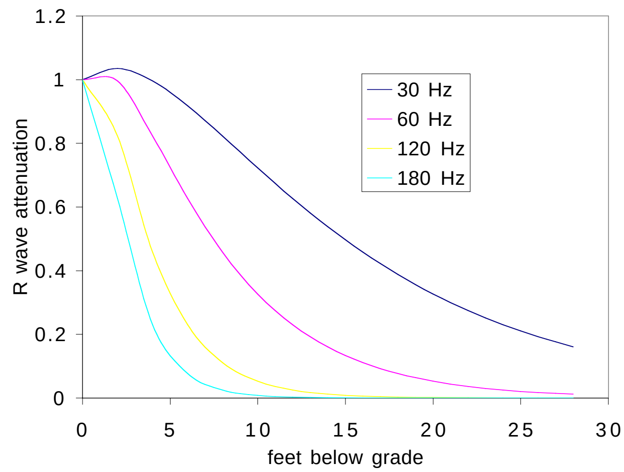

Figure 6: Attenuation of the vertical component of Rayleigh waves as a function of depth at different frequencies.

will dominate. Material damping of the Rayleigh waves also occurs and leads to an additional exponential decrease of amplitude with distance. Measured and recommended values for the material damping attenuation coefficient α range from 0.01 to 0.04 ft^{-1}, with 0.04 good for morainic (silty, gravelly sand) soil [11] page 245, similar to that at the ERL prototype site.

The net attenuation, geometrical plus material damping, for Rayleigh waves may then be expressed as,

$$w = w_1 \sqrt{\frac{d_1}{d}} e^{-\alpha(d-d_1)} \tag{1}$$

where w_1 is the amplitude at distance d_1 and w is the amplitude at distance d. This equation is used to fit the Cryogenics room data in Figure 2 and yields a material attenuation coefficient for a single concrete slab of 0.01 ft^{-1}, consistent with attenuation in unfavorable soil types. A plot of the attenuation is given in Figure 5, assuming the reference distance d_1 is 100 ft, corresponding to the L0 measurements. If the soil properties are favorable, as in the case of $\alpha = 0.04\ ft^{-1}$, there is an order of magnitude difference in attenuation to be gained by going 100 and 150 ft away from the source. However, if the soil properties are more like uniform fine sand, then only geometric attenuation has a significant effect over that distance. As mentioned above the soils at the ERL prototype site are more likely to have the higher attenuation coefficient.

Rayleigh waves are also attenuated with depth; more so with high frequency. For a typically value of the poisson ratio for the soil, the attenuation with depth of the vertical component of Rayleigh waves goes as:

$$W(z) = 0.85e^{-5.32zf/v} - 1.47e^{-2.47zf/v}$$

where $W(z)$ is the vertical motion as a function of vertical depth z and v is the speed of sound in the soil. [11] page 88. Normalized $W(z)$ is plotted for several different frequencies in Figure 6. The horizontal motion has a similar dependence. The wave velocity is estimated to be roughly 800 ft/s based on measured values for clay and a sand-gravel mixture, [11] page 117. Evidently attenuation with depth is very important to the isolation of the cavities from the compressors. With 20 ft depth the 60 Hz component is down by an order of magnitude. However it must be kept in mind that this a very simplified model and ignores the effect of the discontinuity of the wave hitting the walls of the bunker which conceivably could bring the Rayleigh wave down to the floor level.

Vertical motion as a function of distance can now be estimated by scaling from the Level 0 data. Two of the Level 0 points shown in Figure 2 more or less lay on the curve fitted to the third floor data, while the other two lay about an order of magnitude lower. Locations at 54 ft and 118 ft are essentially inside the CESR tunnel structure with earth backed concrete on all sides. Points at 104 ft and 167 ft are in the open areas of Level 0 and are more representative of the situation expected in the ERL bunker. Apparently there is little integrated rms attentuation due to depth for these points. Possibly this is because there is a continuous surface path from the third floor to Level 0. The ERL bunker will by buried with approximately 10 ft of earth above it. It is not clear how much this will cause the Rayleigh waves to be attenuated. To be conservative we assume no attenuation with depth and take as a reference point the data at 104 ft, keeping in mind that at the actual site we may get additional attenuation, particularly at higher frequencies. The appropriate attenuation factor for distance can be taken from Figure 5 with 0.04 being the most likely attenuation coefficient to be found at the site. The question now becomes, how much vibration is tolerable?

4 ESTIMATED DETUNING

A vibrational excitation of the floor excites mechanical resonances in the cavity structure through the supports and cryogenic connections. It also generates motion of the beam line and other components which can act on the cavities. For detuning to occur the length, or more generally the volume of the cavity must change. If there is uniform acceleration of the entire cavity the resonant frequency will not change. In this paper we have made use only of the single point power spectrum of vertical motion. If the motion of all points of supports were perfectly correlated only a net acceleration occurs and no detuning. The estimate in this paper of the effects of the ground motion on the cavities assumes the ground vibrations act on a single point of the cryostat or supports and is therefore overly conservative at the lower frequencies where the wavelength of the ground wave is much longer that the distance between supports. However, large acceleration of the whole cryostat have been known to cause substantial detuning even though the support points are moving in unison and the nominal length change is zero. This is due to the extremely large amplitudes and internal degrees of freedom that are excited. [10]

Ground vibration are basically displacement excitation, more or less independent of force. Other sources of microphonics tend to be force excitations such as beam line components and helium pressure fluctuations. Consequently when the coupling to the ground is good, very large forces can be generated with rather small displacements. Consider the rather small ground motion of 1 nm at 60 Hz. If perfectly coupled to the ground a 3500 kg cryostat would experience a peak driving force of a very palpable 0.5 N. If the driving frequency matches a high Q mechanical resonance, 1 nm of excitation can easily turn into 60 - 200 nm of cavity length change. The ERL cavities will have the same frequency sensitivity as the Tesla cavities which is 0.3 Hz/nm [3]. So 25 Hz detuning corresponds to a change in cavity length of $25/0.3 = 83$ nm. So it is possible to see how 1 nm ground motion can drive detuning frequencies beyond the 25 Hz that is assumed for the ERL prototype. However, buy the same argument if the vibrations are kept at or below 0.1 nm there should not be a problem with excessive detuning from microphonics.

5 RECOMMENDATION FOR ERL PROTOTYPE

We now have the ingredients with which to complete the estimate of the minimum distance between the compressors and the cavities. We have

- determined that a level of vibration of 0.1 nm is acceptable while 1 nm is risky,
- established a reference level of vibration equivalent to the measurements made at the L0 104 ft location,
- estimated the attenuation with distance, taking into account the effects of depth.

It is a simple matter to put them together. Looking at the vertical motion at the L0 measurement point, see Figure 7 we see that oscillations stay below 0.1 nm for frequencies about 180 Hz, but that near 60 Hz reach about 20 nm. Hence we need about a factor of 200 attenuation if we are to avoid the possibility of a near 60 Hz mechanical resonance getting overly excited.

The attenuation in the bunker slab will not be as favorable as in the soil. Material damping along acting along 56 ft foundation between the end of the bunker and the cavity location would only provide an attentuation factor of about 2 if it follows the fit given in Figure 2. There may not be much geometric attenuation because the distance to the source is large. To err on the conservative side we assume there is no geometrical damping along the bunker foundation. That means the rest of the factor of 200 attenuation (i.e. 100) must come from attenuation in the soil between the reference point at 104 from the source and the near edge of the bunker. From Figure 5 for the most favorable soil it can be seen that a factor of one hundred attenuation is reached about 200 ft from the source. The net result is that sufficient attenuation is obtained if the distance from the compressors and the near edge of the bunker is 200 ft or more. This is the estimate we have been seeking. It is probably conservative, possibly as much as a factor of ten in vibration levels which is equivalent to about 50 ft in separation distance.

Techniques exist to ameliorate vibrations beyond just using distance and can be exploited to reduce the distance required. Trenches can be dug around the area that needs to be quiet. The trenches block ground waves causing them to have to go deep and around the trench to get to the cavities. Special pilings can be used to support the foundation of the compressors which filters out the high frequency coupling of the compressors to the ground. Visco-elastic materials may be used in the supports of the cryostat in hopes of damping the mechanical resonances. A cost benefit analysis of utilizing these methods versus the reducing the distance required would be beneficial.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

[1] S. Wolff- “vibrations did not play a role for TTF operation”, H. Weise - “during operation we don’t see any problem with mechanical excitations of the cavities caused by the compressors. But I know that long time ago we had a lot of trouble at Darmstadt. Finally we added some bellows in the transfer line and fixed the compressor end of that line in a very rigid way. ”

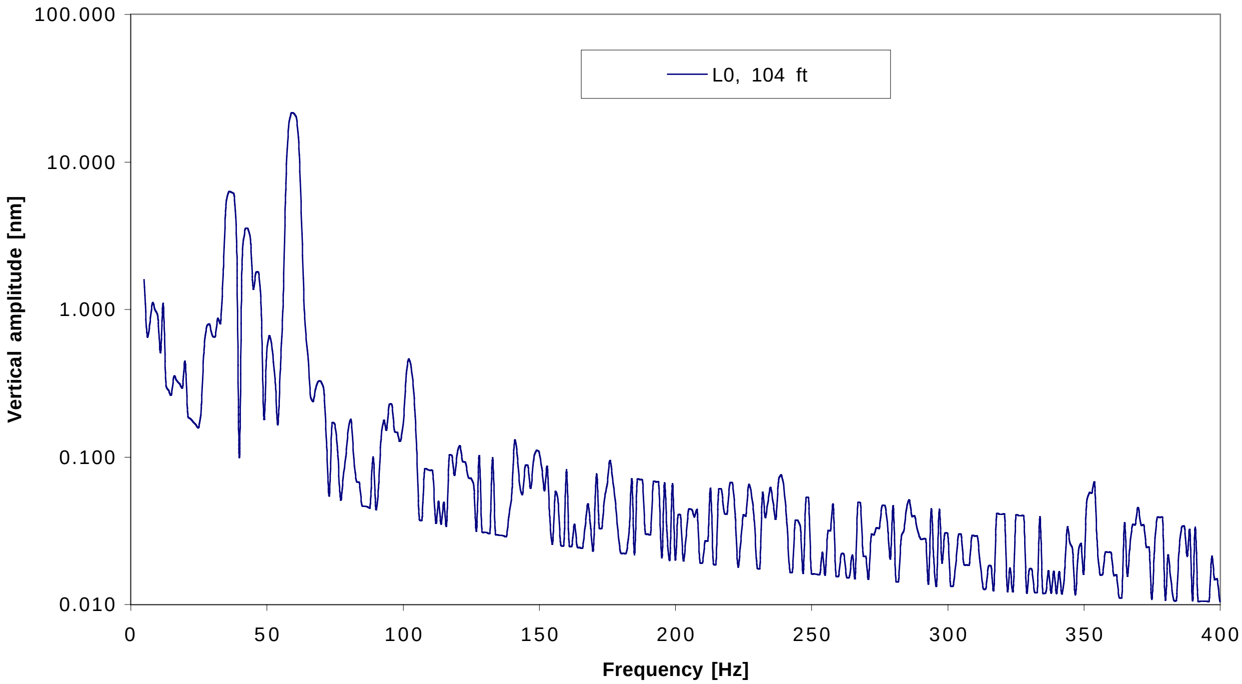

Figure 7: Vertical rms motion measured at the east SRF cavities located about 100 ft from the compressors. This data is used as a reference for scaling.

[2] *Study for a proposed Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University*, July 2001, CHESS Technical Memo 01-003, JLAB-ACT-01-04. editors, S.Gruner, M. Tigner

[3] TESLA Technical Design Report, II-23,

`http://tesla.desy.de/new_pages/TDR_CD /PartII/accel.html`

[4] A. W. Chao and M. . Tigner, *Singapore, Singapore: World Scientific (1999) 650 p.*

[5] H. Padamsee, J. Knobloch and T. Hays, *New York, USA: Wiley (1998) 523 p.*

[6] A. Seryi, “A shaky road to subnanometer beams: NLC ground motion, vibration and stabilization studies,” arXiv:physics/0105016.

[7] Mechanical Modes of Multicell Linac Structures, A. Marziali, H. A.Schwettman, DESY M-92-01, April 92, Proc. 5th Workshop in RF Superconductivity, August 1991, Vol 2.

[8] ‘Superconducting Multicell Cavities for Linear Colliders’, M. U. Liepe, DESY-THESIS-2001-045, October 2001

[9] A. Marziali and H. A. Schwettman [TESLA Collaboration], “Vibrational analysis of the TESLA structure,” TESLA-93-41.

[10] A. Marziali and H. A. Schwettman [TESLA Collaboration], “Microphonic analysis of cryomodule design,” TESLA-93-40.

[11] ”Vibration of Soils and Foundation”, F.E.Richart Jr., R.D. Woods, J.R.Hall Jr. , Prentice-Hall, 1970