| Document Approval: | Date Approved |
|---|---|
| Originator: Georg Gassner, Alignment Engineering Group Leader | 11/18/14 |
| Originator: Chris Adolphsen, RF Technical Lead | 11/18/14 |

**Revision History:**

| Revision | Date Released | Description of Change |
|---|---|---|
| R0 | 11/21/2014 | Original release. |

# 1 Executive Summary

## 1.1 Motivation

The cavities in CW superconducting linacs have very narrow bandwidths (30 Hz for LCLS-II), and are easily detuned by mechanical vibrations and by pressure fluctuations of the helium in the cooling system. The compressors in the cryoplant that cools the helium can create significant nearby ground motion, which propagates outward, decreasing in magnitude along the way. Thus before locating the cryoplant for LCLS-II, one wants some assurance that the resulting vibrations in the SLAC Linac are not large enough to adversely affect the cavity operation.

The CEBAF project at JLAB had a similar concern, and the late 1980's before construction began, did studies of the vibrations induced by their small cryoplant that was used for cavity development (see CEBAF-TN-0077 from 1988). More importantly, they measured how the vibrations of the cryomodules that house the cavities affect the cavity detuning. Basically, they found that motion along the cavity axis mostly does not compress or expand them, and thus minimally detunes them. For example, 1 micron of motion at 30 Hz only detunes a cavity by 2 Hz, compared to 300 Hz if the cavity were compressed by 1 micron. At LCLS-II, we can operate with 2 Hz detuning (we have rf overhead for 10 Hz detuning), so motions on the micron scale, which would require a significant amount of power to generate at the frequencies of interest (above several Hz), can be tolerated. The conclusion of the JLAB study is that the compressors, which are located about 80 m at minimum from their linacs, would have a negligible impact on the cavity detuning, which turned out to be the case.

With the recent upgrade of the JLAB cryoplant, it was decided to revisit the compressor effect on ground motion, and in general, quantify the vibrations at the cryoplant, in the intervening region between the plant and linacs, and in the underground linacs (about 8 m deep, similar to the SLAC Linac). A set of geophones was used for this purpose, which recorded motion along the three axes in the 4 Hz to 1280 Hz range. The data were taken in August of 2014 by Georg Gassner of the SLAC Metrology Department - he also performed the analysis.

The main body of this report details the results from these measurements, and a set of slides are included in the Appendix that highlight some of the measurements. In the following sub-sections, we present the basic findings and a recommendation.

## 1.2 Findings

The MW-level JLAB compressors generate nearby ground motion on the order 1 micron rms at predominately 40 Hz (the rotation rate of the non-driven compressor screw), with a noticeable contribution at 60 Hz (the rotation rate of the driven compressor screw). The remaining rms motion (i.e., ignoring these two components) is of the order 100 nm, similar that on the surface 30 m away from compressors. Thus the compressors do not generate significant broad-band ground motion.

The level of motion at 40 Hz and 60 Hz decreases rapidly with distance from the compressors. Even 16 m away in the cryoplant building, the floor motion is an order of magnitude smaller, about 150 nm vertically. Outside the building, the rms sum of motion along the three axes is about 20 nm at distance of 30 m from the compressors, and decreases to the few nm level in the linac, 95 m away. Thus one can locate the compressors 30 m or even closer to the linac without a significant effect on the cavity detuning from the 40 Hz and 60 Hz vibration components.

The ground vibration on linac floor in the direction of the linac axis is small, around 10 nm, and has a fairly smooth spectrum, without dominate peaks. Also, most of this motion occurs below 10 Hz. On the cryomodules and cryogen supply lines, the motion along this axis is up to 150 nm, and dominated by peaks in the 8 Hz to 20 Hz range, likely from mechanical resonances in the cryomodule and supply line assemblies and supports. Again, this motion should not have a significant effect on the cavity detuning.

## 1.3 Recommendation

The cryoplant layout and ground composition at SLAC will differ from that at JLAB (although the compressor power level will be comparable). To reduce the possibility that the compressors generate significant ground motion, they could be mounted on customized pads to reduce the transmission of the 40 Hz and 60 Hz components into the ground (which was not done at JLAB).

# 2 Measurement Setup

## 2.1 Locations

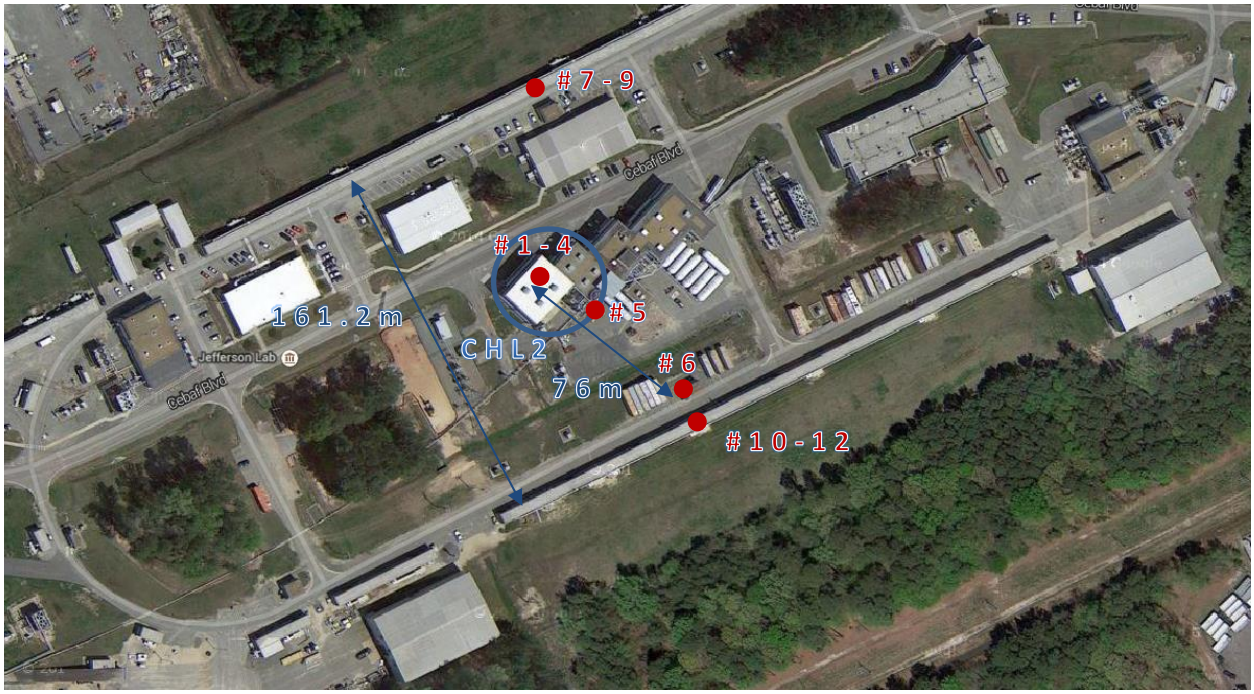



**Figure 1: Site map of the JLAB cryoplant and linac housing. (Source Google Maps).**

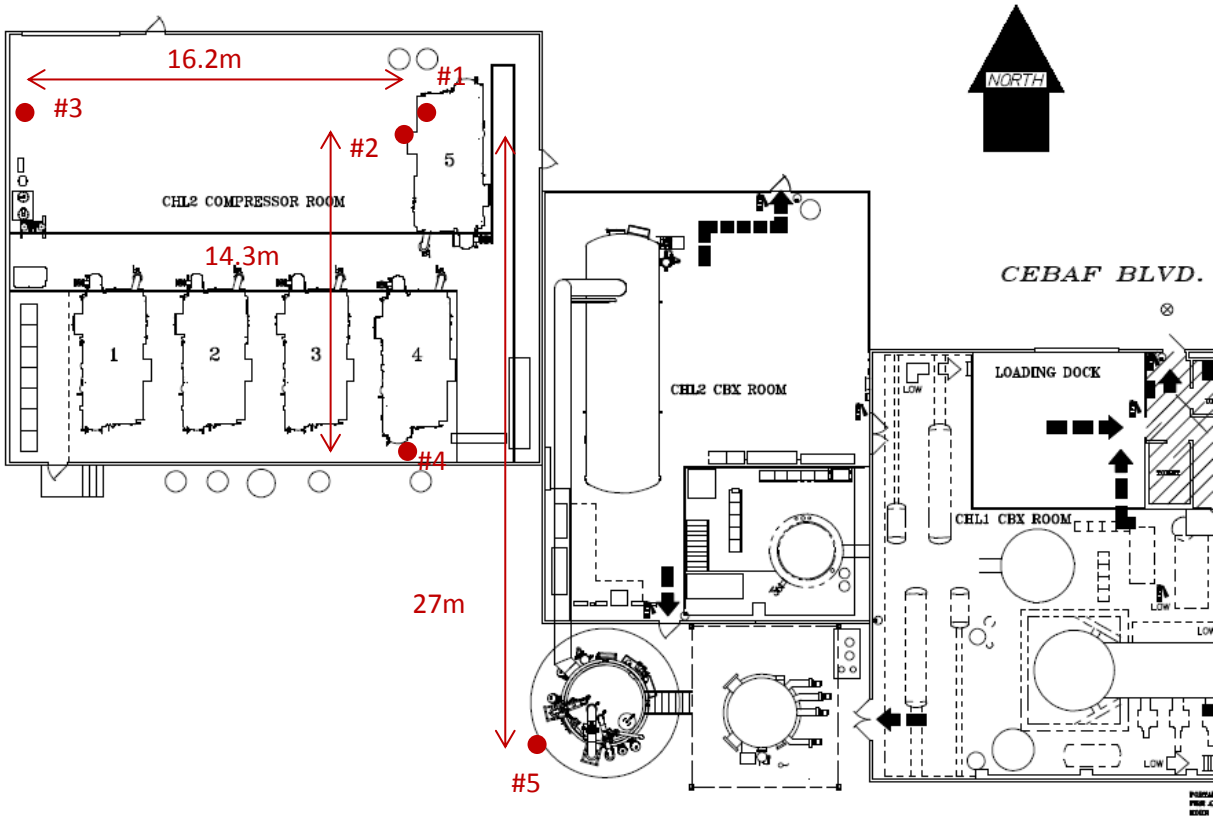
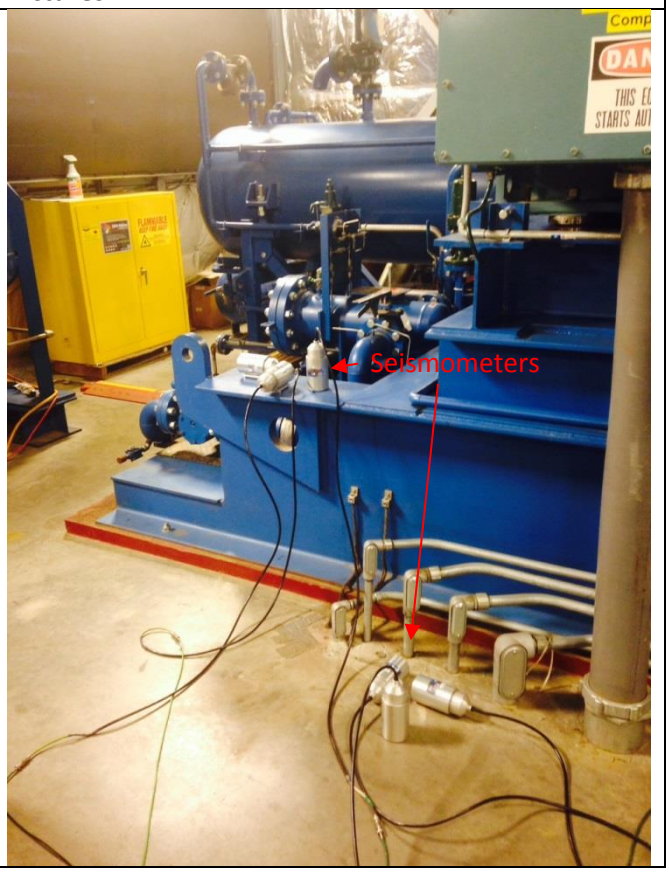
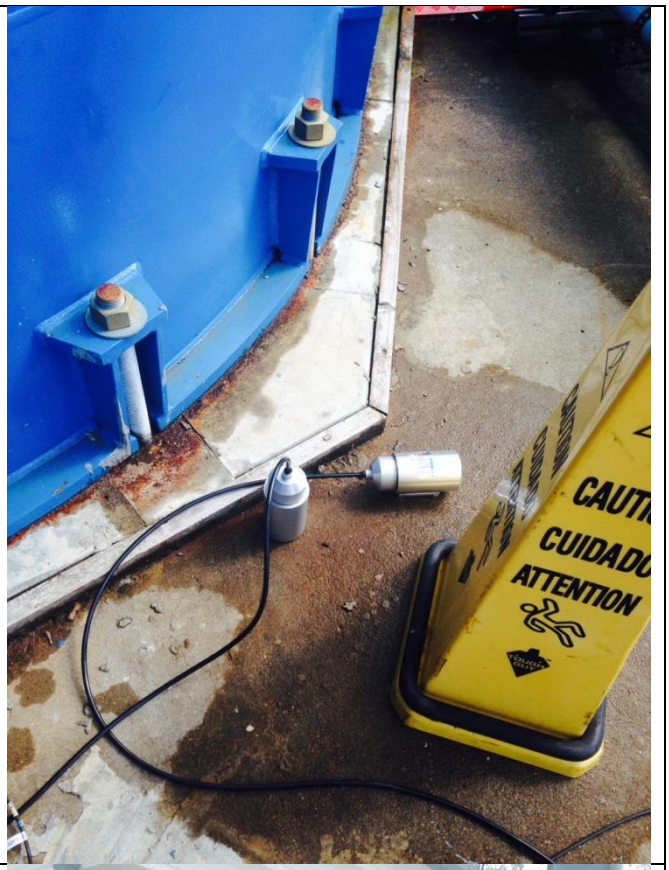



Figure 2: Map of CHL2 compressor room and cold box. (Source JLAB evacuation plan).

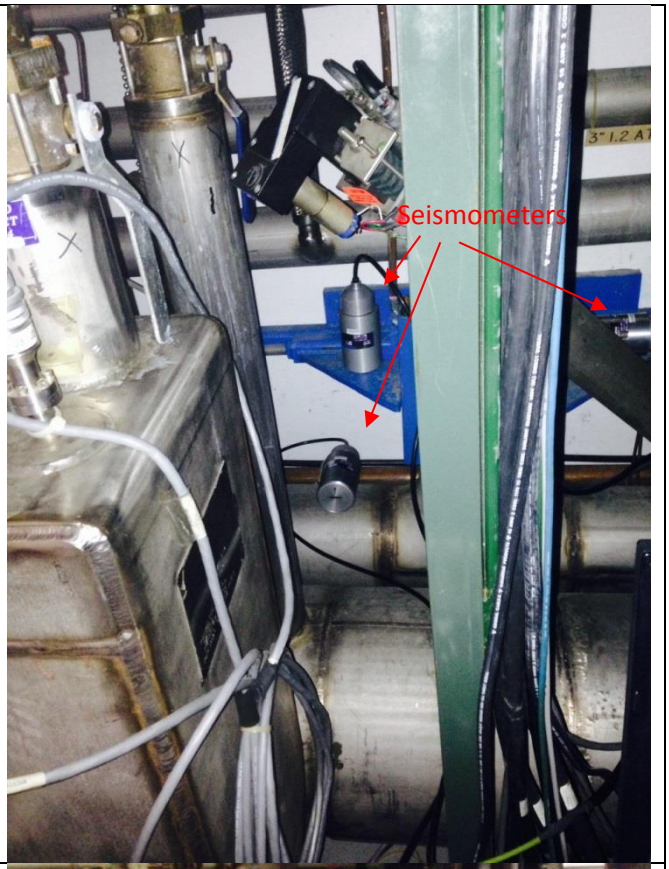
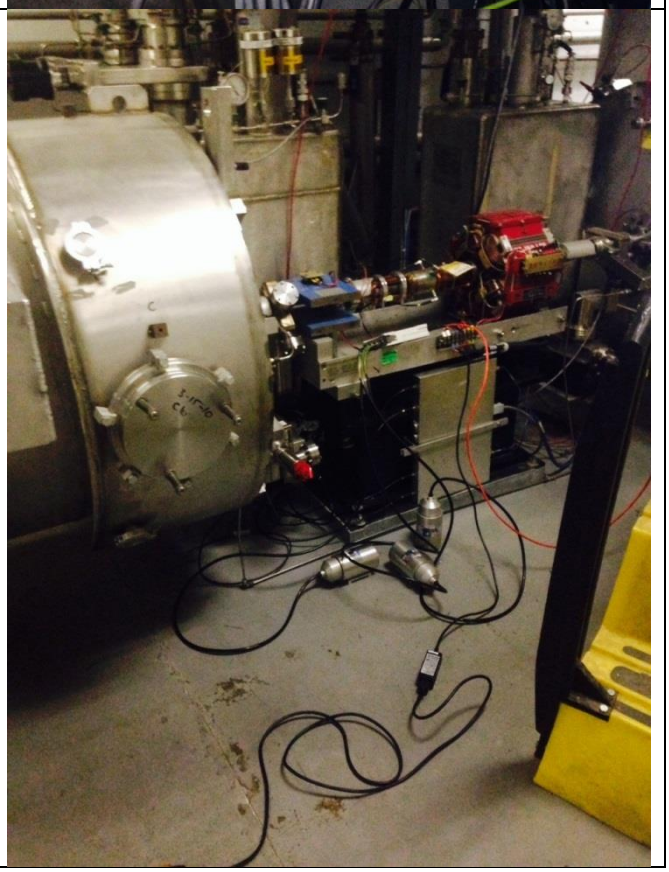
Table 1: Setup of the Seismometers.

| Setup | Description | Pictures |
|---|---|---|
| #1 | Sensor on top of compressor skid. |   |
| #2 | On floor next to the stage 1 compressor. | |

| | | |
|---|---|---|
| #3 | On concrete floor next to west wall (16.2 m from the stage 1 compressor). |  |
| #4 | On concrete floor next to south wall (14.3 m from stage 1 compressor floor sensors) next to the stage 2 compressors. | |

| | | |
|---|---|---|
| #5 | On concrete floor next to cold box (27 m from stage 1 compressor). |   |
| #6 | On concrete floor next to service building (76 m from stage 1 compressor). |   |

| | | |
|---|---|---|
| #7,#10 | On top of cryomodule<br>(~ 95 m to CHL2). |  |

| | | |
|---|---|---|
| #8,#11 | On or next to the cryo-supply line, x-sensor is directly installed on pipe, z and y are installed on the bracket mounting the line to the wall |   |
| #9,#12 | On the floor on the aisles inside the linac at the location of the incoming supply line. |  |

During the measurements, CHL2 (Central Helium Liquefier) was in operation, CHL1 was not running.

## 2.2 Instrumentation

**Seismometers: Sercel L4C Sensors**

Sensitivity: 276.8 Volts / meter / second

Natural Freq.: 1.0 Hz

## 2.3 Data Collection

The data acquisition units used were two National Instruments Model 9234 (24 Bit) with a National Instruments cRIO-9076 controller allowing synchronized collection from 8 sensors.

For the observation inside the linac, 3 sensors were used to take data synchronized with a NI 9234 DAQ unit and a NI-WLS-9163 controller.

## 2.4 Measurements

Above ground, 5 measurement sessions were recorded with 2560 Hz sampling rates. The sensors in the compressor room were setup in the orientation of the compressors, with the x-axis in the direction of the long side of the compressor, the z-axis the short side of the compressors and y-axis vertically. For all other measurements the sensors were oriented to the linac, the compressors system is rotated by 20 deg to the linac system.

**Table 2: Description of measurement sessions.**

| | | |
|---|---|---|
| Session #1 | 17 minutes | Z, X and Y on the stage 1 compressor skid,<br>Z, X and Y on the floor in front of the stage 1 compressor,<br>Z and Y on the floor next to the west wall. |
| Session #2 | 90 minutes | Z, X and Y on the stage 1 compressor skid,<br>Z, X and Y on the floor in front of the stage 1 compressor,<br>X and Y on the floor next to the west wall. |
| Session #3 | 830 minutes (overnight) | Z, X and Y on the floor in front of the stage 1 compressor,<br>Z, X and Y next to the cold box,<br>Z and Y on the floor next to the west wall. |
| Session #4 | 67 minutes | Z and Y on the floor in front of the stage 1 compressor,<br>Z and Y on the floor next to the south wall,<br>Z and Y on the floor next to the cold box,<br>Z and Y on the floor next to service building. |
| Session #5 | 119 minutes | X and Y on the floor in front of the stage 1 compressor,<br>X and Y on the floor next to the south wall, |

| | | |
|---|---|---|
| | | X and Y on the floor next to the cold box,<br>X and Y on the floor next to service building. |
| Session #6 | 3 minutes | Z, X and Y in the north linac on or next to the cryo supply line. |
| Session #7 | 3 minutes | Z, X and Y in the north linac on a cryomodule. |
| Session #8 | 3 minutes | Z, X and Y in the north linac on the floor. |
| Session #9 | 3 minutes | Z, X and Y in the south linac on or next to the cryo supply line. |
| Session #10 | 3 minutes | Z, X and Y in the south linac on a cryomodule. |
| Session #11 | 3 minutes | Z, X and Y in the south linac on the floor. |

# 3 Results

## 3.1 Individual Measurements

The graphics below show the CPSD plots (integrated spectrum from 200 Hz to the frequency plotted) for the different locations investigated. The data were split up in one minute segments and plotted in the same graph - a linear scale was chosen for the graphics to highlight the frequencies with the largest amplitudes.

**On stage 1 compressor skid**

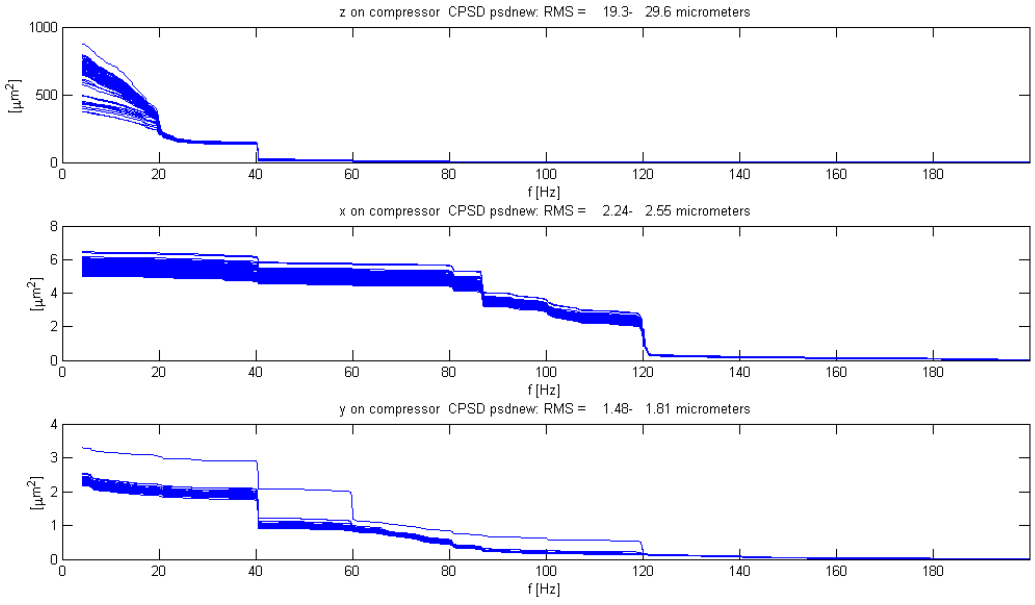



**Figure 3: CPSD on stage 1 compressor skid (session 2).**

Measurements on the skid show a 40 Hz signal on all three axis, in addition the x-axis (along the compressor) shows 80, 86 and 120Hz.

**Floor next to stage 1 compressor**

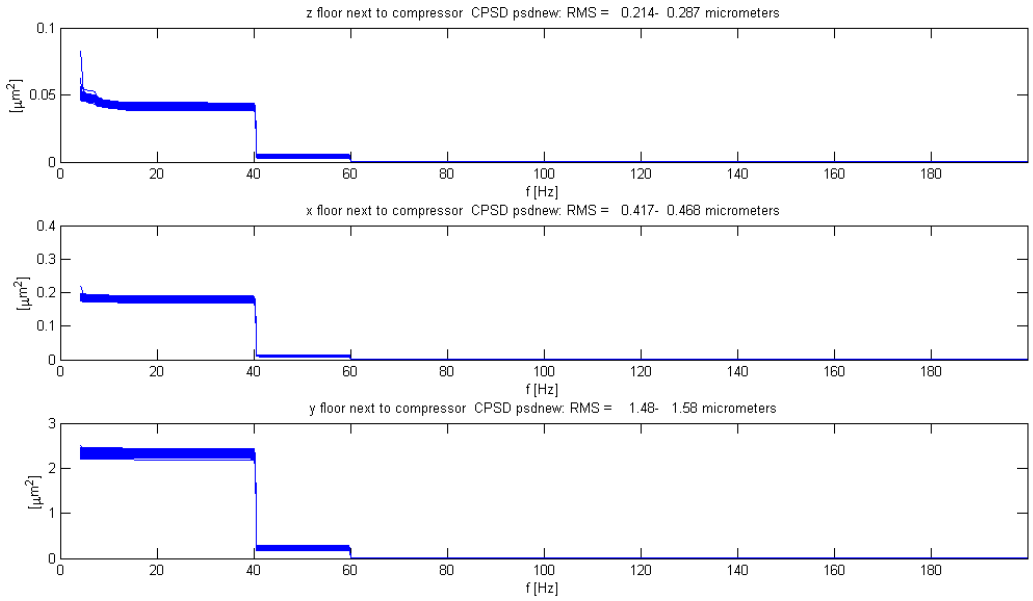



**Figure 4: CPSD on floor next to stage 1 compressor (session 2).**

On the floor next to the compressor, only the 40 Hz (1.5 µm) signal and a weaker 60 Hz (0.5 µm) signal are present.

**Floor next to west wall of compressor room**

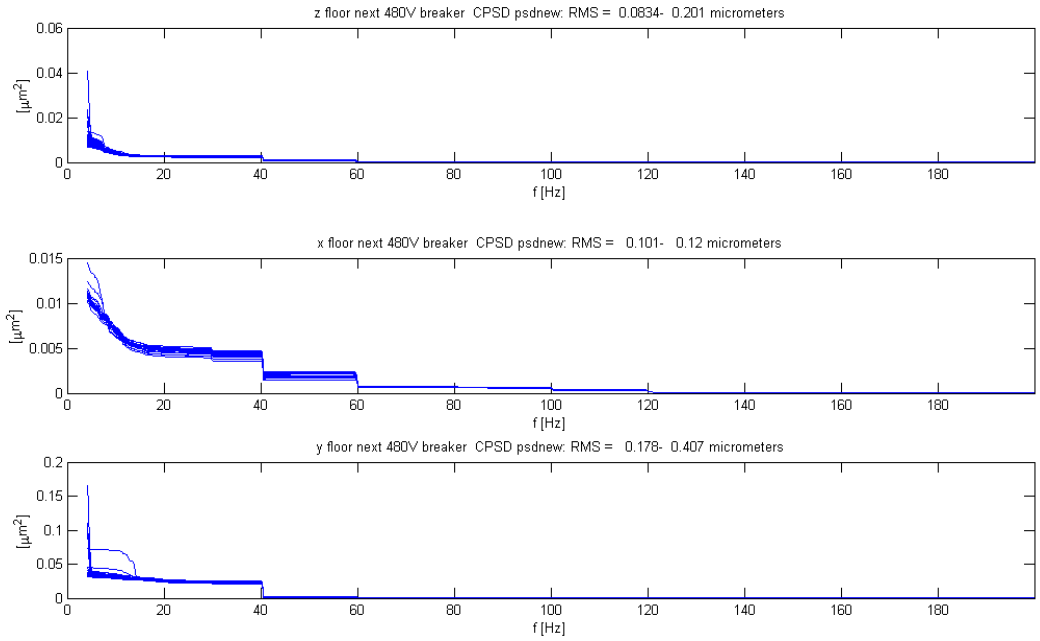



**Figure 5: CPSD, floor next to west wall of compressor room (z, y: session 2, x: session 1).**

16.2 m to the west of the sensors on the floor next to the stage 1 compressor 40 Hz (0.16 µm) and 60 Hz (0.05 µm) signals were measured.

**Floor next to south wall (next to the stage 2 compressors)**

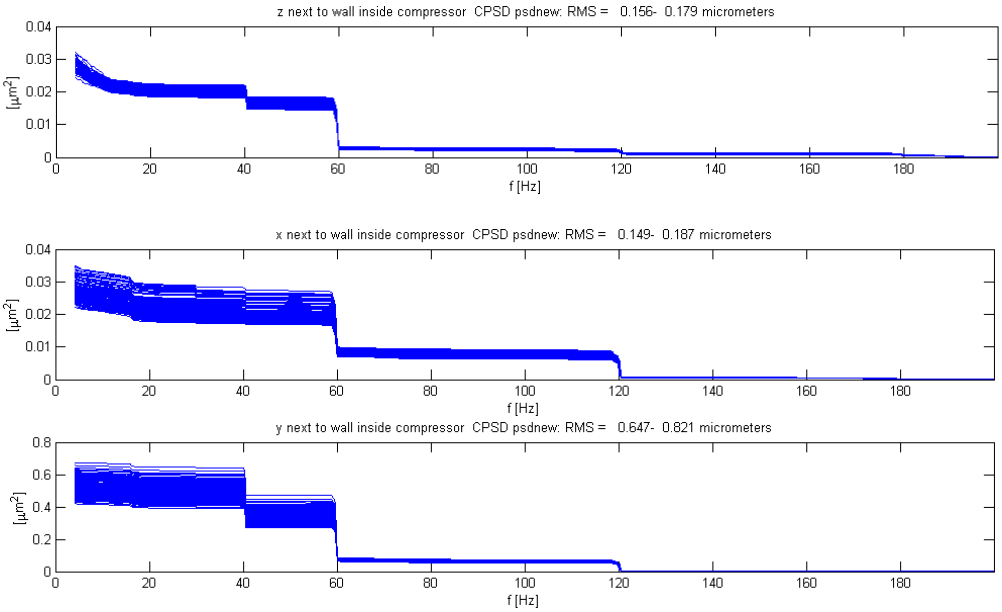



**Figure 6: CPSD, floor next to south wall of compressor room (z, y: session 4, x: session 5).**

On the concrete floor 14.3 m to the south of the sensors on the floor next to the stage 2 compressors, 40 Hz (0.42 µm), 60 Hz (0.58 µm) and 120 Hz (0.24 µm) signals were measured. The 60 Hz and 120 Hz signals are strongest at this location.

**Floor next to cold box**

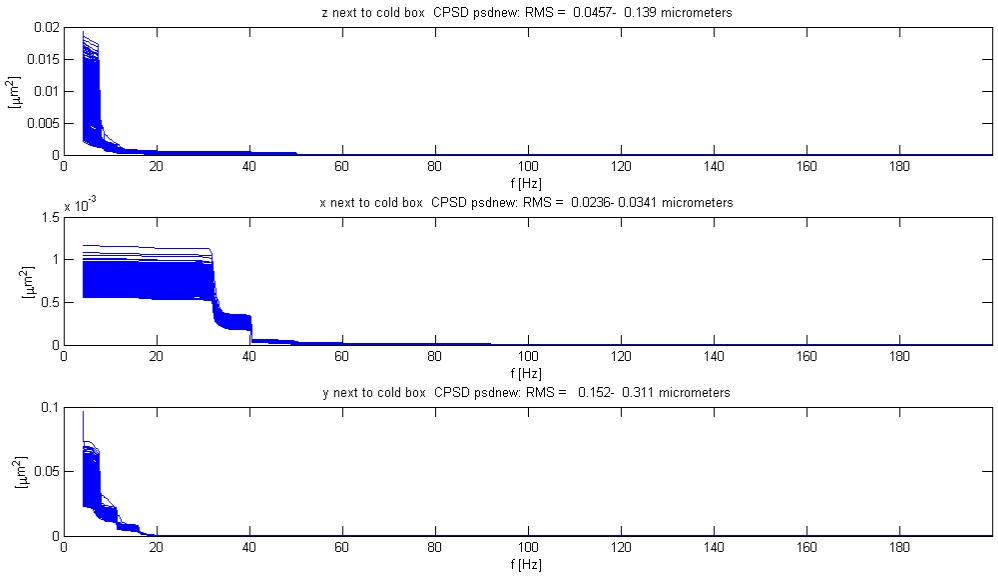



**Figure 7: CPSD, floor next to cold box (session 3).**

The measurements on the floor next to the cold box are 28 m from the stage 1 compressor. Only a small 60 Hz (9 nm) and a 40 Hz (21 nm) signal were measured. The main signal is at lower frequencies (300 nm).

**Floor next to support building**

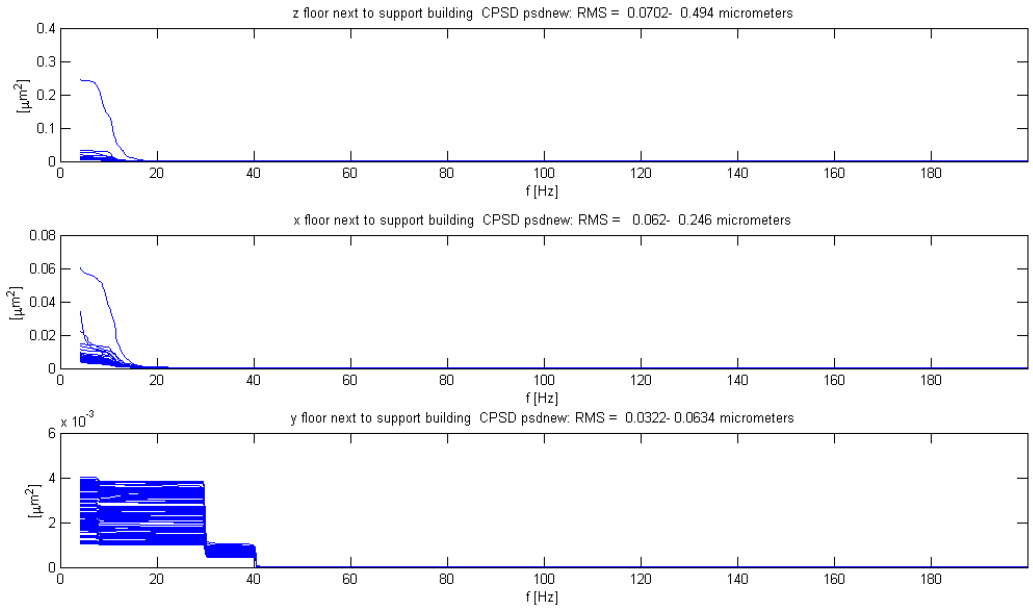
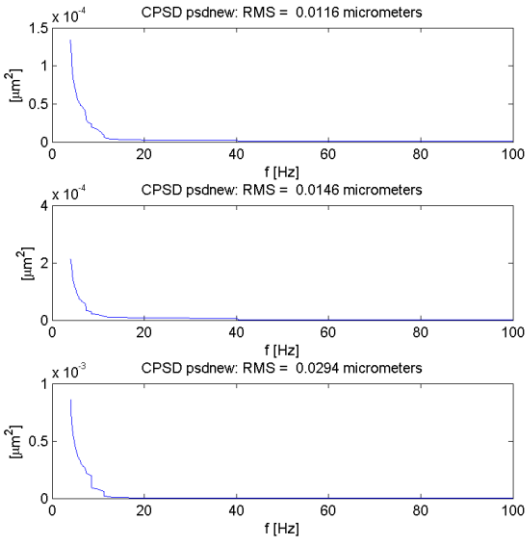



**Figure 8: CPSD, floor next to support building (z, y: session 4, x, y: session 5).**

The support building is 76 m from the CHL2, a small 40Hz signal (6nm) was found. The support building houses vibration sources of its own.

**Linac Floor**

North




South

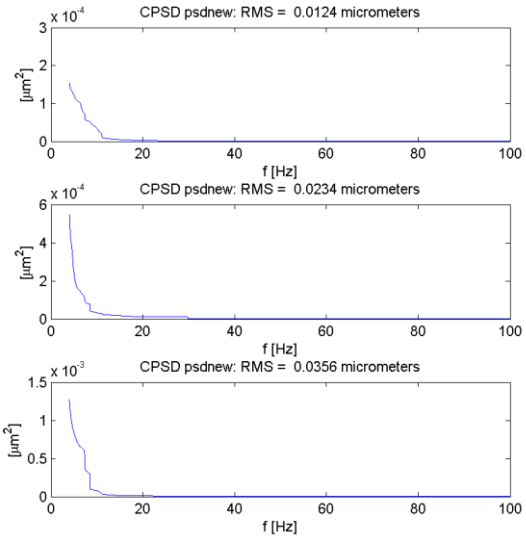
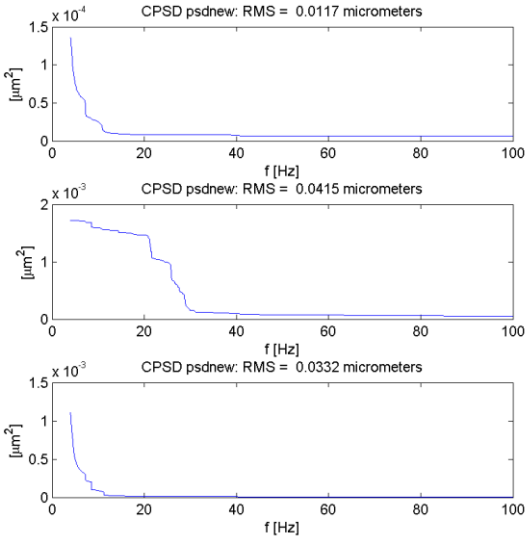



**Figure 9: CPSD, Linac floor (top: z-axis, middle: x-axis, bottom: y-axis).**

The linac floor on both the north and the south side shows similar frequencies as the floor at the SLAC linac around S24 with all pumps running.

**Linac cryo supply line**

North




South

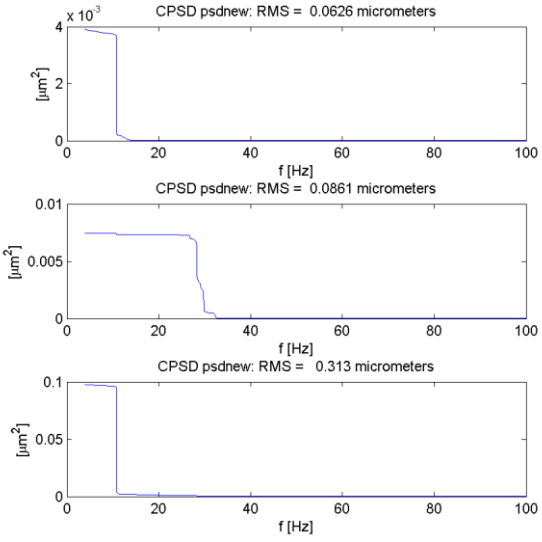
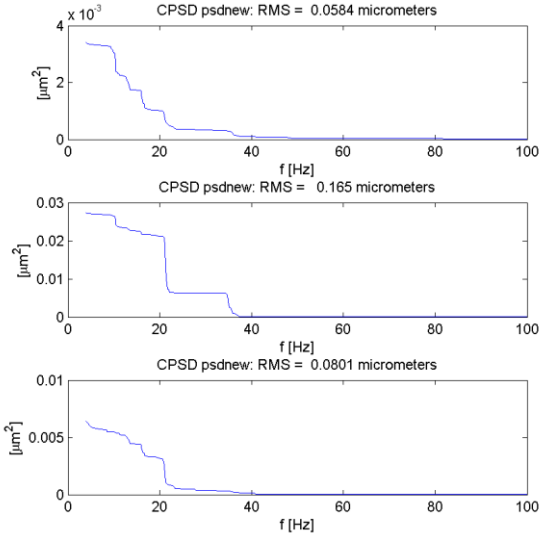



**Figure 10: CPSD, linac cryo supply line (top: z-axis, middle: x-axis, bottom: y-axis).**

The measurements on or next to the cryo supply line produced significantly different results for the north (0.05 µm) and south (0.33 µm).

**Linac Top of Cryomodule**

North




South

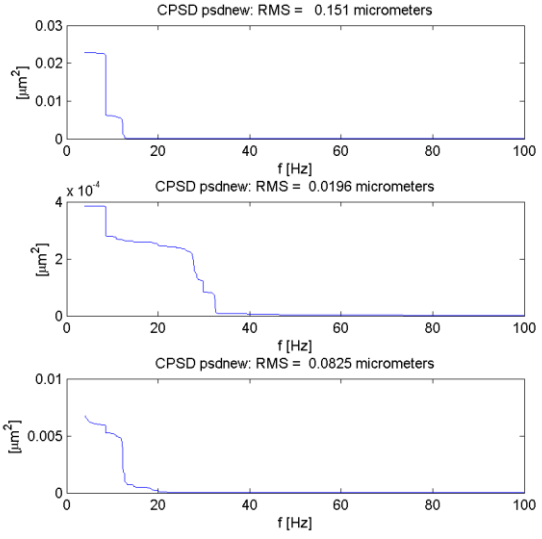



**Figure 11: CPSD, top of cryomodule (top: z-axis, middle: x-axis, bottom: y-axis).**

On the cryomodule itself the RMS in both the north and the south are similar (north: 0.19 µm; south: 0.17 µm). The frequencies are not comparable north to south; in the north the x-axis shows the highest vibrations whereas in the south the z-axis is dominant.

# 4 Compressor Room

The three dominant frequencies present on the floor of the compressor room are 40 Hz, 60 Hz and 120 Hz. Next to the stage 1 compressor the strongest 40 Hz signal could be measured, the 60 Hz and 120 Hz signal is strongest next to the stage 2 compressor (south wall), see Table 3. Comparing the measurements next to the stage 1 compressor and the sensors next to the west wall show a tenfold reduction of the amplitudes. The sensors on the south show a threefold reduction of the 40 Hz signal but an increase in the 60 Hz signal suggesting that the stage 2 compressors are causing most of the 60 Hz signal.

**Table 3: Amplitudes of selected frequencies for different locations in the compressor room (CHL2).**

| Location \ Frequencies | 40Hz | 60Hz | 120Hz | 32Hz | 80Hz | 86Hz |
|---|---|---|---|---|---|---|
| **Floor next to compressor (1.5 m to compressor)** | | | | | | |
| **z [µm]** | 0.192 | 0.066 | 0.005 | 0.001 | 0.002 | 0.003 |
| **x [µm]** | 0.413 | 0.101 | 0.011 | 0.002 | 0.011 | 0.007 |
| **y [µm]** | 1.461 | 0.466 | 0.029 | 0.003 | 0.025 | 0.010 |
| **3D [µm]** | **1.530** | **0.481** | **0.031** | **0.004** | **0.027** | **0.013** |
| **Floor next to west wall (17.7 m to compressor)** | | | | | | |
| **z [µm]** | 0.042 | 0.022 | 0.004 | 0.001 | 0.004 | 0.006 |
| **x [µm]** | 0.047 | 0.034 | 0.012 | 0.001 | 0.005 | 0.007 |
| **y [µm]** | 0.150 | 0.036 | 0.002 | 0.003 | 0.003 | 0.002 |
| **3D [µm]** | **0.163** | **0.054** | **0.013** | **0.003** | **0.007** | **0.009** |
| **Floor next to south wall (12.8 m to compressor)** | | | | | | |
| **z [µm]** | 0.059 | 0.114 | 0.025 | 0.002 | 0.003 | 0.005 |
| **x [µm]** | 0.021 | 0.108 | 0.073 | 0.003 | 0.003 | 0.005 |
| **y [µm]** | 0.419 | 0.553 | 0.225 | 0.009 | 0.014 | 0.016 |
| **3D [µm]** | **0.424** | **0.575** | **0.238** | **0.010** | **0.015** | **0.017** |

## 4.1 Outside of the Compressor Room

As seen above the three dominant frequencies present on the floor of the compressor room are 40 Hz, 60 Hz and 120 Hz. To determine any possible transfer to the tunnel or above ground, the data collected at these sensors were analyzed for these frequencies, see Table 4 and Table 5. There might be other sources producing these frequencies but we assume the worst case for this study.

Table 4: Amplitudes of selected frequencies for different locations above ground between the compressors and linac.

| Location \ Frequencies | 40Hz | 60Hz | 120Hz |
|---|---|---|---|
| **Floor next to cold box (27 m to compressor)** | | | |
| **z [µm]** | 0.0103 | 0.0026 | 0.0003 |
| **x [µm]** | 0.0113 | 0.0024 | 0.0001 |
| **y [µm]** | 0.0115 | 0.0080 | 0.0002 |
| **3D [µm]** | **0.0191** | **0.0087** | **0.0004** |
| **Floor next to support building (76 m to compressor)** | | | |
| **z [µm]** | 0.0041 | 0.0007 | 0.0000 |
| **x [µm]** | 0.0041 | 0.0011 | 0.0001 |
| **y [µm]** | 0.0024 | 0.0005 | 0.0000 |
| **3D [µm]** | **0.0063** | **0.0014** | **0.0001** |

Table 5: Amplitudes of selected frequencies for different locations in the north and south linac.

| Location \ Frequencies | 40Hz north | 40Hz south | 60Hz north | 60Hz south | 120Hz north | 120Hz south |
|---|---|---|---|---|---|---|
| **Floor (95 m to compressor))** | | | | | | |
| **z [µm]** | 0.0008 | 0.0004 | 0.0004 | 0.0002 | 0.0000 | 0.0000 |
| **x [µm]** | 0.0022 | 0.0012 | 0.0005 | 0.0002 | 0.0001 | 0.0000 |
| **y [µm]** | 0.0012 | 0.0006 | 0.0006 | 0.0006 | 0.0000 | 0.0000 |
| **3D [µm]** | **0.0026** | **0.0014** | **0.0009** | **0.0006** | **0.0001** | **0.0000** |
| **On or next to cryo supply line** | | | | | | |
| **z [µm]** | 0.0010 | 0.0004 | 0.0002 | 0.0001 | 0.0001 | 0.0001 |
| **x [µm]** | 0.0034 | 0.0009 | 0.0009 | 0.0003 | 0.0004 | 0.0000 |
| **y [µm]** | 0.0015 | 0.0024 | 0.0013 | 0.0007 | 0.0003 | 0.0001 |
| **3D [µm]** | **0.0039** | **0.0026** | **0.0016** | **0.0007** | **0.0005** | **0.0001** |
| **On top of cryo module** | | | | | | |
| **z [µm]** | 0.0033 | 0.0007 | 0.0004 | 0.0004 | 0.0002 | 0.0001 |
| **x [µm]** | 0.0048 | 0.0009 | 0.0005 | 0.0002 | 0.0001 | 0.0001 |
| **y [µm]** | 0.0108 | 0.0009 | 0.0005 | 0.0004 | 0.0001 | 0.0000 |
| **3D [µm]** | **0.0123** | **0.0015** | **0.0008** | **0.0006** | **0.0002** | **0.0001** |

None of the vibration values for 40 Hz are above 20 nm at the points we observed, for the 60 Hz signal assumed to be caused mostly by the stage 2 compressors this is even lower (10 nm).

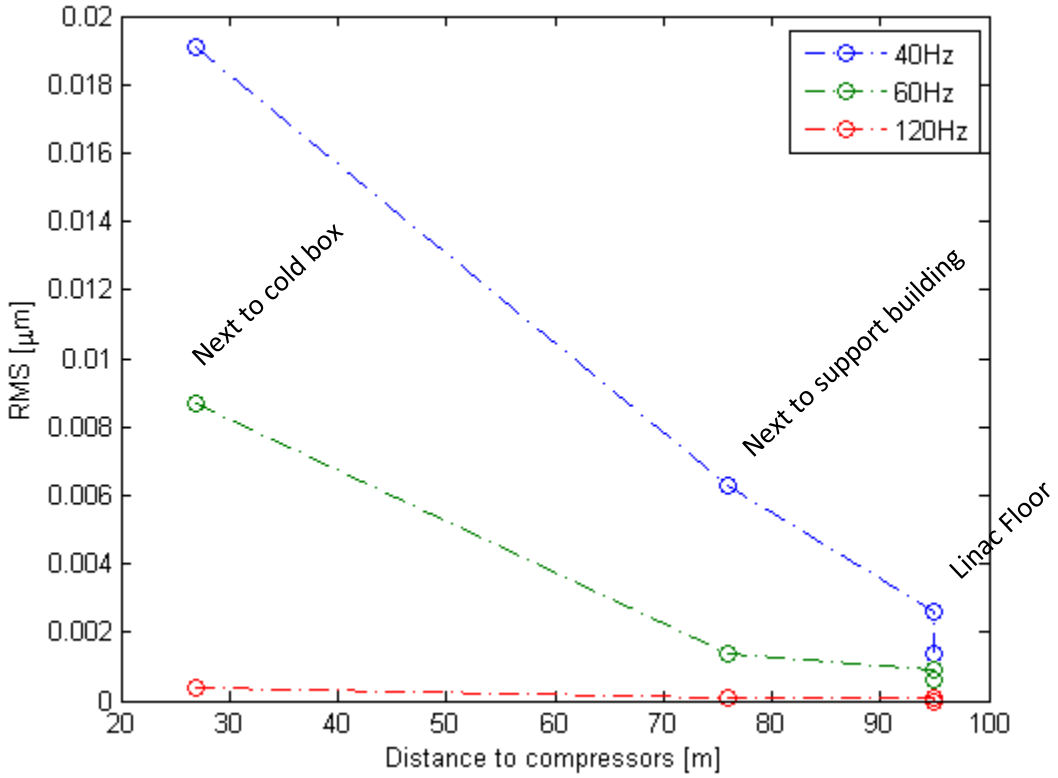



Figure 12: RMS vs. Distance to the Compressors

## 5 Summary

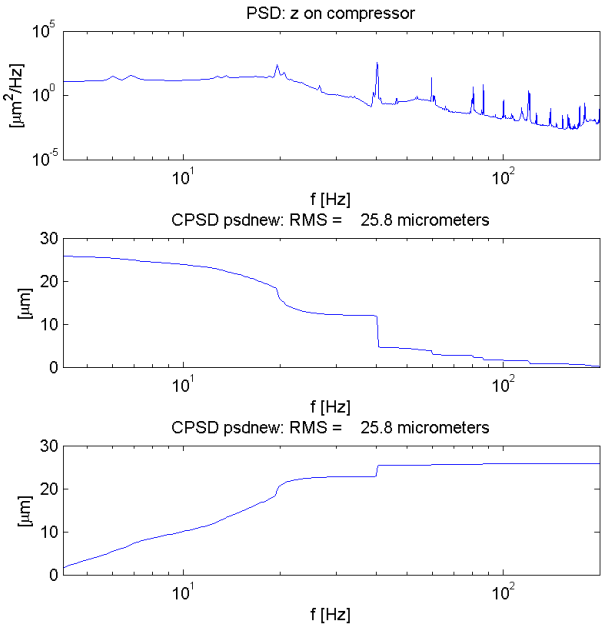
The compressors in the compressor room of CHL2 cause the concrete floor to vibrate at around one micrometer with frequencies of mainly 40, 60 and 120 Hz.

There are only very small 40 Hz or 60 Hz signals present in the measurements taken inside the linac (< 2 nm) except for an 11nm signal in y direction on top of a cryomodule in the north linac. The measurements on the floor are similar to data from SLAC's linac with the cooling system running. A stronger vibration is present on the south cryo-supply line (2-6 fold depending on axis) and on the floor in the x-direction.

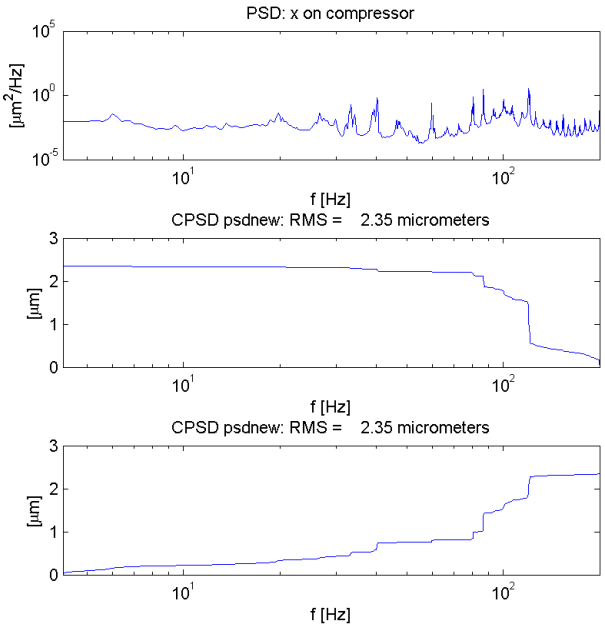
# 6 Appendix

6.1 Power spectrum (top plot), integrated rms motion from 200 Hz to frequency plotted (middle plot) and from 4 Hz up to the frequency plotted (bottom plot) on a log frequency scale.

Z-axis




X-axis




Y-axis

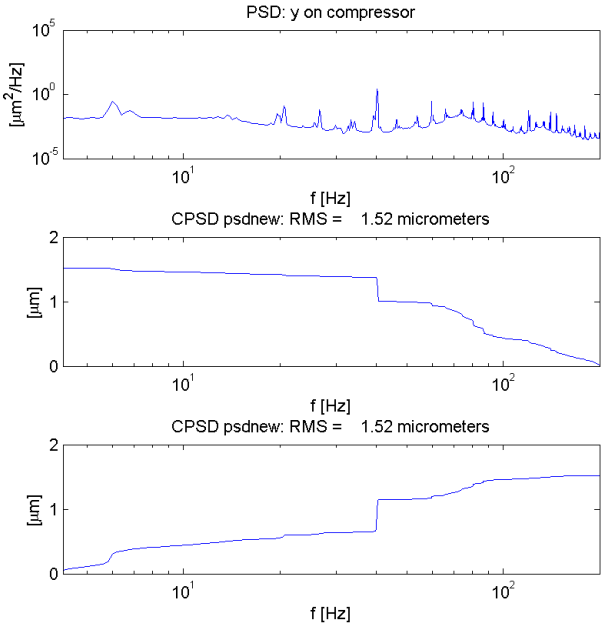
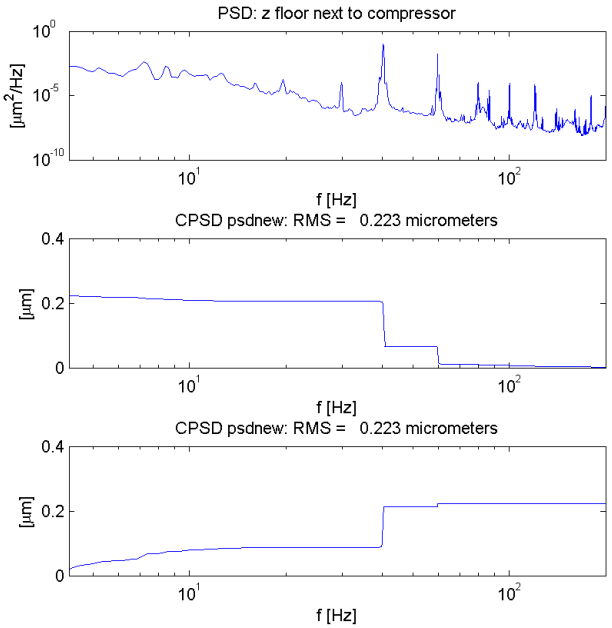
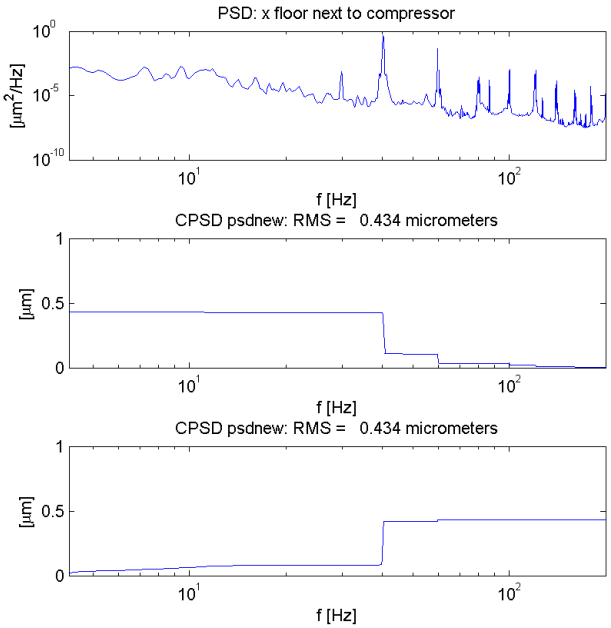



**Figure 13: On stage 1 compressor skid.**

Z-axis




X-axis




Y-axis

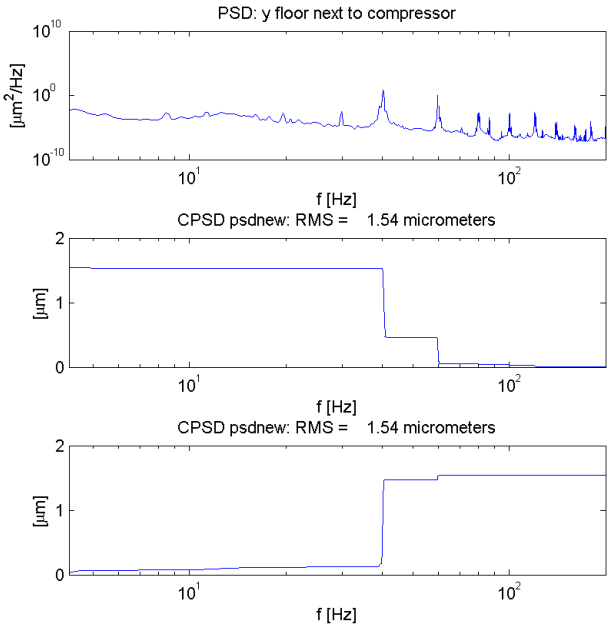
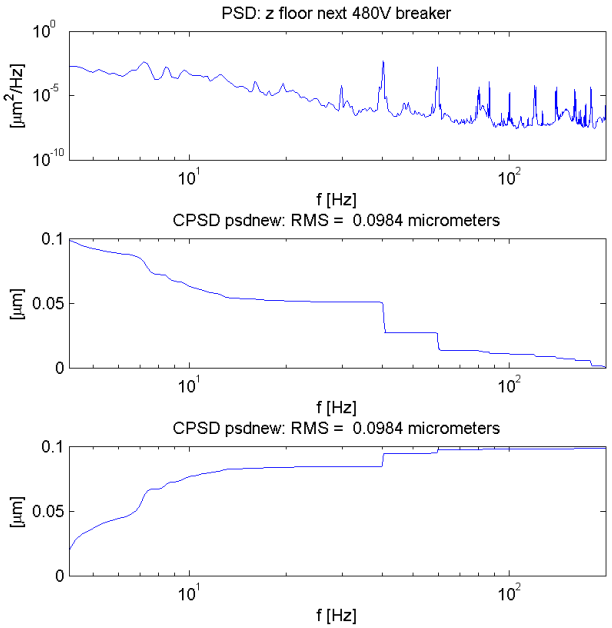
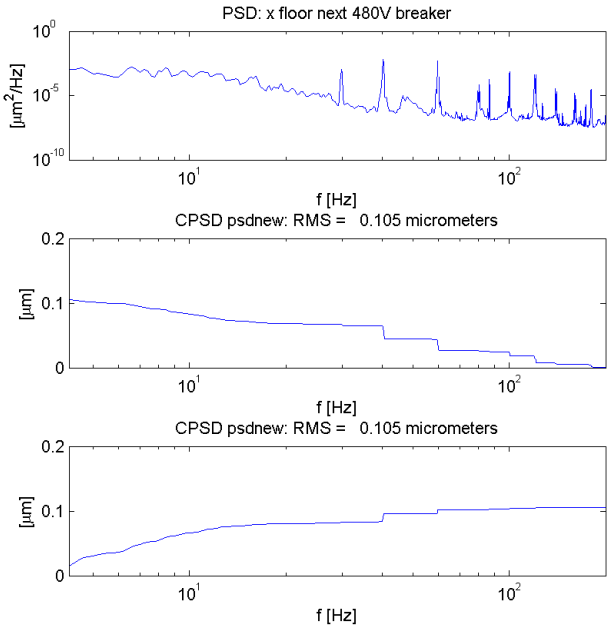



**Figure 14: Floor next to stage 1 compressor.**

Z-axis




X-axis




Y-axis

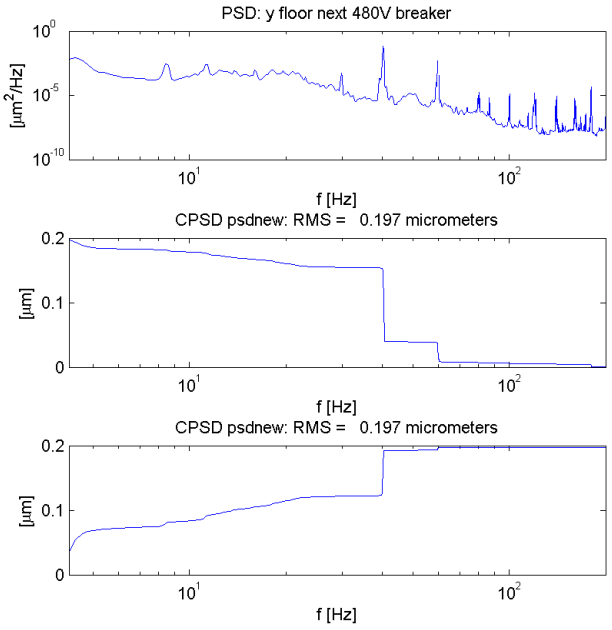
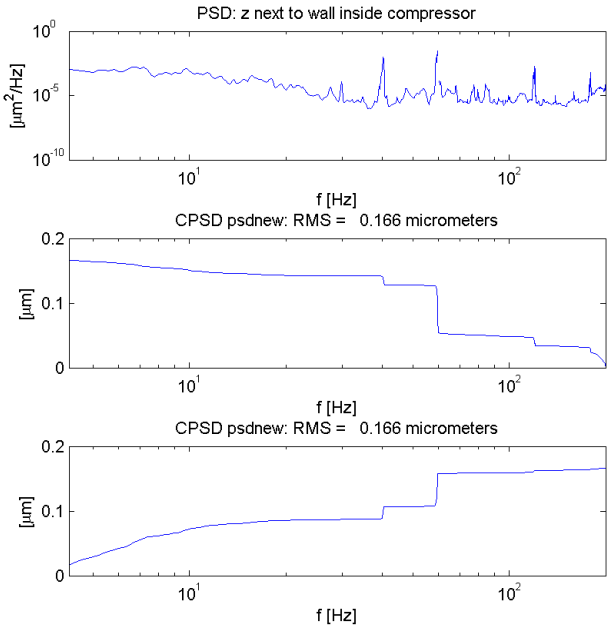
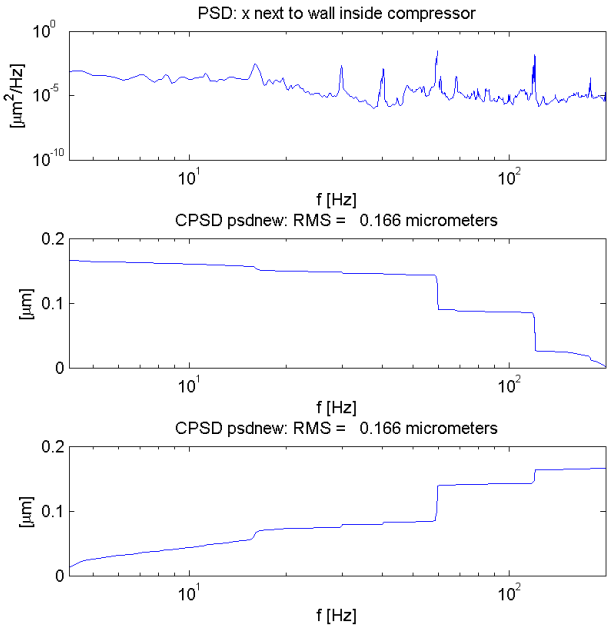



**Figure 15: Floor next to west wall of compressor room.**

Z-axis




X-axis




Y-axis

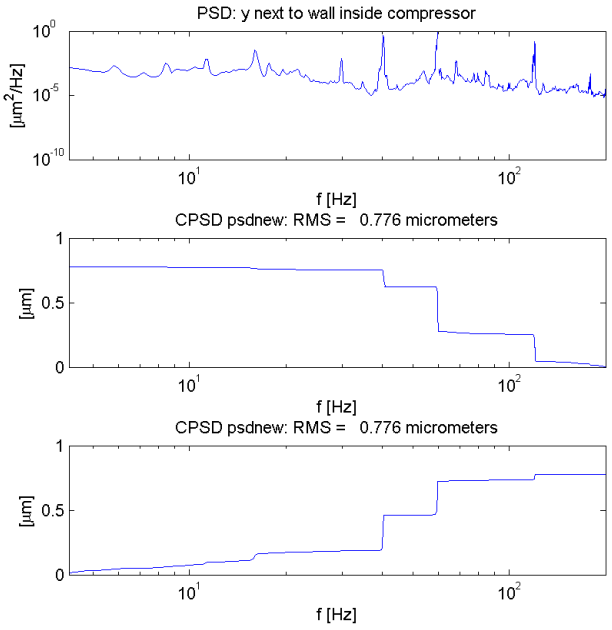
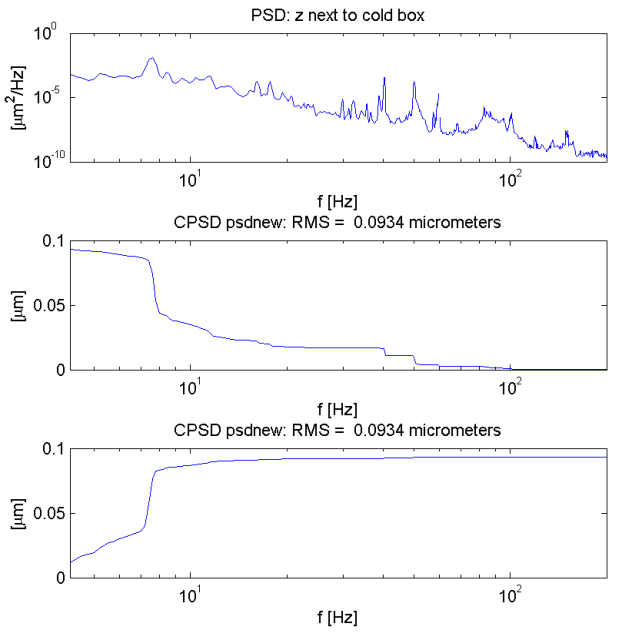
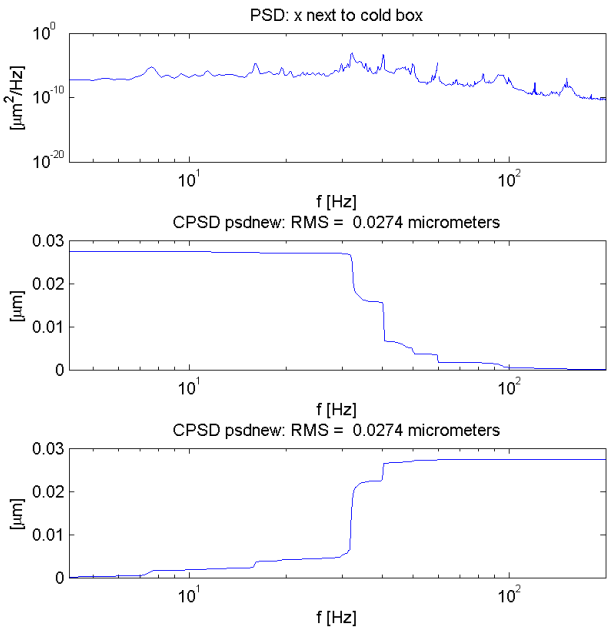



**Figure 16: Floor next to south wall (next to stage 2 compressors).**

Z-axis




X-axis




Y-axis

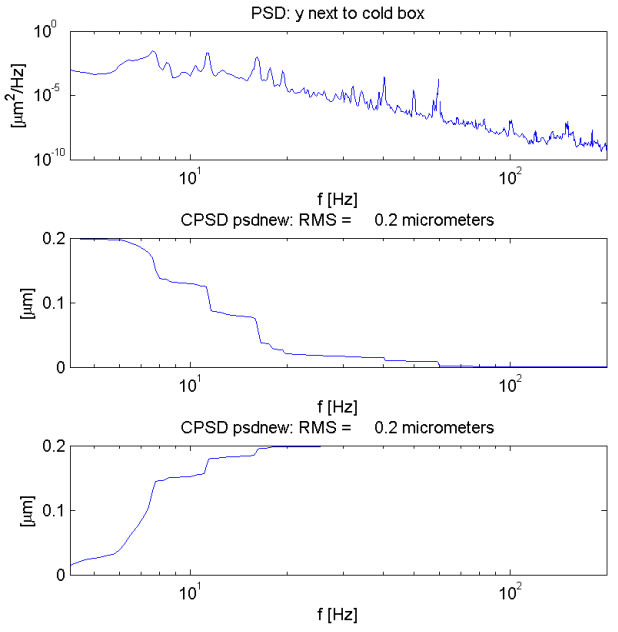
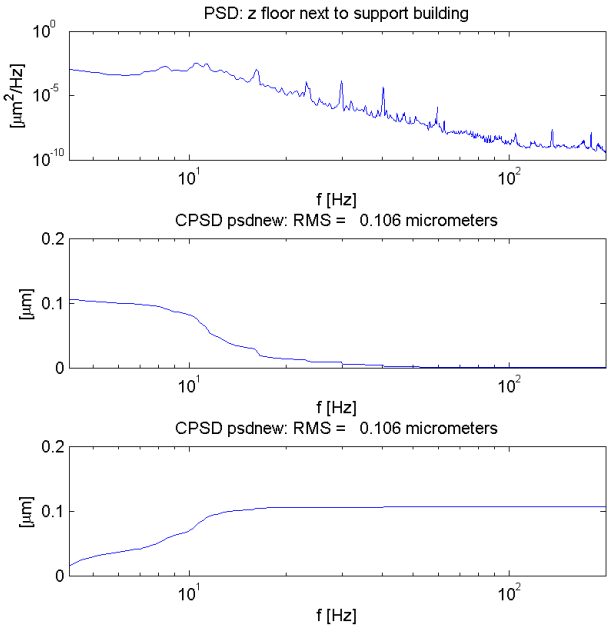
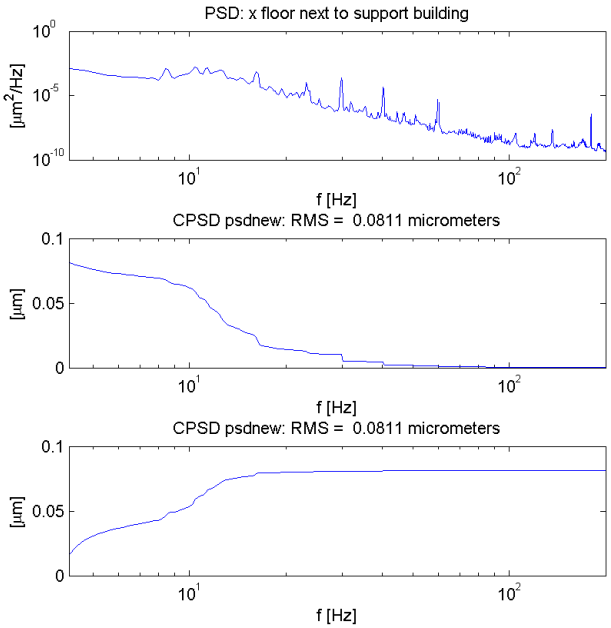



**Figure 17: Pad next to cold box.**

Z-axis




X-axis




Y-axis

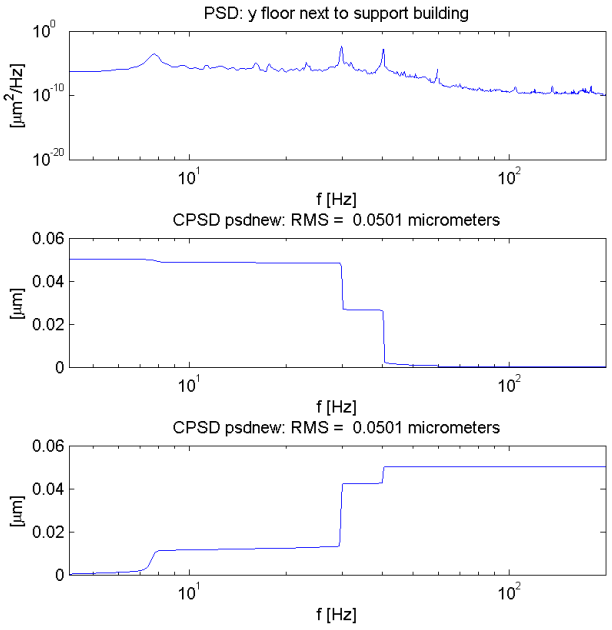
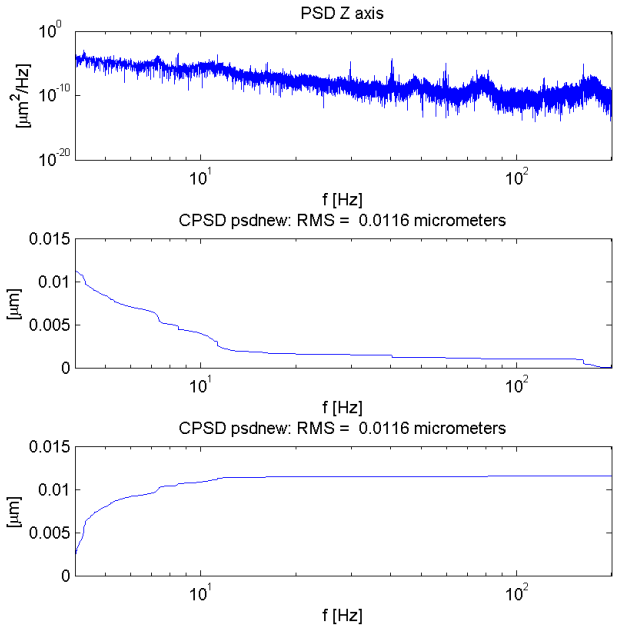
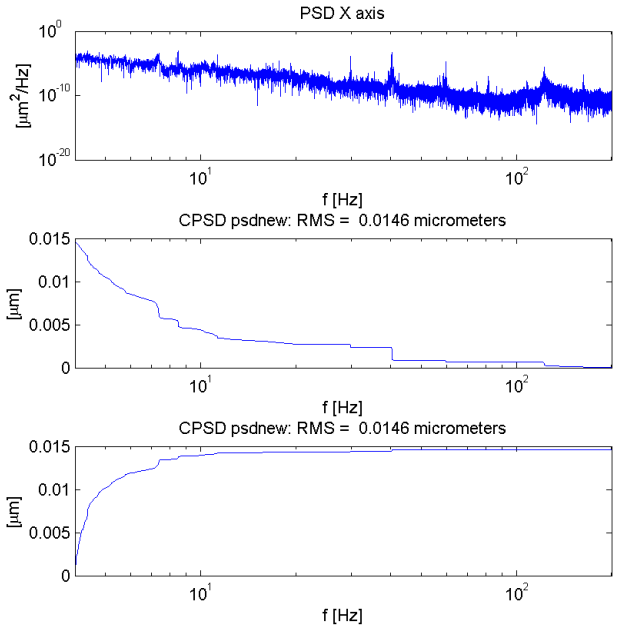



**Figure 18: Pad next to support building.**

Z-axis




X-axis




Y-axis

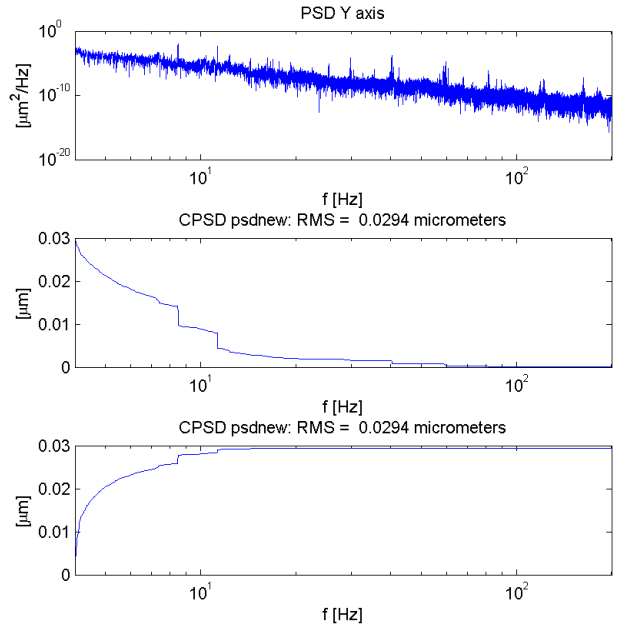
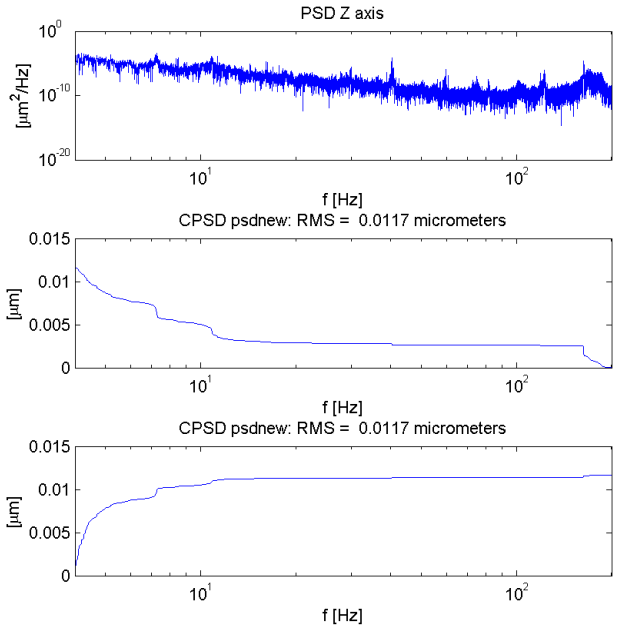
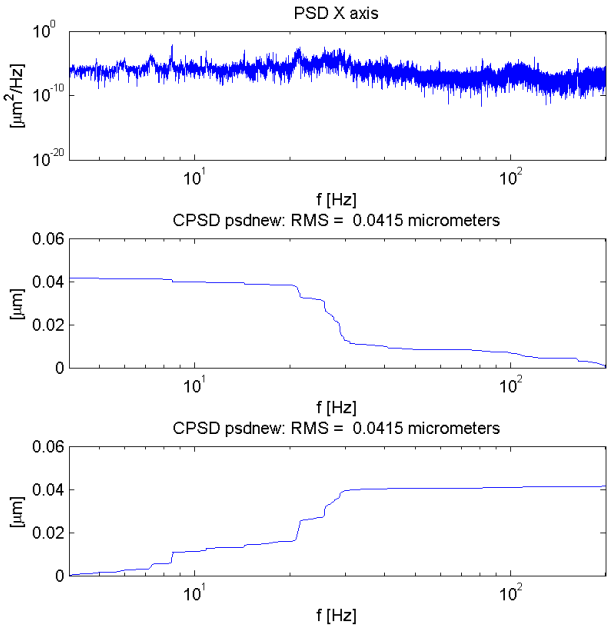



**Figure 19: North Linac floor.**

Z-axis




X-axis




Y-axis

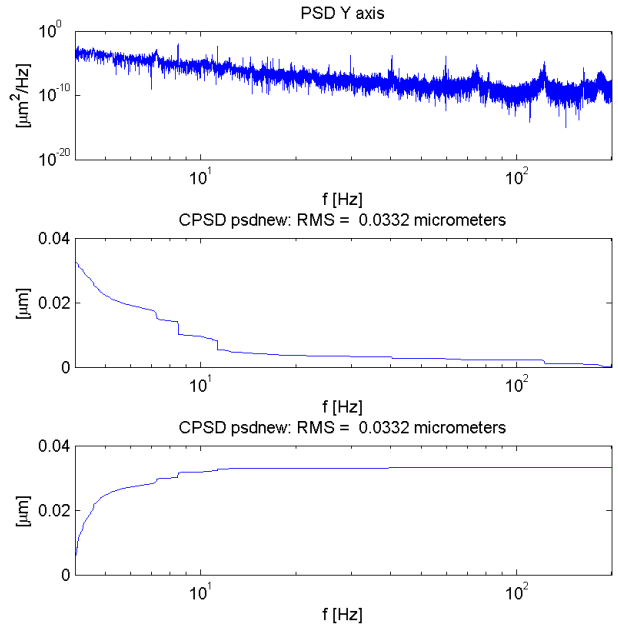
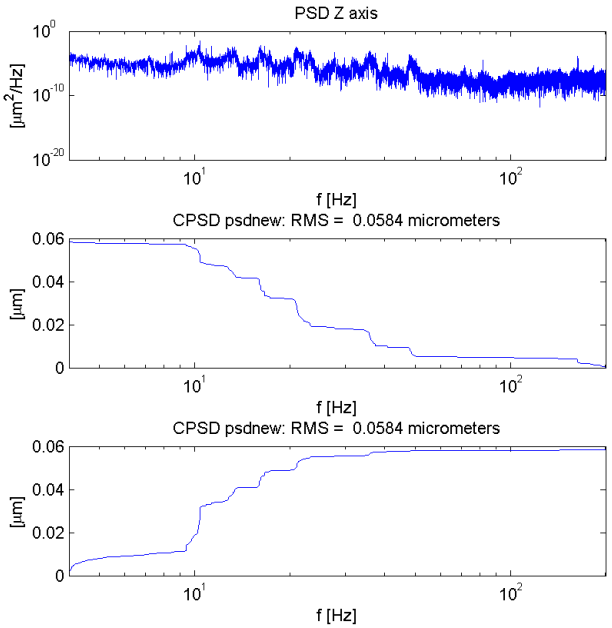
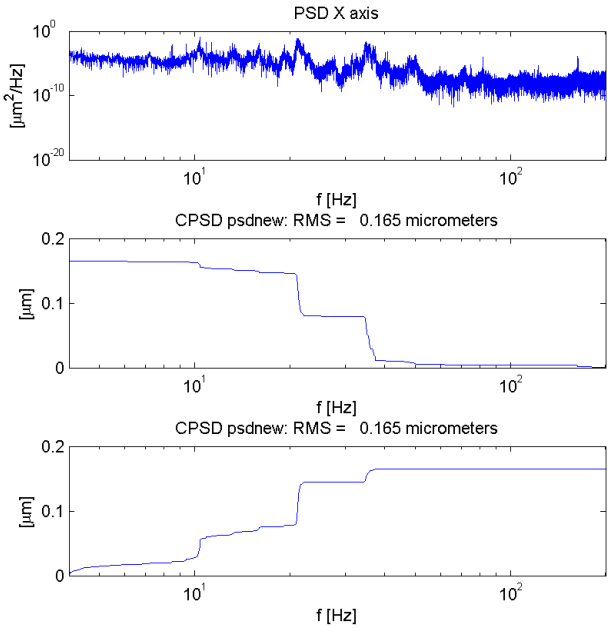



**Figure 20: North Linac at cryo supply line.**

Z-axis




X-axis




Y-axis

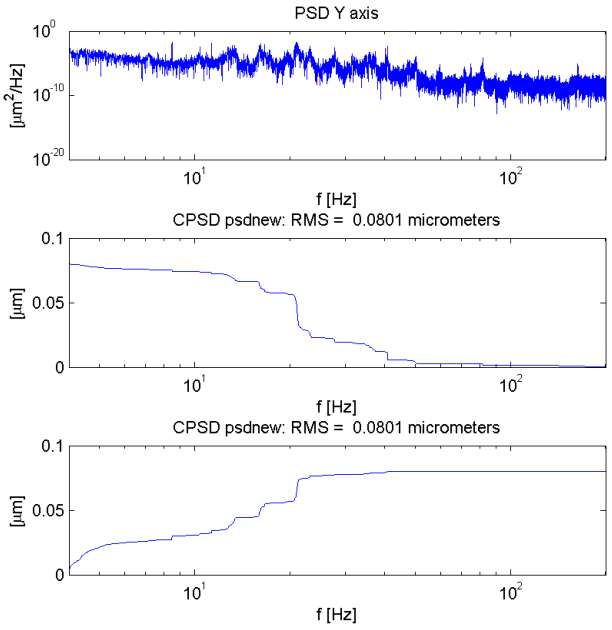
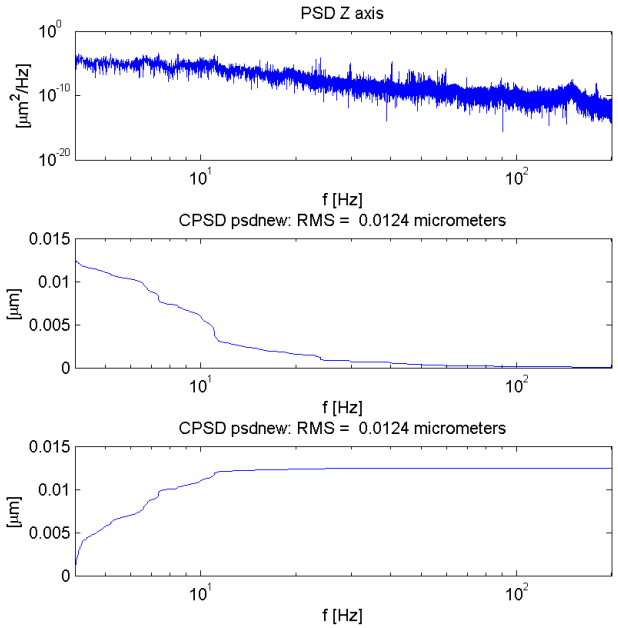
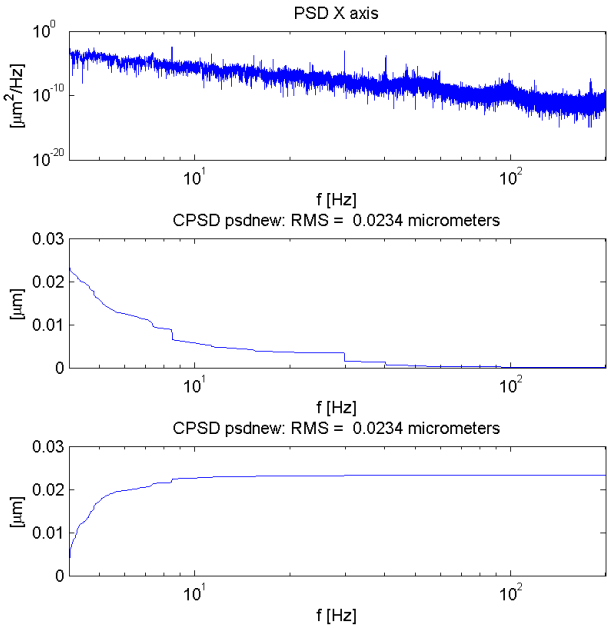



**Figure 21: North Linac top of cryomodule.**

Z-axis




X-axis




Y-axis

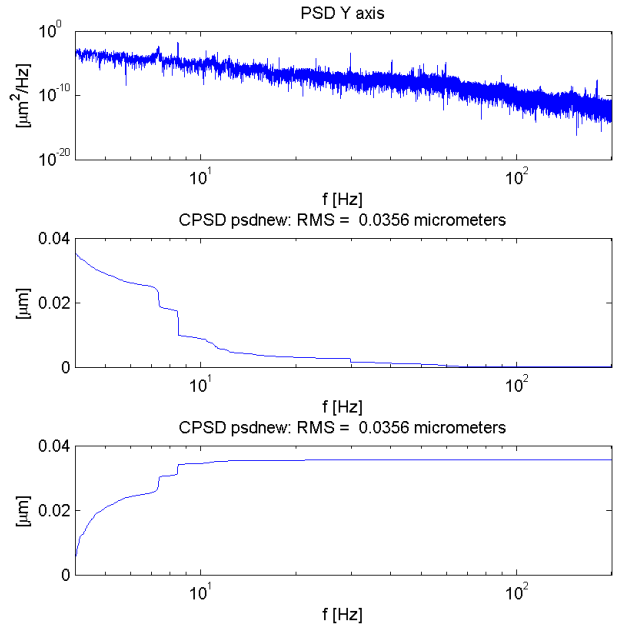
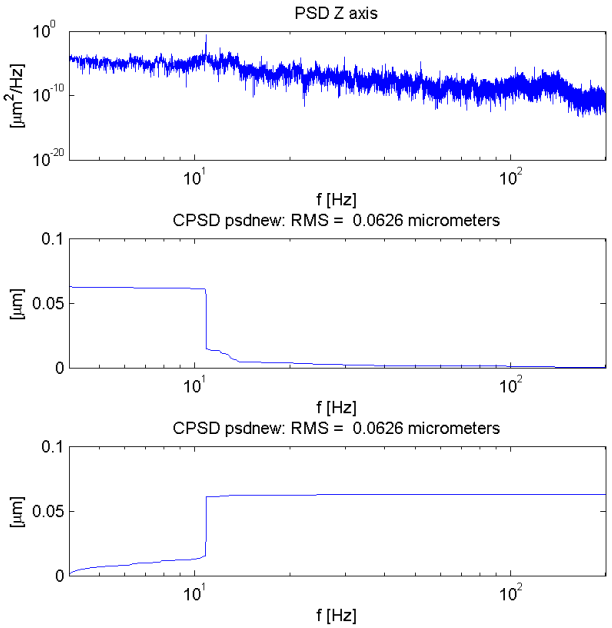
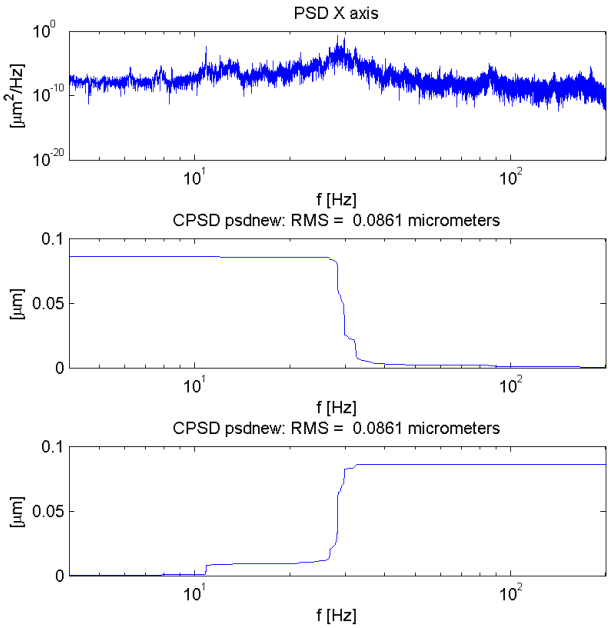



**Figure 22: South Linac floor.**

Z-axis




X-axis




Y-axis

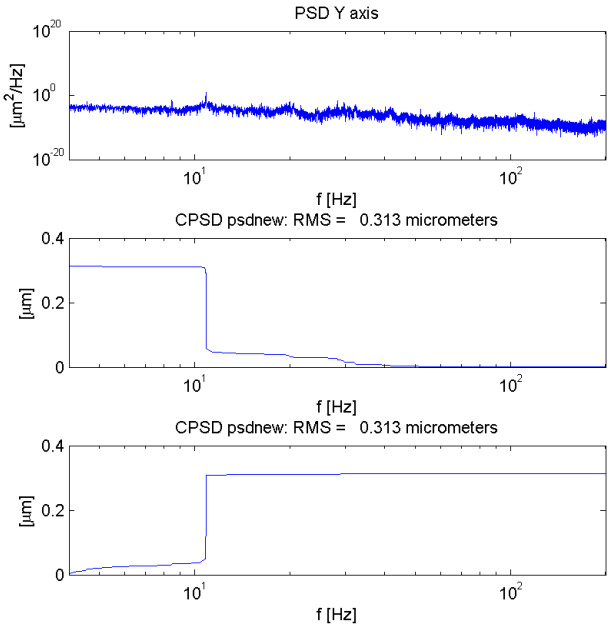
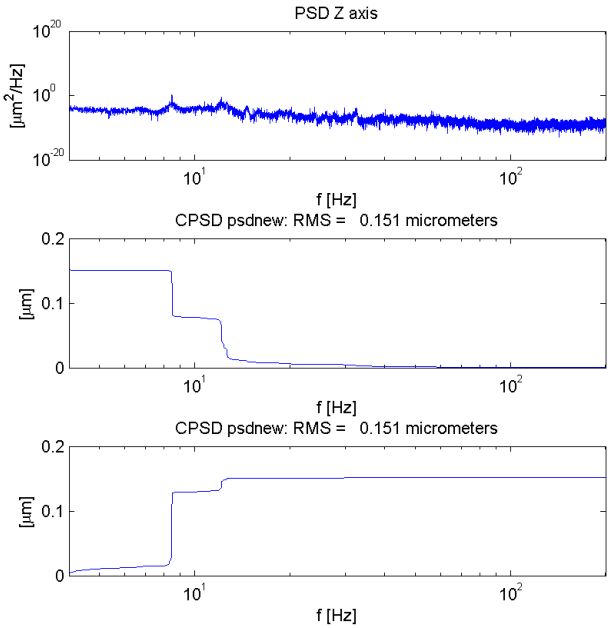
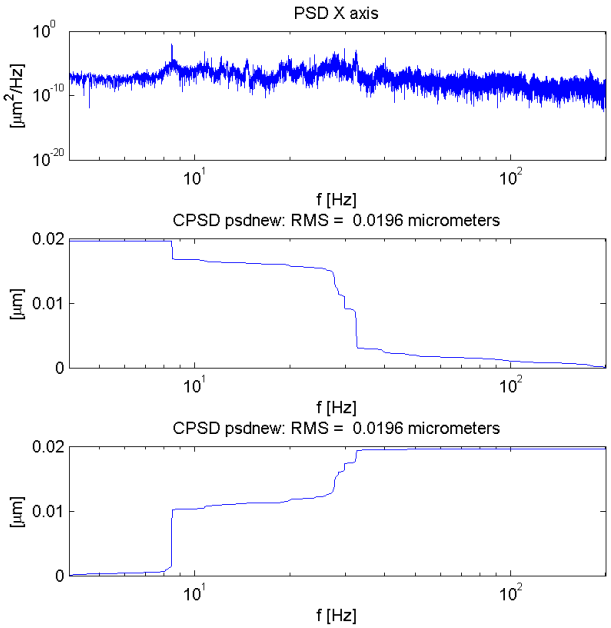



**Figure 23: South Linac at cryo supply line.**

Z-axis




X-axis




Y-axis

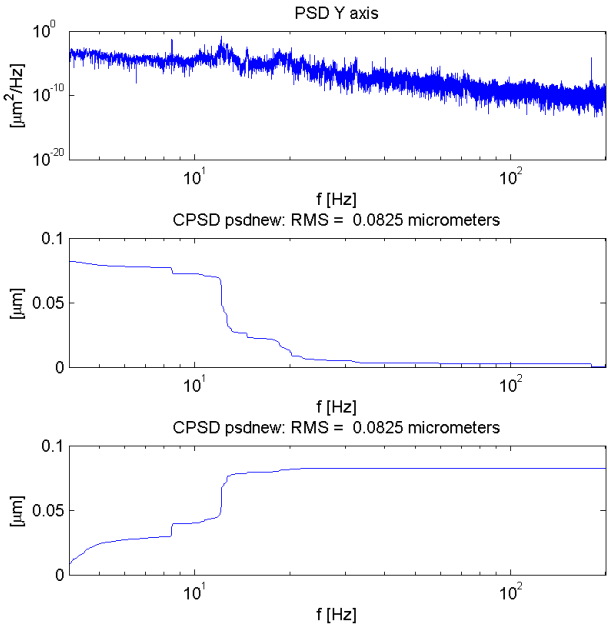


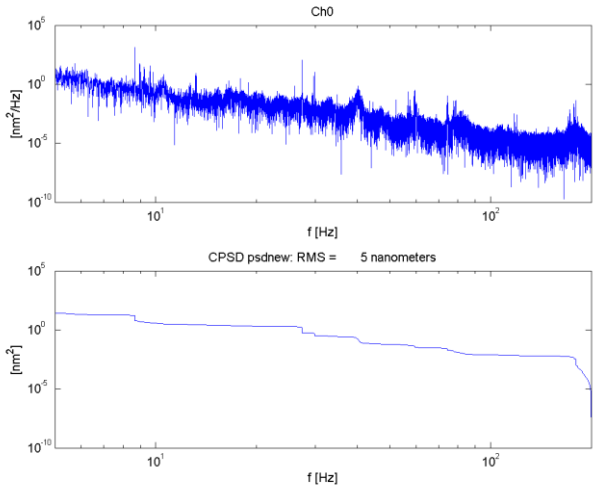

**Figure 24: South Linac top of cryomodule.**

## 6.2 L-4C Sensor background noise:

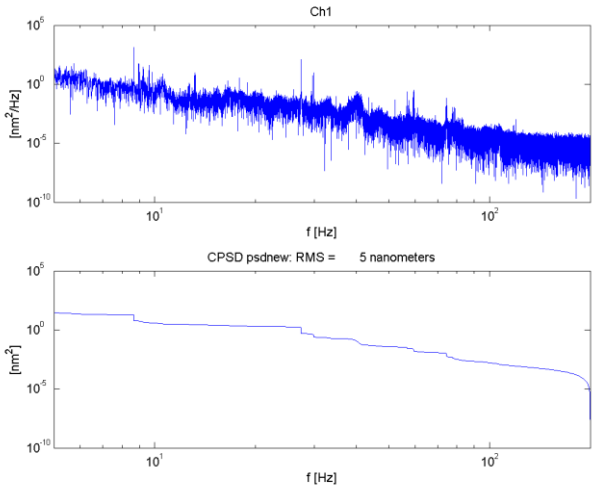
To determine the background noise two vertical and two horizontal seismometers were setup next to each other in a very low noise environment (S10 alignment lab). The instrument background noise was determined by analyzing the differential raw signal of the two sensors setup next to each other. The cumulative RMS of the differential signal is 0.3nm for the horizontal and 0.2nm for the vertical sensors, see Figure 25 and Figure 26.

**Horizontal**

Sensor 1 horizontal




Sensor 2 horizontal




Sensor 1-Sensor 2 Horizontal

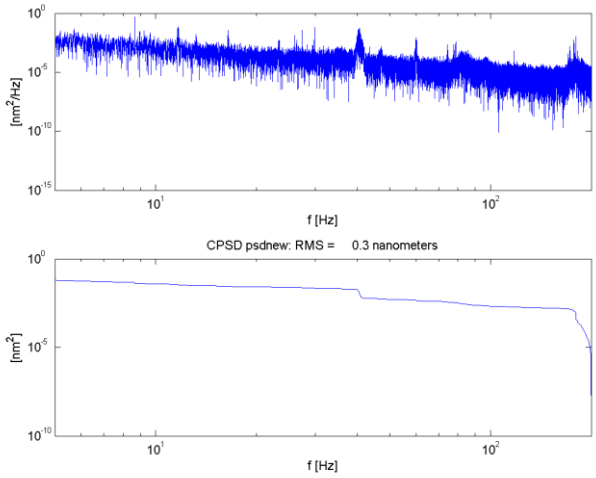
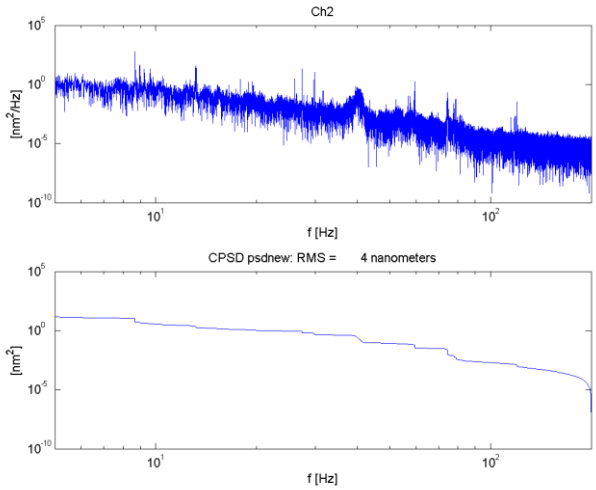
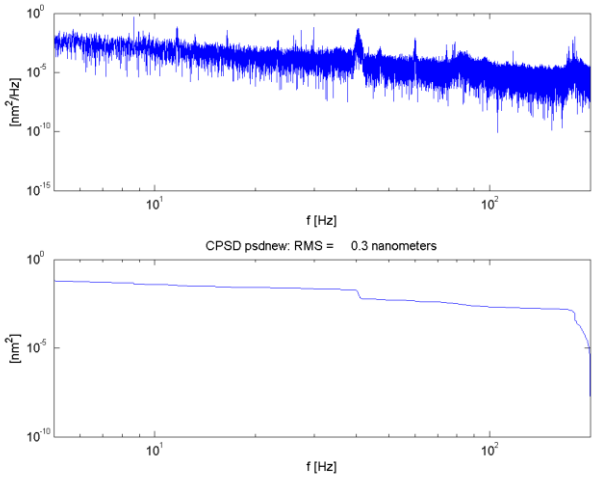



**Figure 25: Test of horizontal sensor background noise.**

Sensor 1 vertical




Sensor 2 vertical




Sensor 1-Sensor 2 vertical

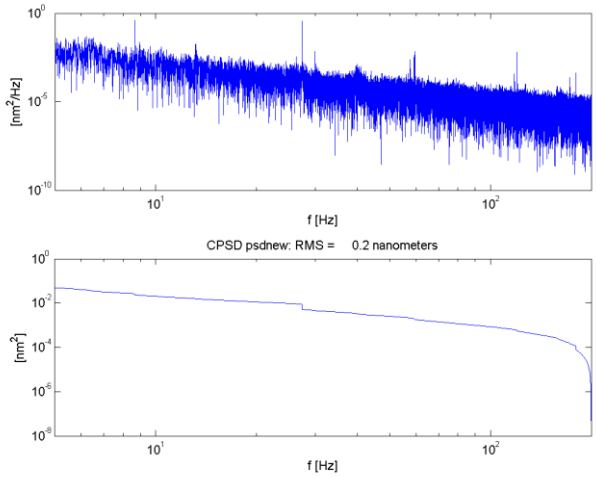



**Figure 26: Test of vertical sensor background noise.**

## 6.3 Correlation between measurements:

To determine frequency dependent correlation of two signals, a Butterworth bandpass filter (+/-1Hz) was applied to the raw data and the cross-correlation value was calculated from the filtered data. This was repeated for a frequency range from 4 to 150 Hz. In the example below, the y-axis measurements on the floor next to the compressor were correlated with the measurements next to the cold box.

| Y floor compressor vs cold box | Z floor west wall (480V breaker) vs cold box |
|---|---|

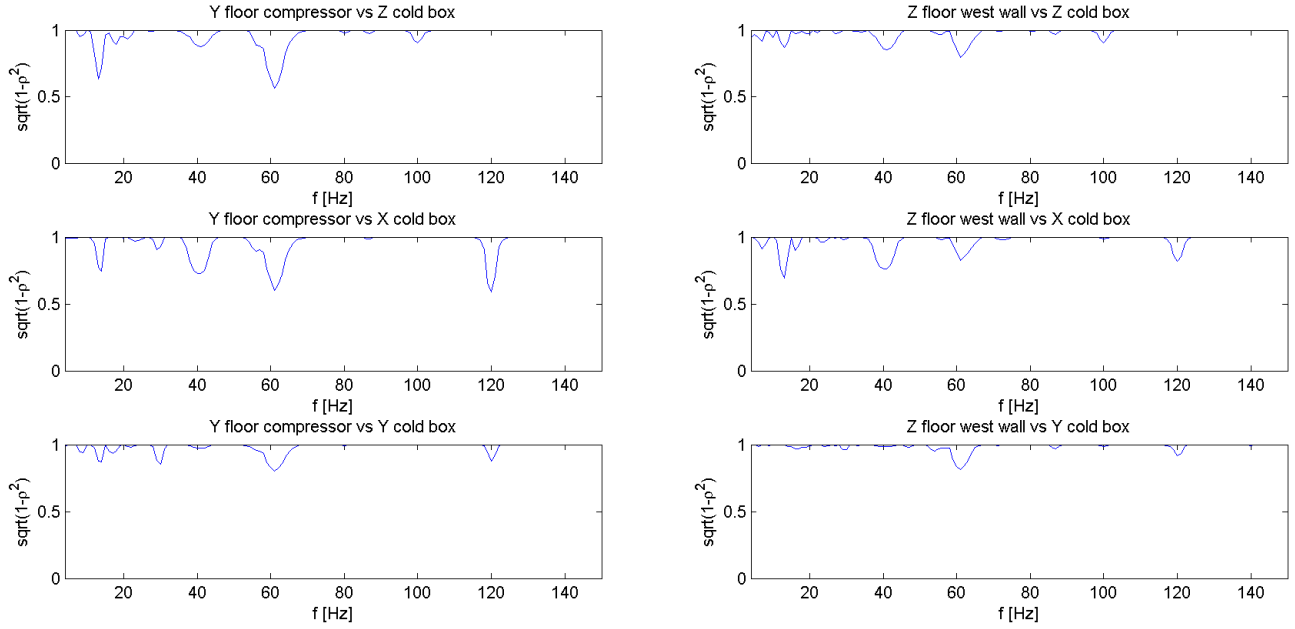
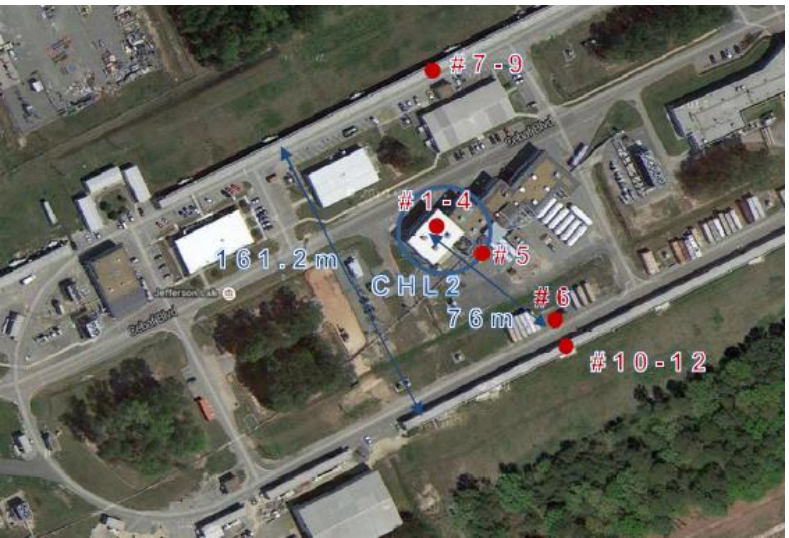
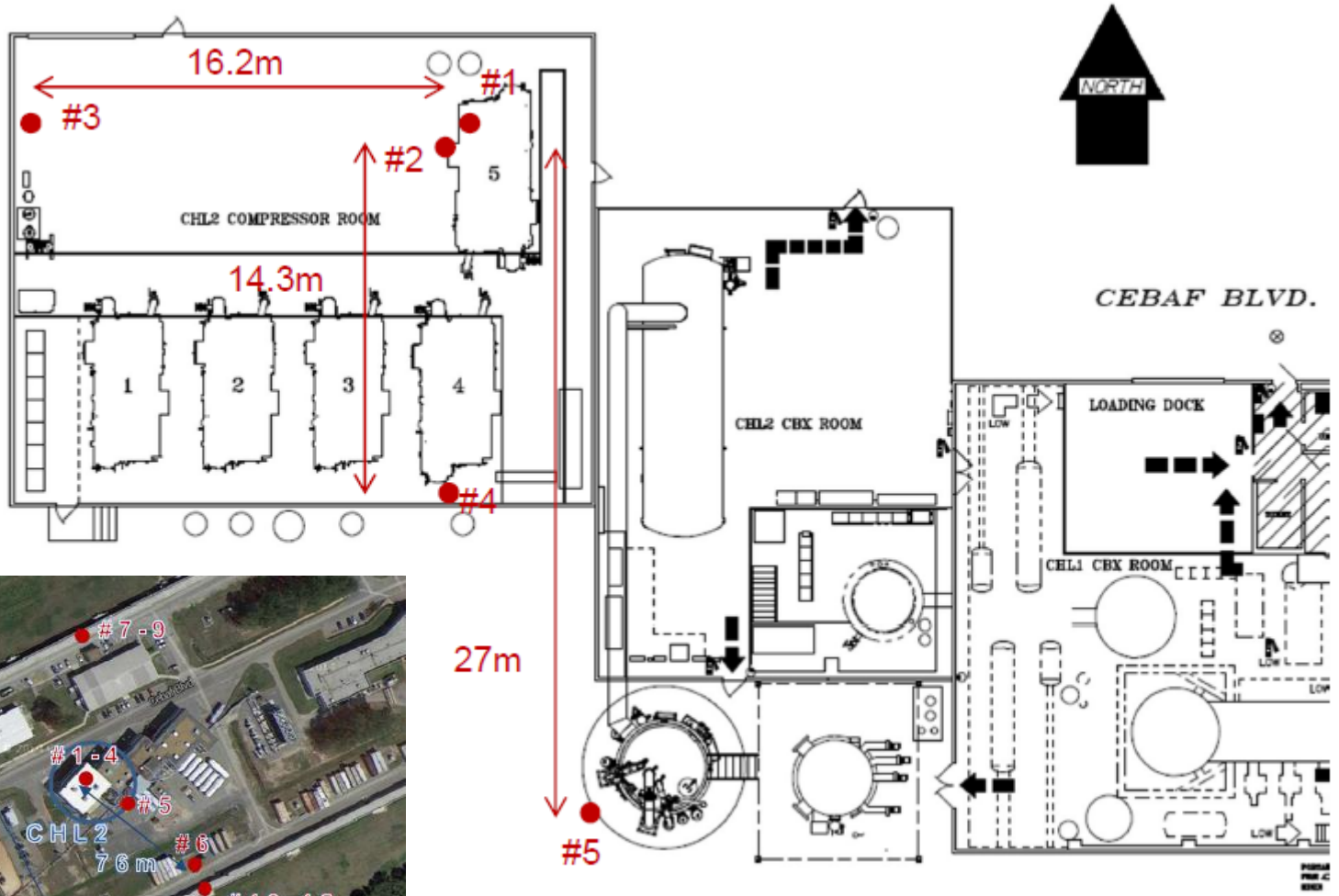



**Figure 27: Cross-correlation values for the cold box vibration measurements vs. the z axis vibration measurements next to the west wall of the compressor room.**

## 6.4 Slides highlighting some of the measurements:

# Location of Geophones at JLAB

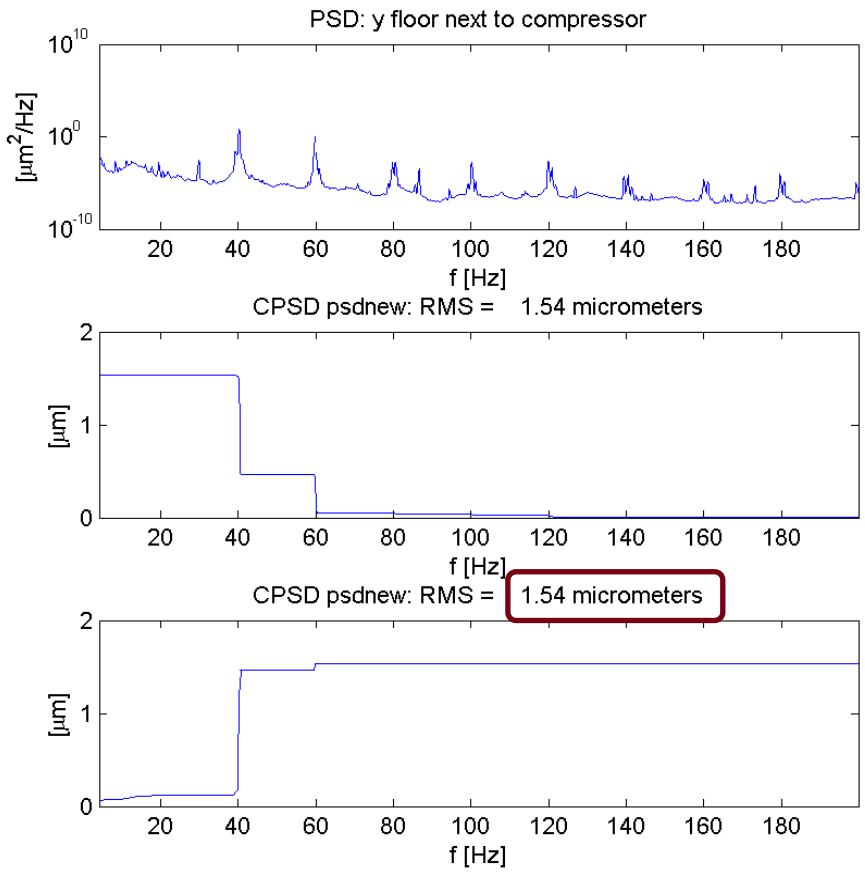


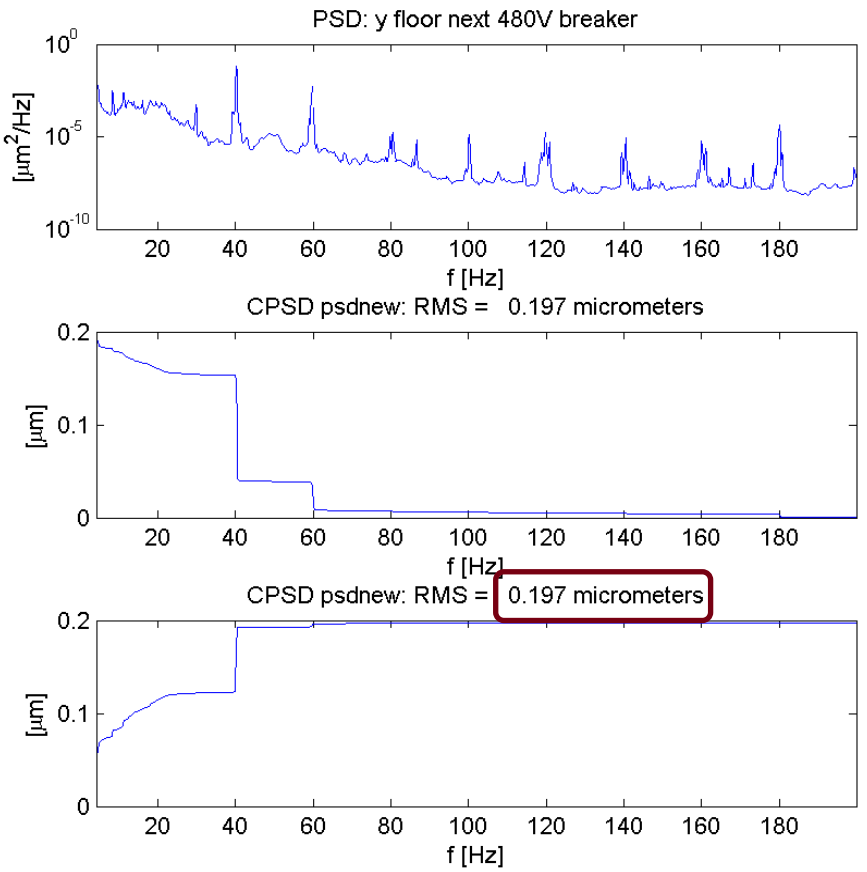
# Examples of Geophone Setups

# CHL2 Compression Room Vertical Motion (1)

Near Compressor #5

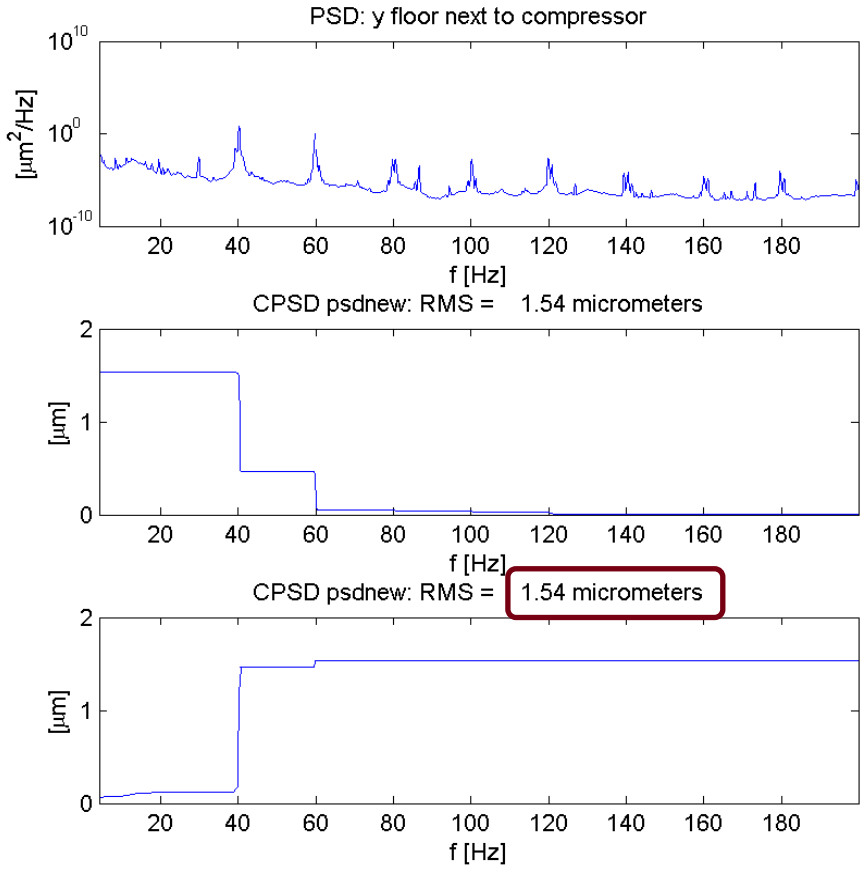



16 m to the West

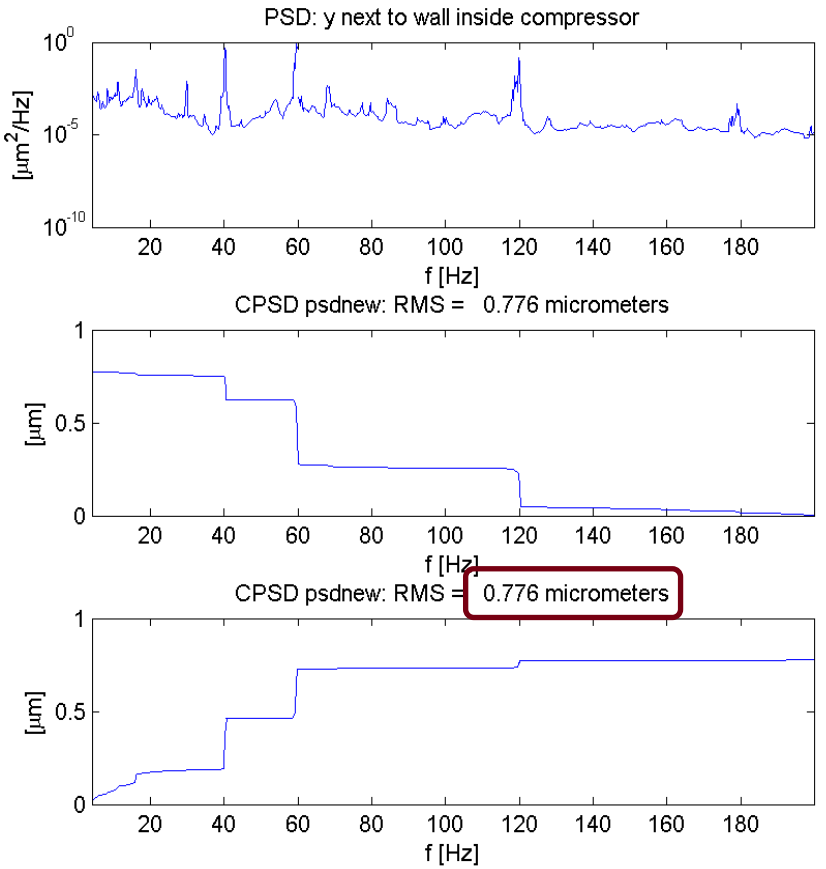


# CHL2 Compression Room Vertical Motion (2)

Near Compressor #5

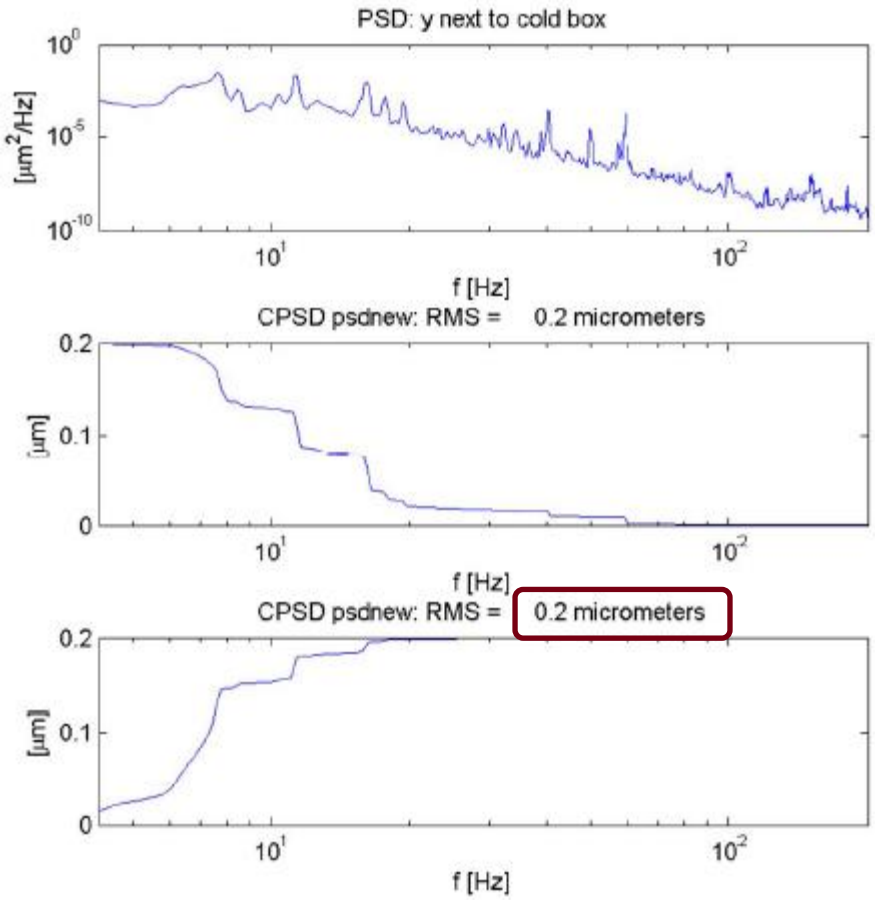



14 m to the South, Near #4

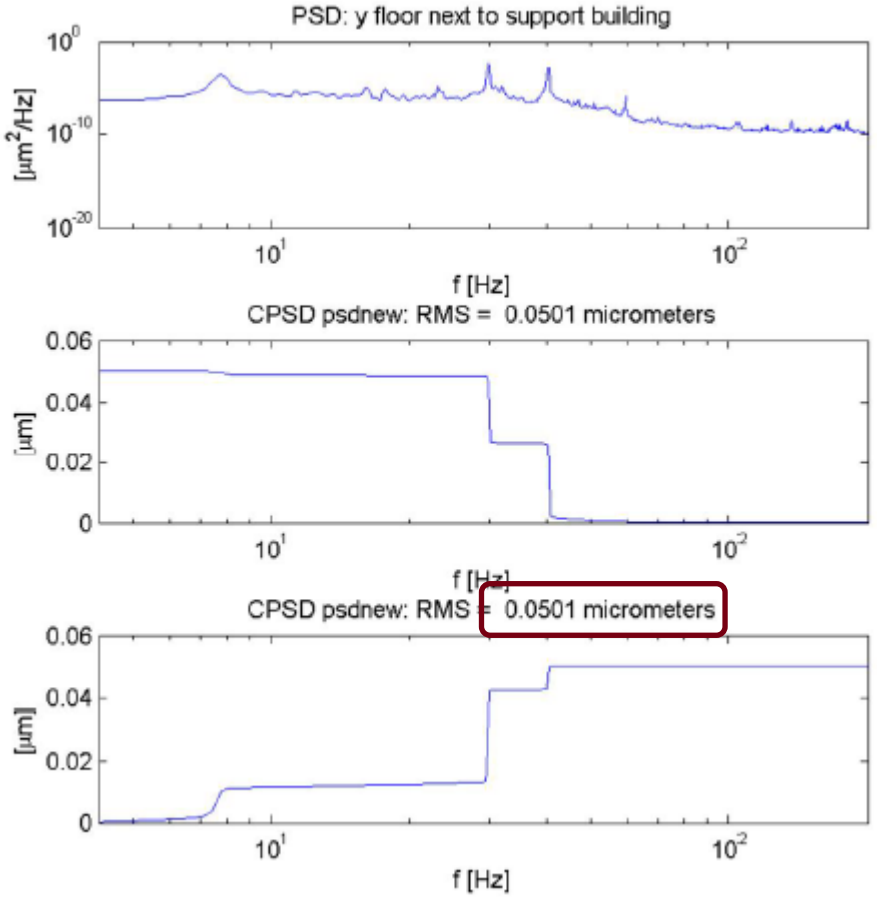


# Vertical Motion Outside on Concrete Pads

Near Upper Cold Box
(27 m from Compressor #5)

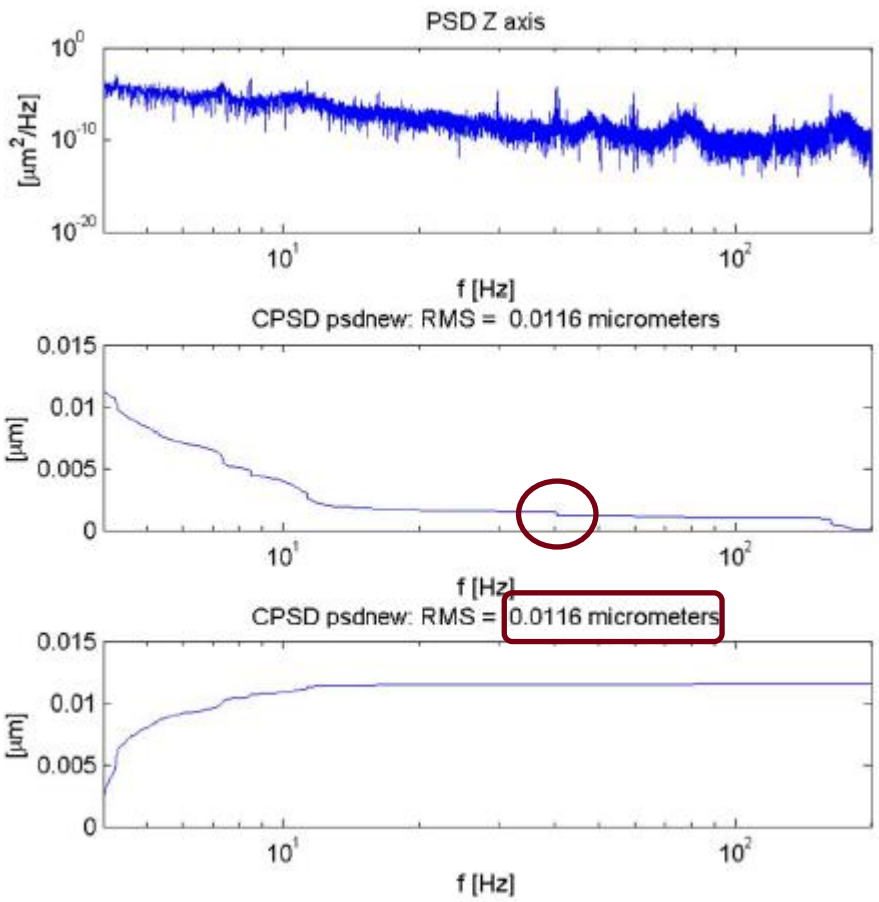



Near Linac Service Building
(76 m from Compressor #5)

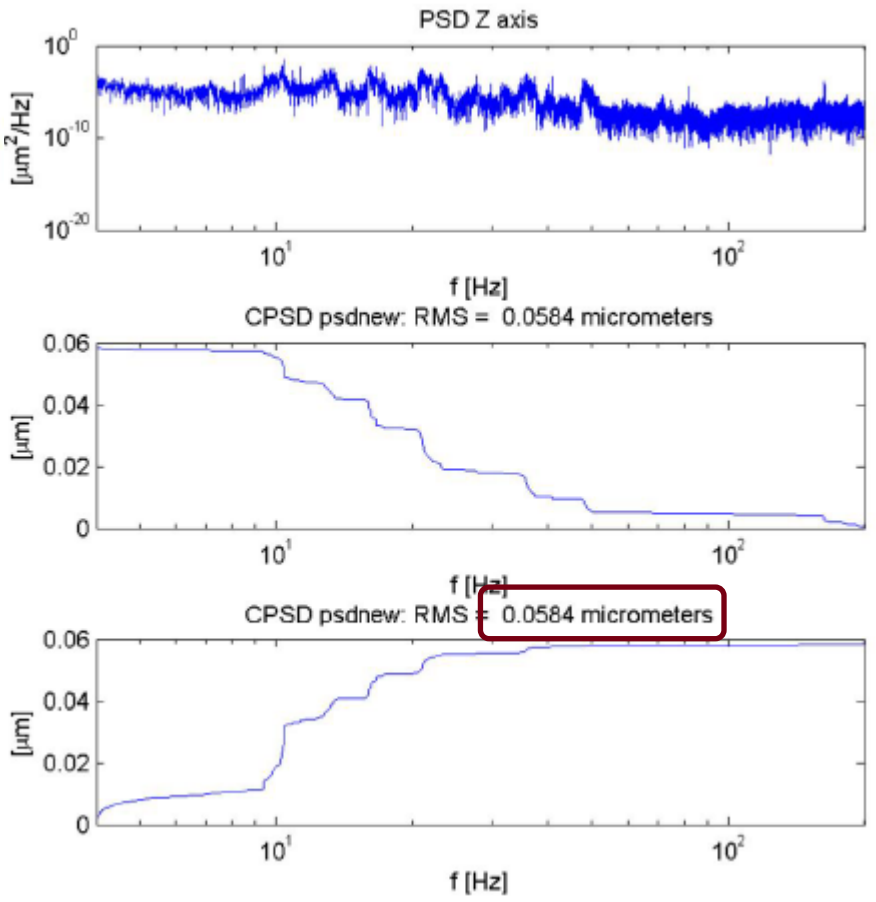


# North Linac Longitudinal (Z) Motion

On Floor



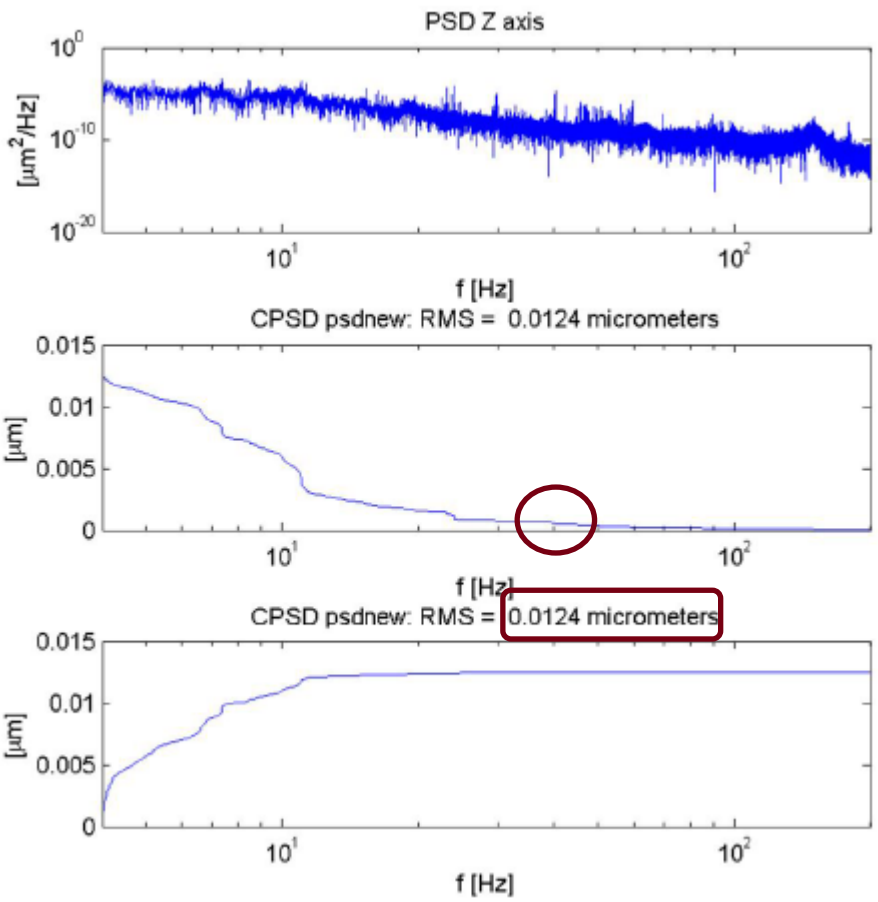

On Cryomodule



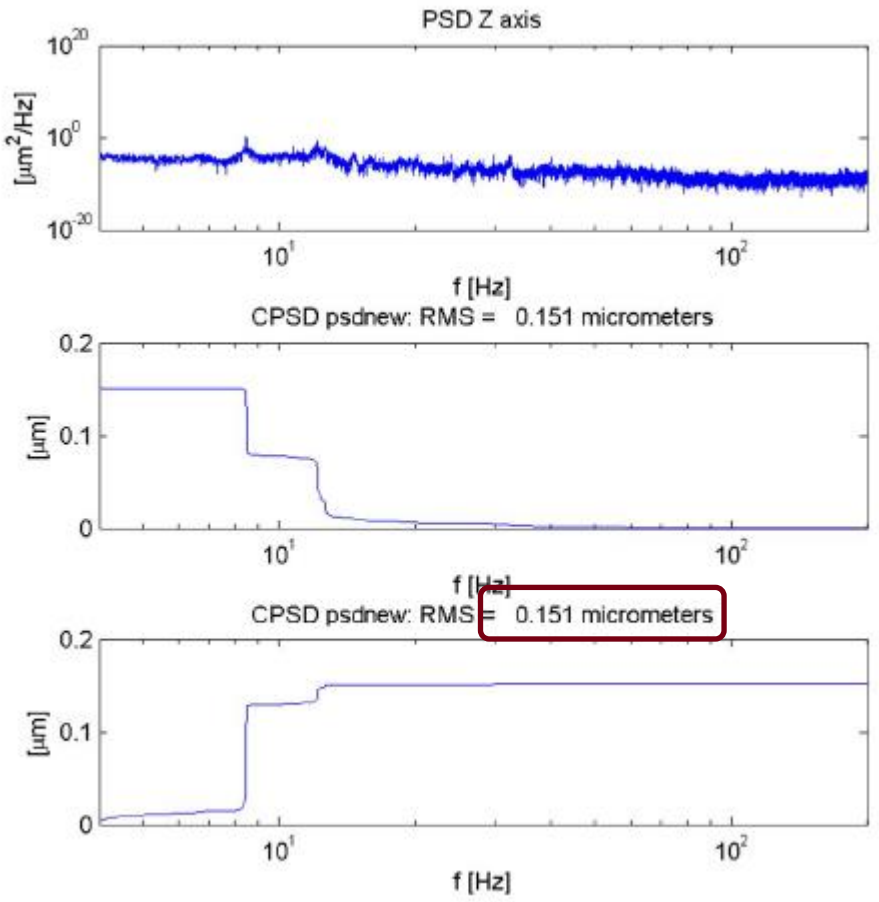

For JLAB CM, 1 um Z motion produces ~ 2 Hz detuning (vs 30 Hz BW)

# South Linac Longitudinal (Z) Motion

On Floor



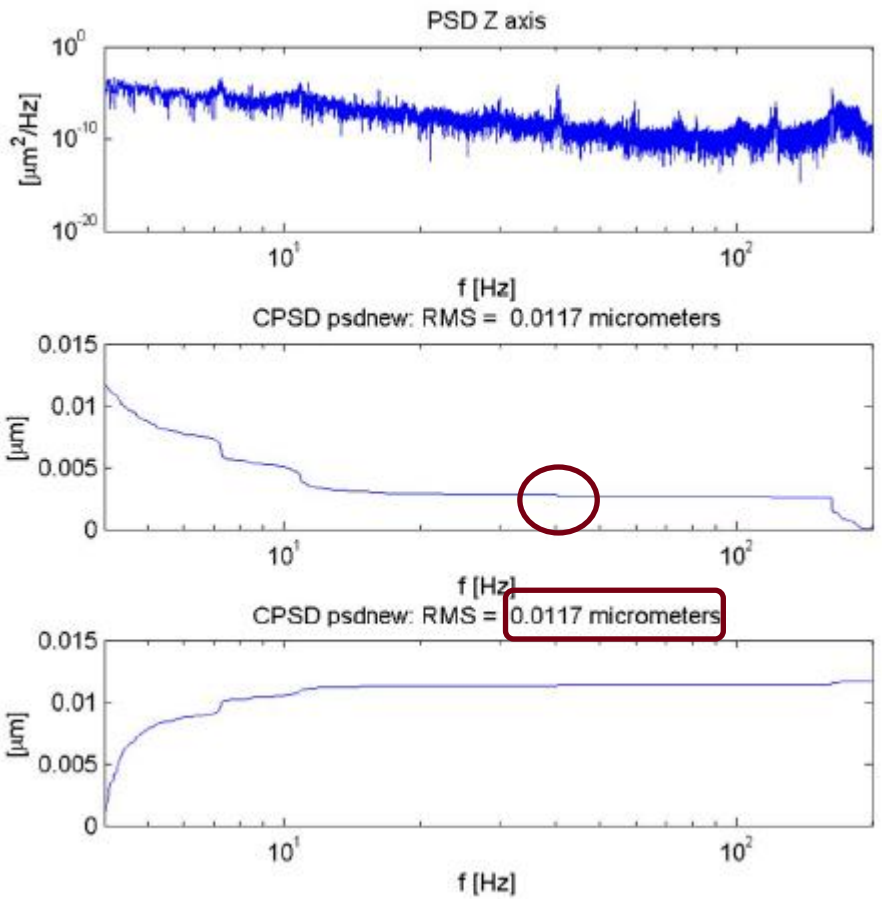

On Cryomodule



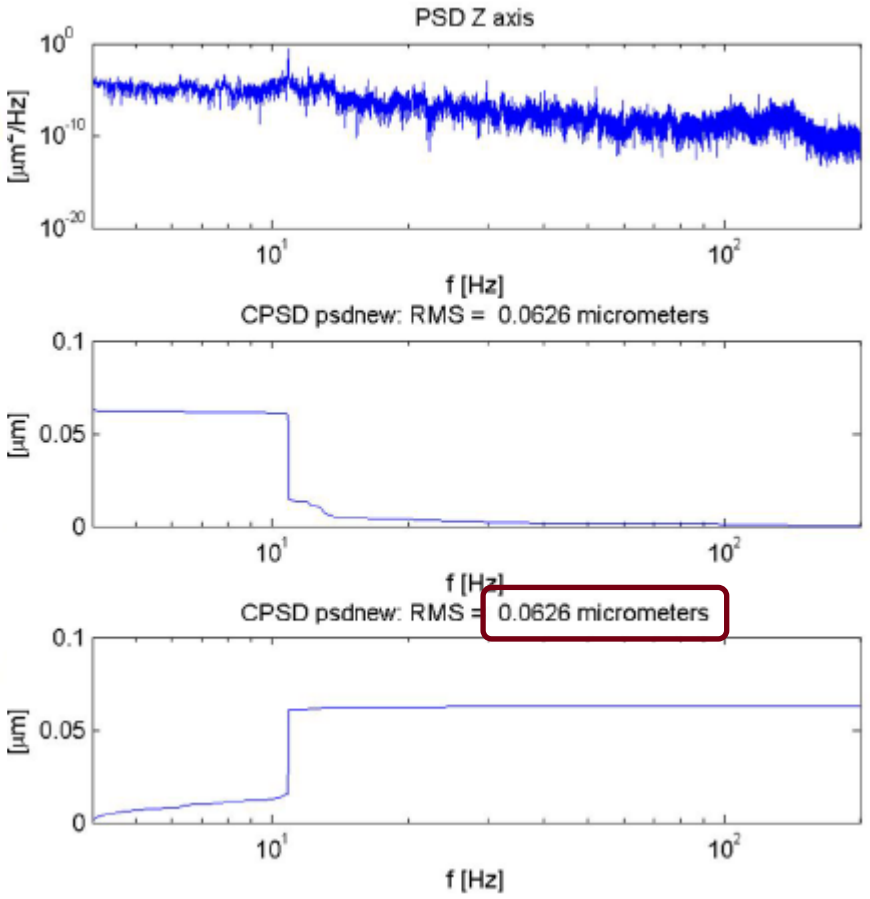

For JLAB CM, 1 um Z motion produces ~ 2 Hz detuning (vs 30 Hz BW)

# Linac Cryo Supply Linac Longitudinal (Z) Motion

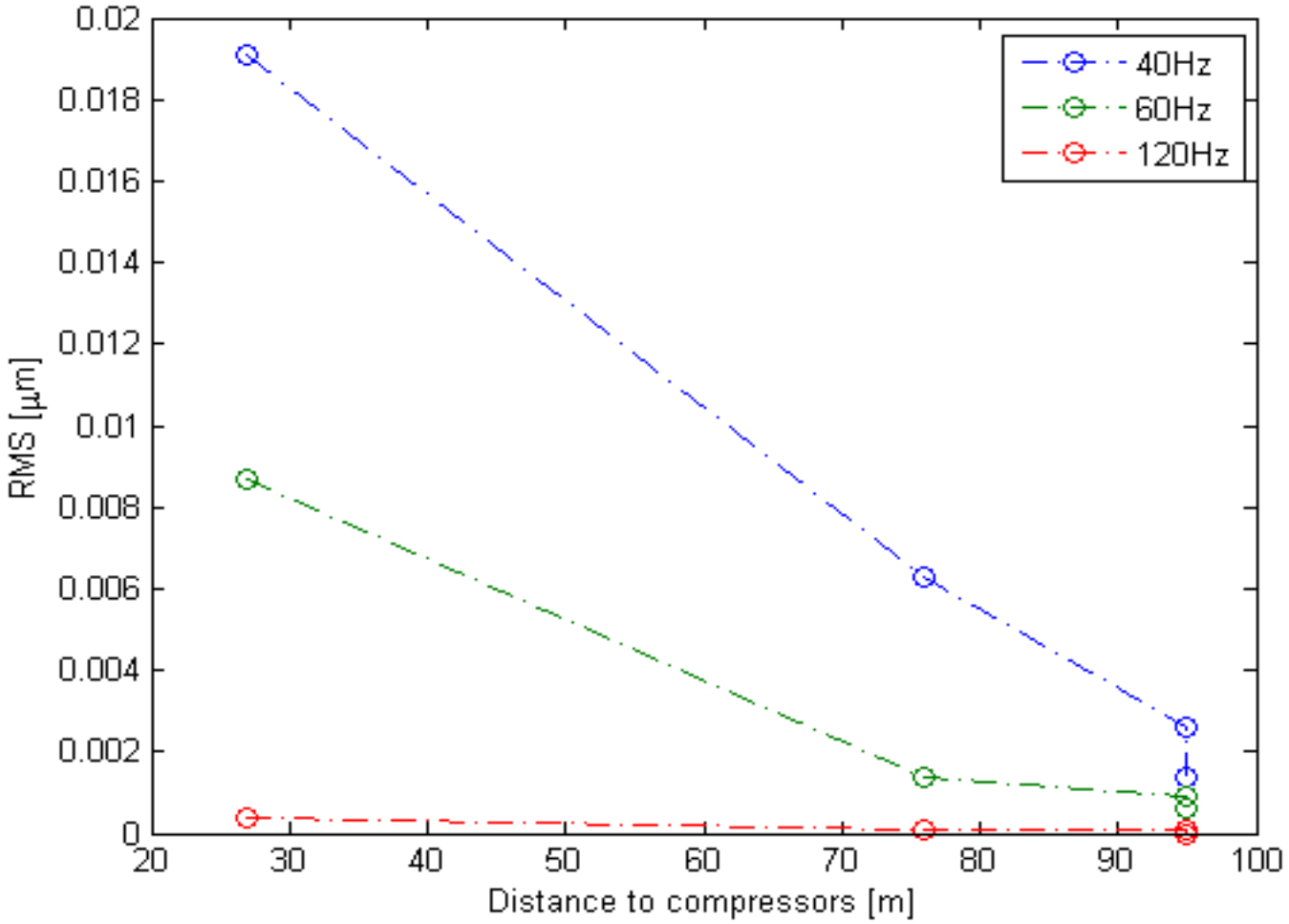
North




South



# 3D RMS Compressor-Induced Motion Versus Distance




Expect Rayleigh surface wave amplitude to fall off as $w = w_1 \sqrt{\frac{d_1}{d}} e^{-\alpha(d-d_1)}$