Linear Collider Collaboration Tech Notes

QUADRUPOLE VIBRATION MEASUREMENTS FOR QM1B AND QC3 IN THE FINAL FOCUS TEST BEAM at SLAC

January 12, 2000

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1 ABSTRACT

We have taken vibration measurements of quadrupoles QM1B and QC3 in the Final Focus Test Beam (FFTB) tunnel at SLAC. We present results for power spectra and integrated power spectra of the vibrations in the frequency range 1 –128Hz. For QM1B, we find 2nm rms vertical motion with respect to the FFTB tunnel floor for f>3Hz. The relevance of this data to NLC performance is discussed. In particular, we estimate a 4% luminosity loss if an IR quadrupole were to have similar vibrations as QM1B.

2 INTRODUCTION

Quadrupole vibrations at the NLC cause the colliding electron and positron beams to be offset by an amount, Δy, at the Interaction Point (IP). This leads to a luminosity loss, which can be approximated by

$$\frac{L(\Delta y)}{L_0} = \exp\left(-\frac{\Delta y^2}{8\sigma_y^2}\right) \quad \textbf{(1)}$$

If one requires the luminosity loss due to beam offsets from quadrupole vibrations be less then 5%, one arrives at a tolerance of $\Delta y < 3$nm, for a vertical beam spotsize of σ_y=5nm. The vibrations of the quadrupole magnets along the beamline affect this offset at the IP by differing amounts according to the lattice optics. Vibrations of magnets far from the IP cause a small displacement, while vibrations of final focus Interaction Region (IR) quads cause an offset comparable to their movement.

A detailed discussion of how vibrations impact NLC operation can be found in SLAC Report 474, '*Zeroth Order Design Report for the Next Linear Collider.*' [1] Appendix C in this Report gives a detailed description of the theory of ground motion and how ground motion at SLAC has been characterized with seismometers. Definitions for the power spectrum, integrated power spectrum and correlation functions can be found there. The power spectrum, P(ω), is expressed in units of μm^2/Hz and describes the frequency content of the measured vibrations. The integrated power spectrum is expressed in units of μm and describes the rms vibration amplitude for all frequencies above some frequency f. The correlation functions describe the correlation between vibrations at two different locations and are important for understanding the wavelengths of vibration disturbances at different frequencies. The correlation functions also assist understanding of mechanical resonances in support structures, as we discuss in Section 6 of this paper. Appendix C also discusses the lattice response functions, G(k,s), which give the mapping of the quadrupole vibrations to the IP and allow one to derive sensitivities and tolerances for individual quadrupole vibrations along the beamline. Sensitivities refer to the impact of the motion of a single quadrupole on the luminosity loss. An example of this is given in Figure 11-24 in Reference [1], which displays the vertical vibration sensitivity for quads in the CCX, BX, CCY and FT that correspond to a luminosity loss of 1%. Tolerances refer to requirements on vibrations such that vibrations from a grouping of quadrupoles will result in a luminosity loss below some level. For example, Figure 7-40 in Reference [1] gives a tolerance curve (corresponding to 1.5% luminosity loss) for the integrated power spectrum for vertical vibrations of Linac quadrupoles assuming that their vibrations follow the local ground motion. A third important ingredient (in addition to the vibration power spectrum and the lattice response function) influencing the beam offset, Δy, at the IP is the feedback suppression function, F(ω). The deflection angle of the colliding beams can be accurately measured with beam position monitors, and a feedback can then steer the beams into collision. The feedback will be very effective at suppressing slower vibration drifts below about 1-10 Hz. Figure 7-38 in Reference [1] plots F(ω) for two candidate feedback algorithms. A functional description for how the vibration power spectrum, the lattice response function, and the feedback suppression function affect the beam offset, Δy, can be expressed by

$$\left\langle \Delta y_{IP}^{2} \right\rangle = \iiint P(w,k;s)G(k;s)F(w)\frac{dk}{2p}\frac{dv}{2p}\,ds \qquad \textbf{(2)}$$

3 VIBRATION MEASUREMENTS

Many measurements of vibrations pertinent to future linear collider operation have been done, such as in References [2, 3, 4, 5, 6]. In particular, Reference [2] has studied the vibrations of the LINAC quadrupoles at SLAC. It found the vertical motion of quadrupole Q701, for example, to be 230nm rms (50nm rms) for f>2Hz with accelerator structure water on (off). This size of vibration would be unacceptable for NLC operation. Some noted causes of the large vibrations were water flow to the accelerator structures, water flow to the quadrupoles, and inadequate design of the quadrupole support structure. Reference [3] presents vibration measurements for a Fermilab Tevatron quadrupole magnet during accelerator operation. It shows about 20nm rms vertical motion for f>2Hz, and the paper makes the statement that the main ring tunnel would not be a quiet enough location for a future linear collider. (That statement should be qualified, however, since the Tevatron was not designed and built for tolerances of a few nanometers. Perhaps with reasonable improvements, such as achieving isolation from the helium liquefier plant, vibrations of a few nanometers could be achieved.)

At the Final Focus Test Beam (FFTB) at SLAC, vertical beam spotsizes of 70 nm rms have been achieved [7,8]. This includes a sizable contribution of about 40nm rms due to beam jitter, caused by mechanical vibrations of the final quadrupole triplet (QC1, QX1 and QC2), with respect to the interferometer fringe pattern of the KEK Beam Spotsize Monitor. [9,10,11] However, not all of the FFTB quadrupoles exhibit such large jitter. Vibration data has been taken on many of the quadrupoles in the FFTB, and the data indicate that the magnet vibrations are much smaller [12] (typically 10-25 nm rms for f>2Hz) for magnets located in the upstream part of FFTB where the concrete floor is situated on compactified soil that was part of the original SLAC Beam Switchyard. This is in contrast to the downstream portion of FFTB that was extended out into the Research Yard. It is also noted in Reference [1] p.395 that "Seismometer measurements that were made on top of the quadrupoles and on the floor in the FFTB show that there is only a few nm of relative motion (f>0.1Hz) between them when the quadrupoles are powered." Unfortunately, there is no figure or reference given to support that statement. Subsequent searching of vibration data records from FFTB did yield supporting figures that indicated the data was taken on quad QM1B at 2am on 11/22/95 (Figure A.1 in the Appendix).

The purpose of the study reported in this paper was to repeat the vibration data measurements on QM1B, and to quantify and document the results. We also wanted to take vibration data on a larger quadrupole magnet, QC3 in FFTB, for comparison. And we wished to develop standard data taking and analysis procedures for characterizing quadrupole vibrations and how they would affect luminosity at a future linear collider. This work was part of the DOE ERULF summer student program at SLAC. Rachel Fenn was the student for the project; Tim Slaton and Mike Woods supervised it. A copy of Rachel's report can be found in Reference [13].

4 SETUP AND DATA ACQUISITION

Measurements of quadrupole displacement were made with LC-4 geophones [14], whose signals were fed through battery-powered amplifiers and then digitized in a 4-channel National Instruments AT-A2150 DAQ board with 16-bit resolution. Data taking used Labview on a PC. The sampling rate was 256 Hz. All data was saved for offline analysis with Matlab.

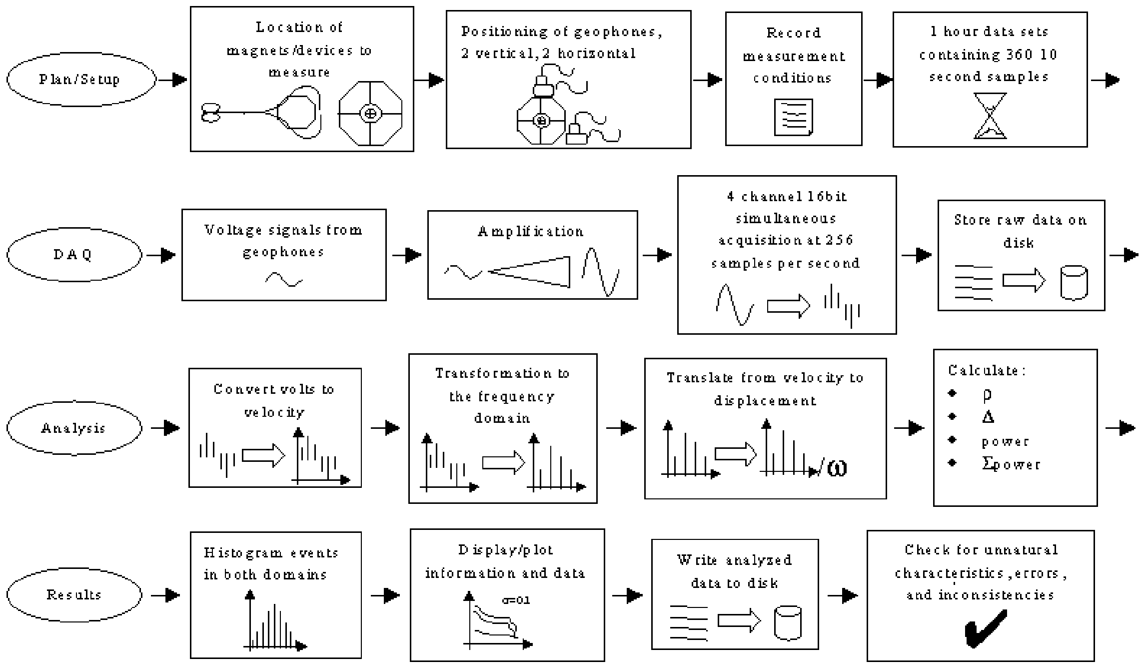
The geophone output signals are proportional to the velocity. Four geophones were used, two vertical (1, 2) and two horizontal (3, 4). The relevant dynamic range of these devices in our study is 1-128 Hz. 1 Hz is the natural frequency of the geophone, and as we will see in the calibration data the noise of these devices becomes significant at the nanometer level for frequencies below 3 Hz. 128Hz is half of the sampling frequency, 256Hz.

Figure 1. QC3 magnet in FFTB tunnel.

Both the QM1B and QC3 magnets are located in the Final Focus Test Beam (FFTB) tunnel. They are supported on similar mounts – anocast steel blocks on a concrete floor. QC3 is larger with more water flow. It is supported on a long pier extending about 10 feet down into sandstone, which was an effort to achieve better stability for it since its flooring is on an extension into the Research Yard. QM1B is located further upstream in the FFTB tunnel, where the floor is much more stable. In both cases, beam height is about 5 feet (~ 6 feet for QC3 and 5 feet for QM1B) above the tunnel floor.

5 ANALYSIS

The flowchart pictured below outlines the process of acquiring vibration measurements and analyzing them. The first two rows were just described in the previous section; now we describe the analysis portion of the chart (rows 3 and 4).



The analysis was done in Matlab with programs written by Tim Slaton and Rachel Fenn. The programs are outlined below.

Summary of Programs written by Tim Slaton:
Ana_prg (analysis program):

- Labview_read:

  This function loads in vibration data from a LabVIEW data file and converts voltage signals to velocity (m/s).
- Ana_filt_fun:

  Converts the velocity matrix into a single column and subtracts an offset to make the average velocity zero.
- Ana_fft_fun:

  Uses Fourier transforms to convert velocity to the frequency domain and computes the power spectra, and integrated power spectra.

Summary of programs written by Rachel Fenn:
Display_data:

- Plot_power:
  Function to plot three sets of power data on one page; i) power spectra from channels 1, 2, 3, 4, and the differences (between ch1 – ch0 and ch3 – ch2), ii) integrated power spectra for channels 1 – 4, and the differences, and iii) the real and imaginary parts of the correlation function.
- Plot_velocity:
  Plots the four channels of velocity data against time.
- Plot_vel_hist:
  Function creates and plots a histogram of the velocity data.
- Plot_pwr_hist:
  Creates the power spectra, integrated power spectra, and correlation plots for 8 individual frequencies (not used for this report).
- Print_plots:
  Writes all plots to file.
- Write_power:
  Writes the power spectra and integrated power spectra data, in tables, to a file.
- Write_velocity:
  Writes the velocity data, in tables, to a file.
- Write_vel_hist:
  Writes the histogram velocity data, in tables, to a file.
- Luminosity:
  Takes the velocity and integrates it to get a displacement function, which we interpret as the offset, Δy, of the 2 colliding beams. It then estimates the corresponding luminosity loss using Equation 1 with and without the use of a next pulse feedback (described below).
- Rms_data:
  Plots 24 hours of rms values.

The Matlab analysis programs can be found on the NT network on the users' disk at u:\m\mwoods\Nlc2\Rafen\Lib\Matlab. The data files reported on in this paper can be found at u:\m\mwoods\Nlc2\Rafen\Data. To run the analysis, run Matlab and change directories to the location of the Matlab programs. Next, run Ana_prg and that will call the programs needed to retrieve the data, perform the Fourier transforms on it and compute the power spectra, the integrated power spectra and the correlation functions. Then, run Display_data to create some standard plots. This program will prompt if you wish to print and save the plots as well.

6 RESULTS

Results from four data sets are presented. The first data set was taken in the Sector 10 alignment room for one hour with all four geophones side-by-side on the floor. Data sets two and three were on the QM1B magnet for 1 hour and 24 hours respectively. The fourth set of data was taken on QC3 for one hour. Geophone channels one (on quad) and two (on floor) are vertical, and channels three (on quad) and four (on floor) are horizontal. The "velocity" and "histogram" plots include either the vertical or horizontal data, and the difference between the two geophones. The "power" plots include the power spectra, the integrated power spectra, and the real and imaginary parts of the correlation function.

6.1 Geophone noise data

Data file name: CAL00.000; 07/12/99 15:00

These measurements were made to characterize the intrinsic noise of the geophones. The geophones were placed next to each other on the floor in the Sector 10 alignment room. The results for the power spectrum (PS), integrated power spectrum (IPS) and correlation function for the 2 vertical geophones are displayed in Figure 2. We find that the IPS(3Hz)=0.9nm for the difference of these 2 geophones, and that this increases to 2.1nm at 2Hz and 4.3nm at 1Hz. Thus, the instrumental noise of the geophones limits the lower frequency to about 3Hz for which vibration measurements can be studied with one nanometer accuracy.

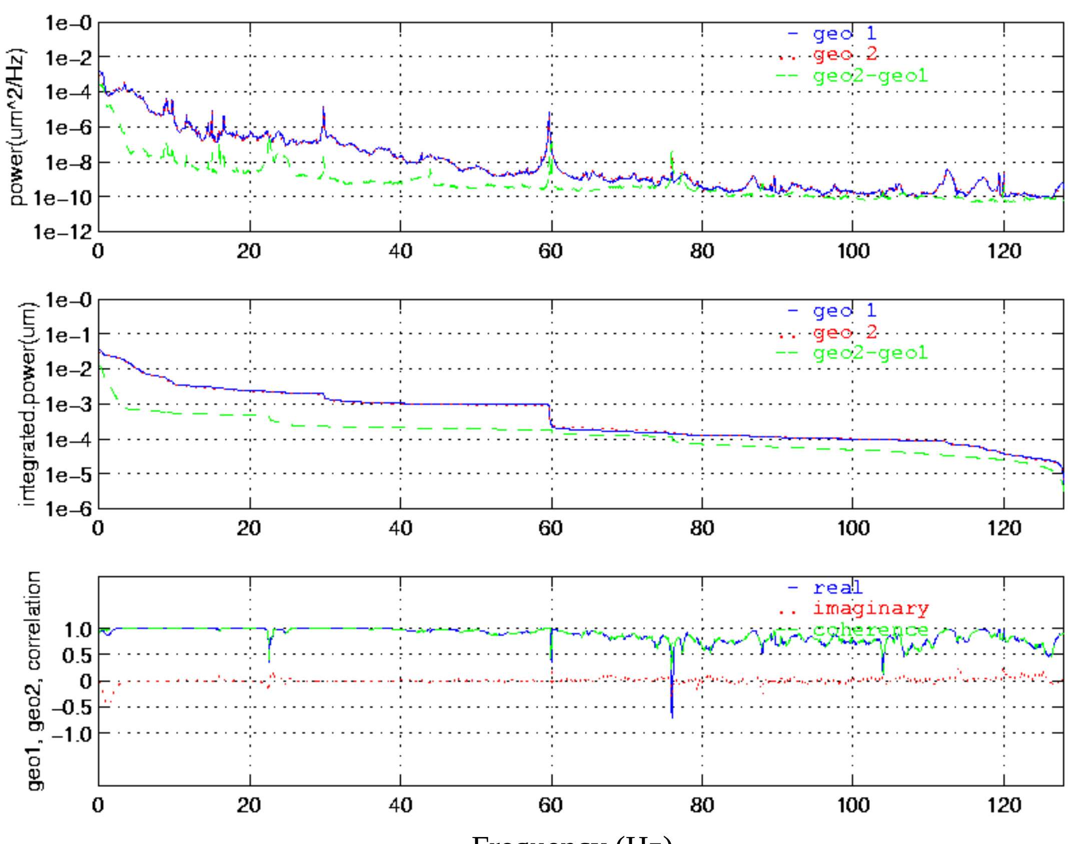


Figure 2. Power plots for vertical vibrations of 2 geophones side-by-side

6.2 QM1B 1-hour data set
File name: QM1B01.001; 07/15/99 17:00

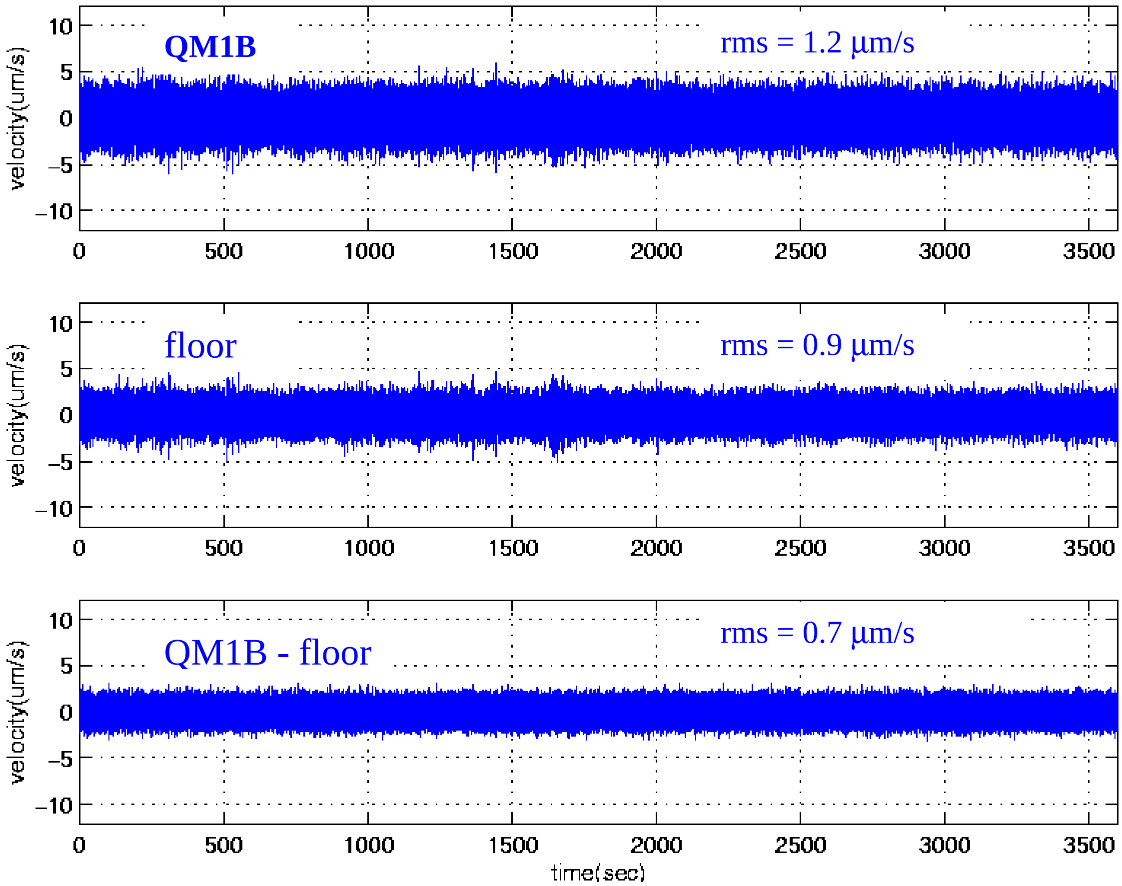


Figure 3. Vertical velocity at QM1B

The vertical velocity measurements at QM1B over a 1-hour time period are plotted in Figure 3. We find the rms vertical velocity to be 1.2 µm/s on top of the quad, 0.9 µm/s on the floor adjacent to the quad, and 0.7 µm/s for the difference signal, QM1B-floor. As shown in the histograms in Figure 4, the distribution of the measurements is well described by a gaussian. The corresponding power plots for these data are shown in Figure 5. Noise peaks at 60 Hz and 30 Hz are observed, though these give a small contribution of about 1nm to the IPS. At 3Hz, the IPS for QM1B is 18nm and for the difference, QM1B-floor, is 2.0nm. This is consistent with the result referred to in Reference [1], which we believe refers to an online data plot that we have reproduced in Figure A.1.

The corresponding data plots for the horizontal velocity measurements are shown in Figures 6 and 7. The horizontal floor velocity is similar to the vertical floor velocity, but the quad horizontal velocity is much increased compared to the vertical. From the power plots in Figure 7, we observe again the noise peaks at 60 Hz and 30 Hz and also a broad resonance near 45 Hz. The correlation plot shows that the quad is moving out of phase with the floor above 45 Hz, indicating a 45 Hz mechanical resonance for horizontal vibrations of the quad support structure. At 3 Hz, the IPS for the difference, QM1B-floor, is 16nm.

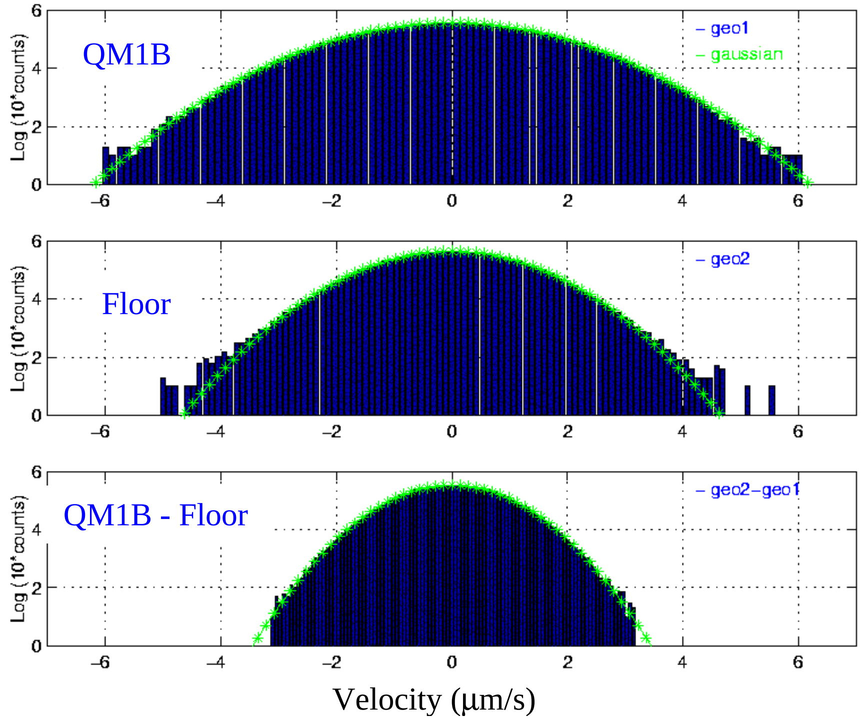


Figure 4. Histogram of vertical velocity data at QM1B

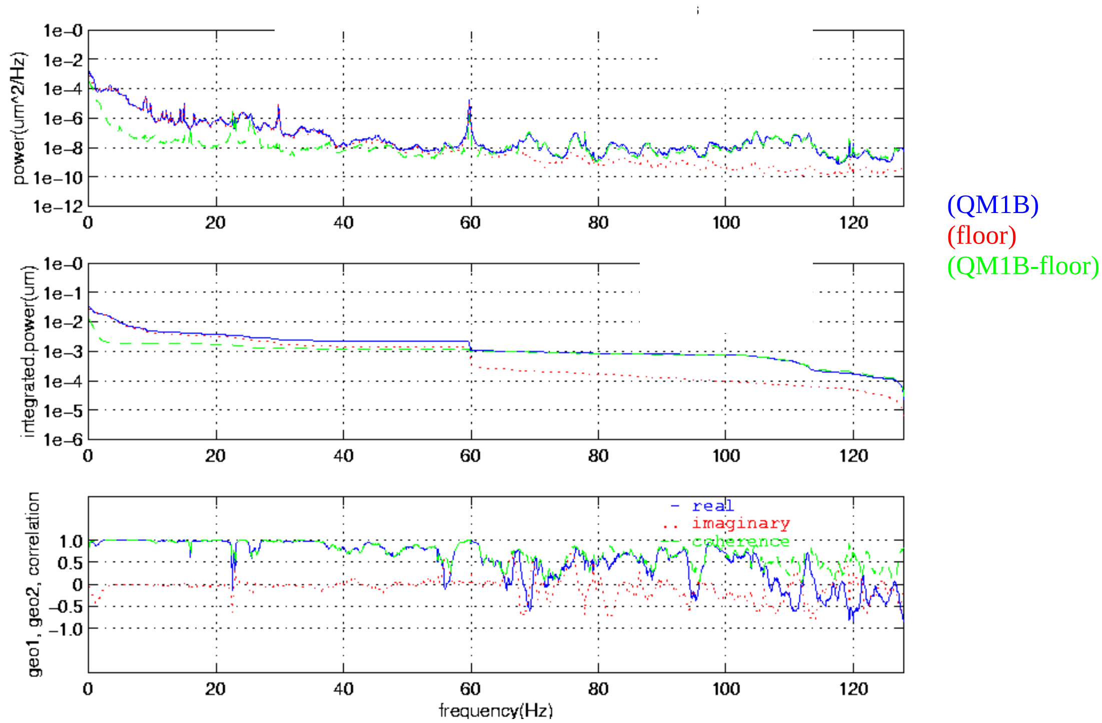


Figure 5. Power plots for vertical vibrations at QM1B

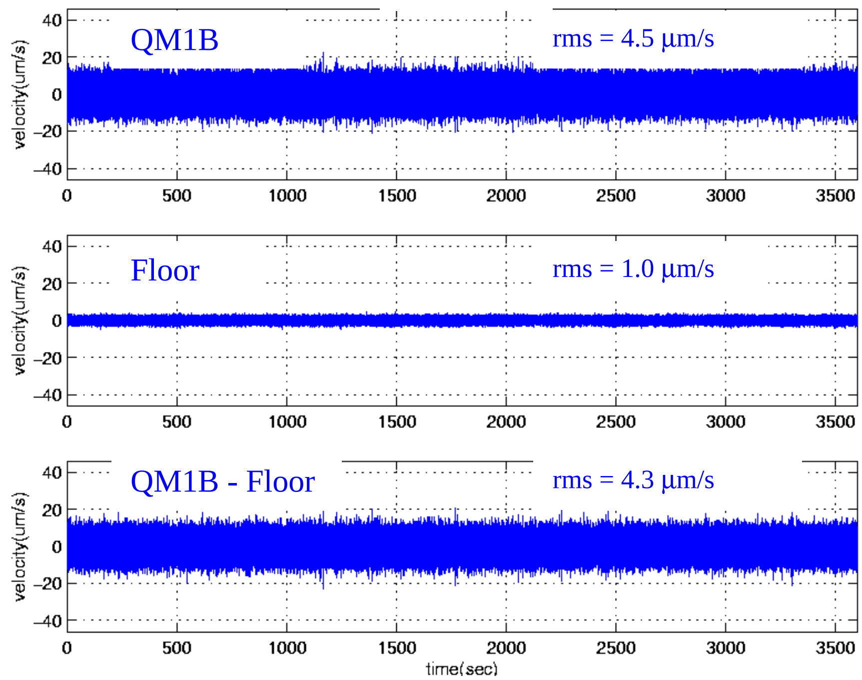


Figure 6. Horizontal velocity at QM1B over 1 hour

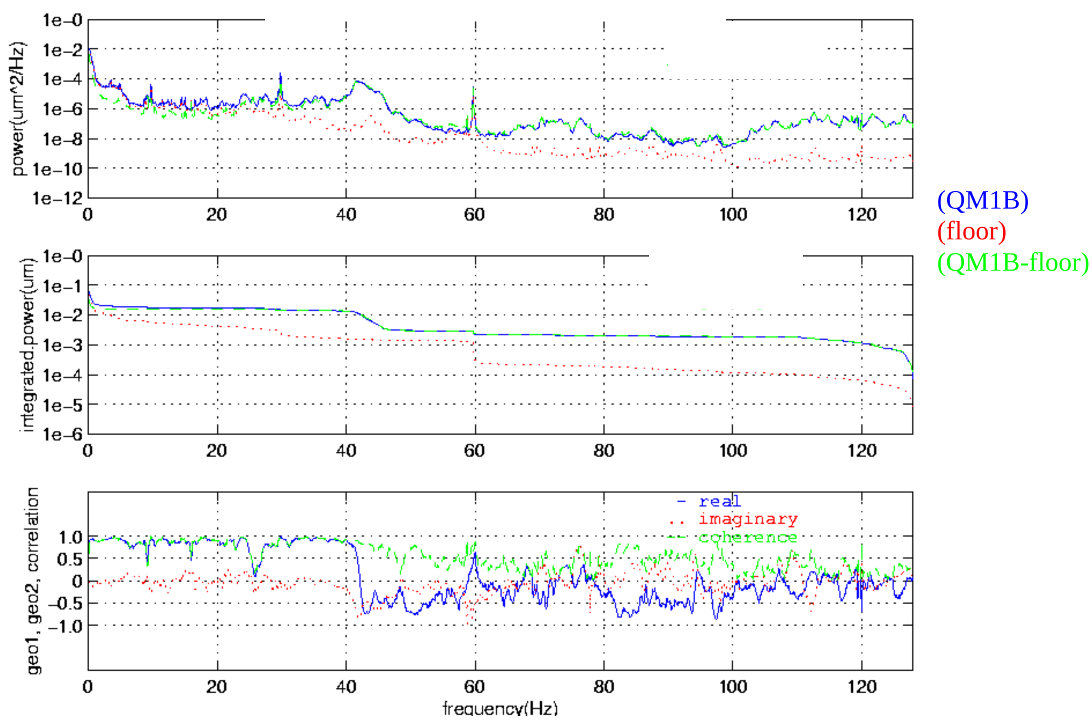


Figure 7. Power plots for horizontal vibrations at QM1B

6.3 QM1B 24-hour data set

File name: QM1B03.(00 - 23); 07/29/99 13:30 to 07/30/99 13:30; weekday beam on

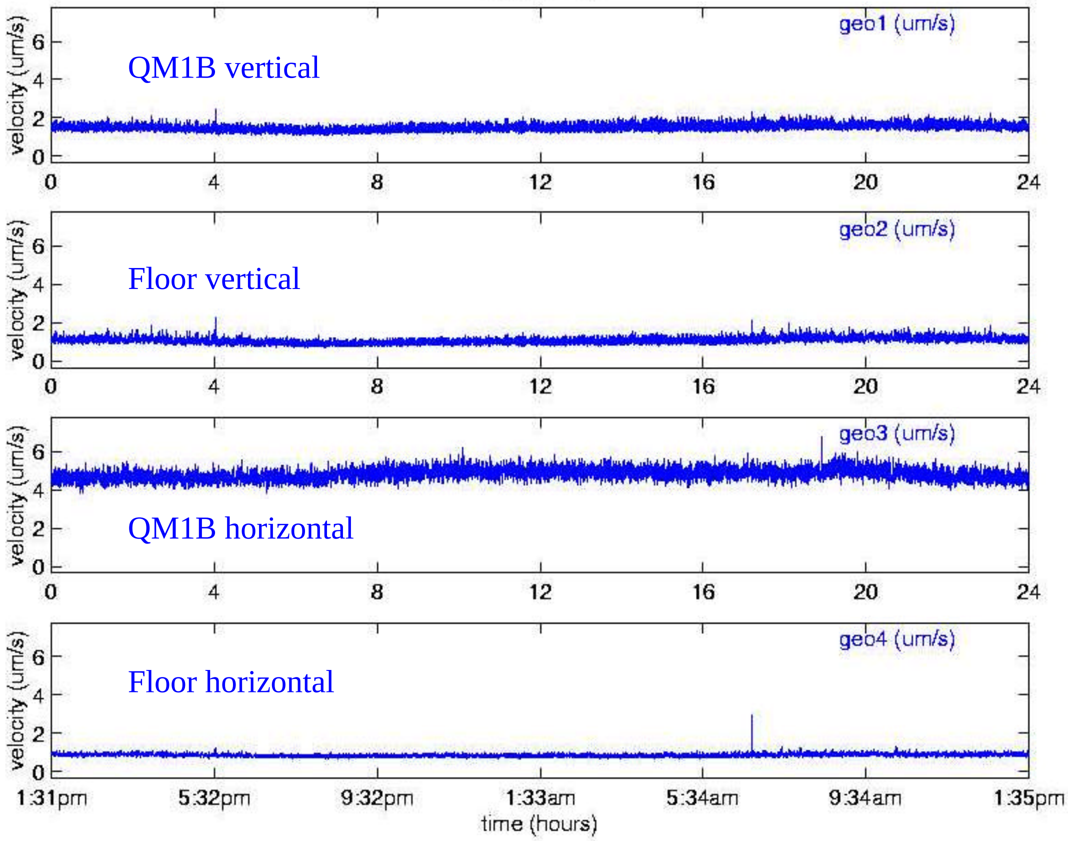


Figure 8. Vertical velocity rms at QM1B over 24 hours

Diurnal effects of vibrations for QM1B were studied and the results are presented in Figure 8. Each point of the 24-hour data plots is the rms for a 10-second sample. We observe that the diurnal variations are small. These data were taken on a weekday with the accelerator beam on for an FFTB experiment.

6.4 QC3 1-hour data set
File name: QC301.008; 08/03/99 07:00

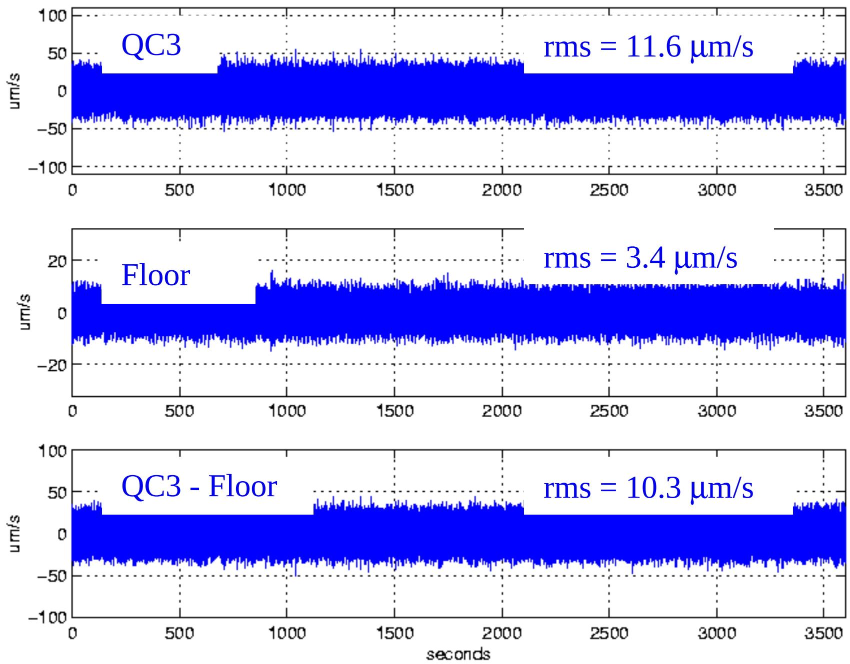


Figure 9. Vertical velocity at QC3 over 1 hour

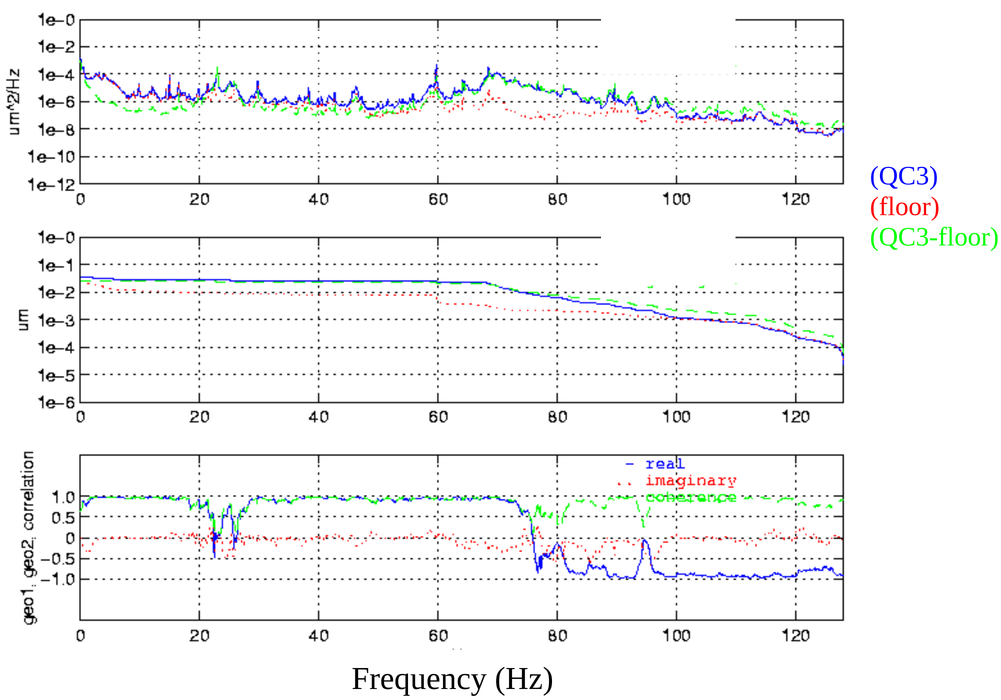


Figure 10. Power plots for vertical vibrations at QC3

The vertical velocity measurements at QC3 over a 1-hour time period are plotted in Figure 9 and the corresponding power spectra plots are shown in Figure 10. Similar plots for the horizontal velocity measurements are shown in Figures 11 and 12. We find that the vibrations are much larger than for QM1B. A vertical vibration mechanical resonance is evident at 70 Hz and a horizontal resonance at 25 Hz. At 3 Hz, the vertical IPS for QC3-Floor is 25nm and for horizontal it is 64nm. QC3 is a much larger magnet than QM1B with greater water flow as well. It is mounted on a 10-foot pier into sandstone as previously mentioned, while QM1B is mounted onto the tunnel concrete floor. The floor near QC3 also exhibits large vibrations. We investigated whether some of the larger vibrations for QC3 were due to its water flow. On 09/15/99 we compared one hour of vibration measurements with water on/off to FFTB and found little difference. The results are summarized in the following table.

Table 1. IPS results for QC3-Floor vibration measurements with cooling water on/off to FFTB magnets.

	Water On/Off	**Vertical IPS (3 Hz)**	**Horizontal IPS (3Hz)**
08/03/99 0700	On	25 nm	64 nm
09/15/99 1130	On	25 nm	70 nm
09/15/99 1030	Off	23 nm	78 nm

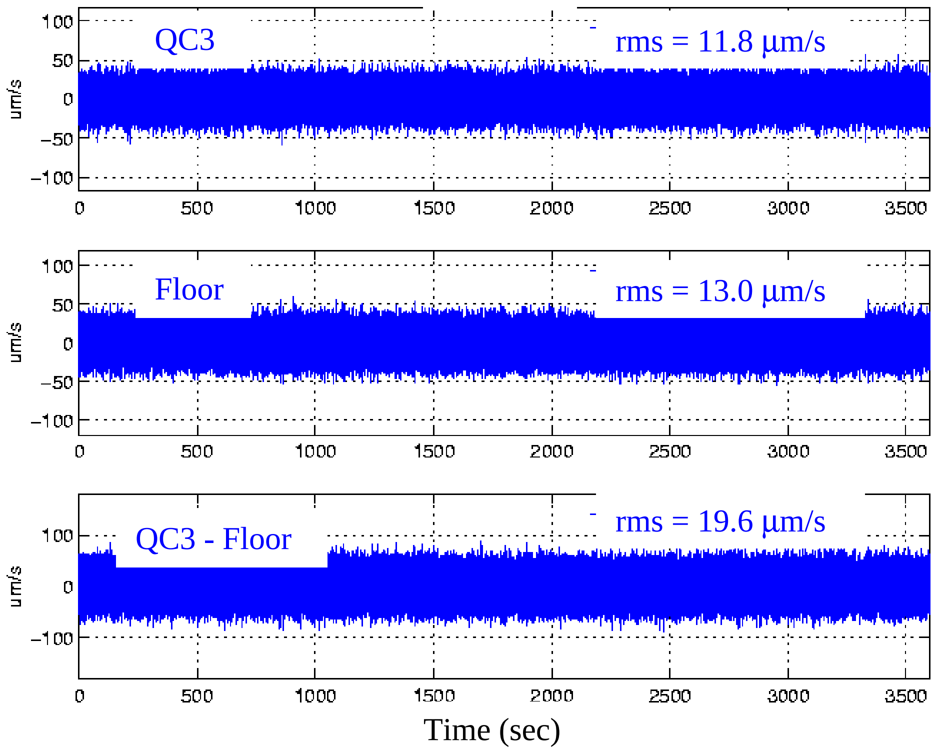


Figure 11. Horizontal velocity at QC3 over 1 hour

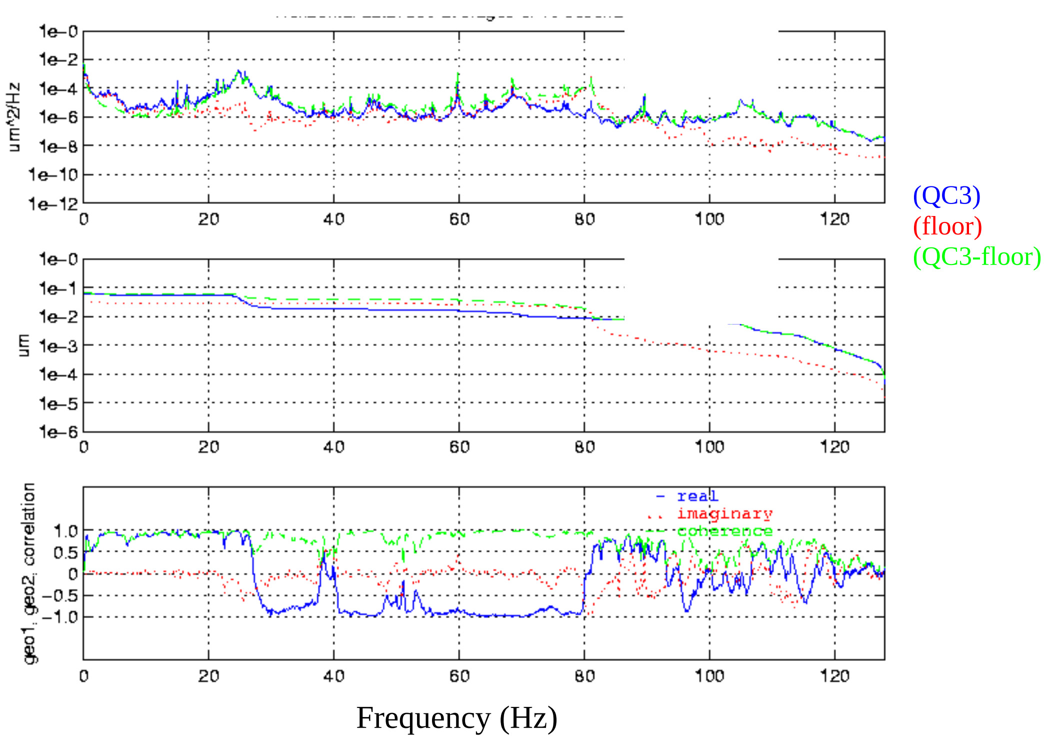


Figure 12. Power plots for horizontal vibrations at QC3

7 ESTIMATING LUMINOSITY LOSS

We now wish to quantify somewhat the effect of quadruple vibrations on potential luminosity loss. This was discussed in the Introduction, where we introduced Equation (1) to describe the effect on luminosity of a vertical offset between the colliding beams, Δy. We have noted that the vibrations of IR quadrupoles cause offsets, Δy, comparable to their motion. As a simple model, we suppose an IR quad to have vibrations as measured in data sets QM1B01.001 or QC301.008 and then calculate the offset and luminosity loss that would occur. We assume a 1:1 transfer function between the quad vibration and the resulting offset. We consider 2 scenarios for the incoming beam motion: a) the incoming electron beam is fixed in an inertial reference frame, and b) the incoming electron beam follows the tunnel floor motion. We expect that in general, scenario 2 more closely approximates reality. We also allow for a beam-based feedback, which makes use of observed deflection angles of the colliding beams to kick offset beams back into collision. We implemented a next pulse feedback [15] with a gain of 1.0, with a sampling and correction rate of 120 Hz, i.e. the machine repetition frequency. The feedback assumed that the colliding beam offsets, Δy, (as determined from the observed deflection angles) were measured with negligible error. We also assumed that at time t=0 the colliding beam offset is 0.

A set of luminosity plots is shown in Figure 13, where scenario a) is assumed to apply and we have input vibration data from QM1B. The first of the 4 plots shows Δy over 10 seconds with no feedback operating. The second plot shows the resulting normalized luminosity that would be achieved. We observe a rms for Δy of 32nm with a corresponding luminosity loss of 72%. If we allow the next pulse feedback to operate, the new Δy data is shown in plot 3 and the corresponding normalized luminosity is shown in plot 4. Now the rms offset is only 7.6nm and the luminosity loss is reduced to 20%.

If the incoming beam motion is instead assumed to follow the tunnel floor motion (scenario b), and we input the QM1B-Floor data), then the luminosity plots become those shown in Figure 14. The rms for Δy without feedback is reduced from 32nm to 12nm, and with the next pulse feedback operating it is reduced from 7.6nm to 2.8nm. The luminosity loss is 43% without feedback and is only 4% with the feedback.

We also studied the luminosity loss that would result if we input the QC3 vibration data rather than the QM1B vibration data. This is summarized in Figures 15 and 16. The luminosity loss is very large, and even worsens when the next pulse feedback is applied. This is due to the large vibrations above 10 Hz, which get magnified by the feedback [15].

8 SUMMARY

We have presented vibration measurements in the frequency range of 1-128Hz for quadrupoles QM1B and QC3 in the FFTB at SLAC. We find the vertical vibrations of QM1B with respect to the nearby tunnel floor to be very good, with an IPS(3Hz)=2.0nm. This is consistent with earlier measurements mentioned in Reference [1] (but which were not published). This indicates that the QM1B quadrupole support design provides a good starting point for design of supports for NLC quads. However the horizontal vibrations are much larger with IPS(3Hz)=16nm for the QM1B-Floor motion, and there is a horizontal mechanical resonance at 45Hz. QM1B is a relatively small quadrupole, while QC3 is substantially larger with more water flow to it. QC3 is part of the final transformer optics for FFTB. It is therefore interesting to examine its vibrations compared to those for QM1B. Unfortunately, the tunnel floor where QC3 is located is much inferior to the floor near QM1B and exhibits a lot of vibration itself. The vertical vibration of QC3-Floor was observed to have IPS(3Hz)=25nm. We observed no significant contribution to this from the cooling water to QC3 or nearby magnets. A mechanical vibration resonance is observed at 25Hz for horizontal motion of QC3, substantially lower than the 45Hz horizontal resonance observed for QM1B. Coupling of QC3's mechanical resonances with the large ground motion at QC3 appears to cause its large motion with respect to the floor.

We found little diurnal variation in the vibration data for QM1B.

A simple model was developed for estimating luminosity loss that would result if an IR quadrupole would have vibrations similar to those of QM1B or QC3. Utilizing a next pulse feedback algorithm and assuming that the incoming beam motion follows the tunnel floor motion, we find that vibrations typical of QM1B would cause a luminosity loss of 4%. For QC3, it is much larger.

9 REFERENCES

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[9] M. Woods et al., FFTB 98-02 (1998).

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[12] T. Slaton, unpublished.

[13] R. Fenn, see http://www.slac.stanford.edu/th/erulf-sise/rafen.

[14] G. Bowden, NLC ME Note 1-94 Rev 2 (1995). (See also Reference [1], Appendix C, Section C.3.)

[15] See Reference [1], pp. 394-395 for a description of the next pulse feedback.

[16] G. Bowden, NLC ME Note 4-95 Rev 0 (1995). (See also Reference [1], Appendix C, Section C.3.)

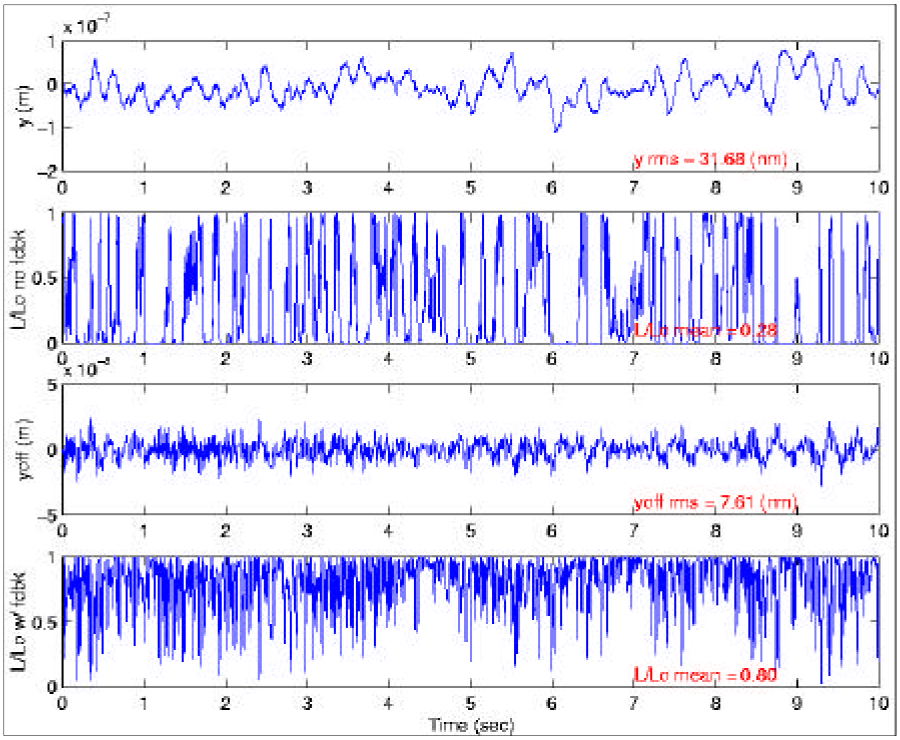

Figure 13. Luminosity plots for QM1B data, assuming incoming electron beam stays fixed in an inertial reference frame.

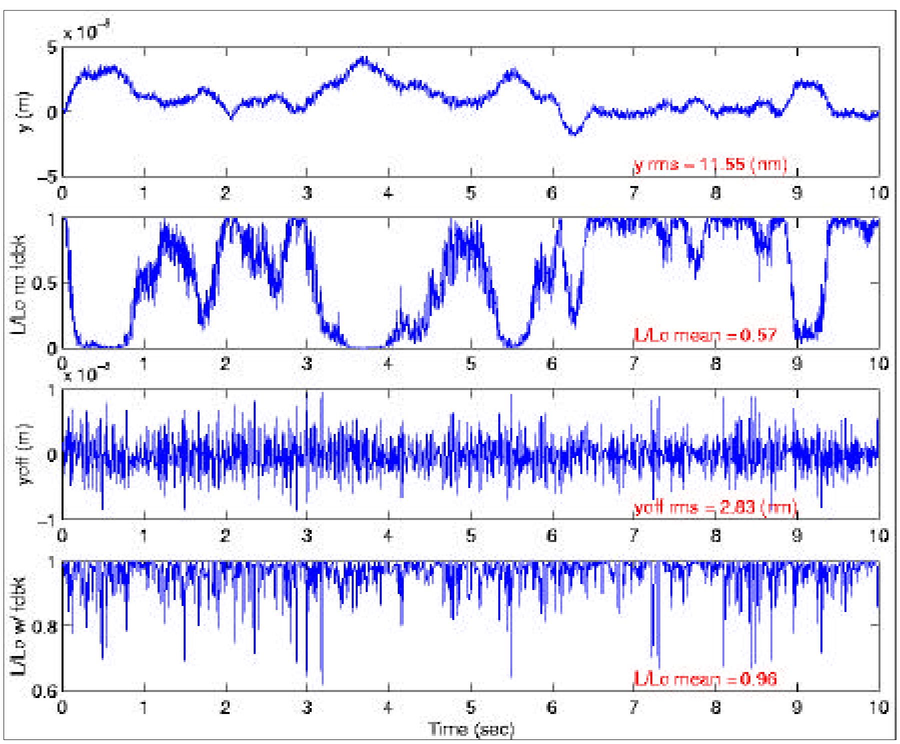

Figure 14. Luminosity plots for QM1B data, assuming incoming electron beam follows the tunnel floor motion

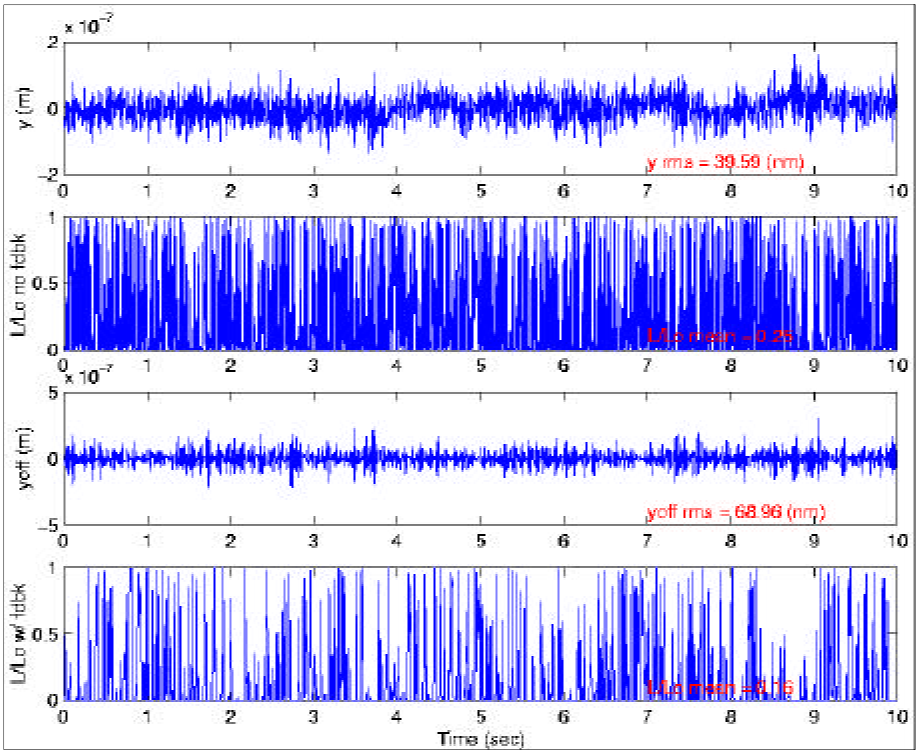

Figure 15. Luminosity plots for QC3 data, assuming incoming electron beam stays fixed in an inertial reference frame.

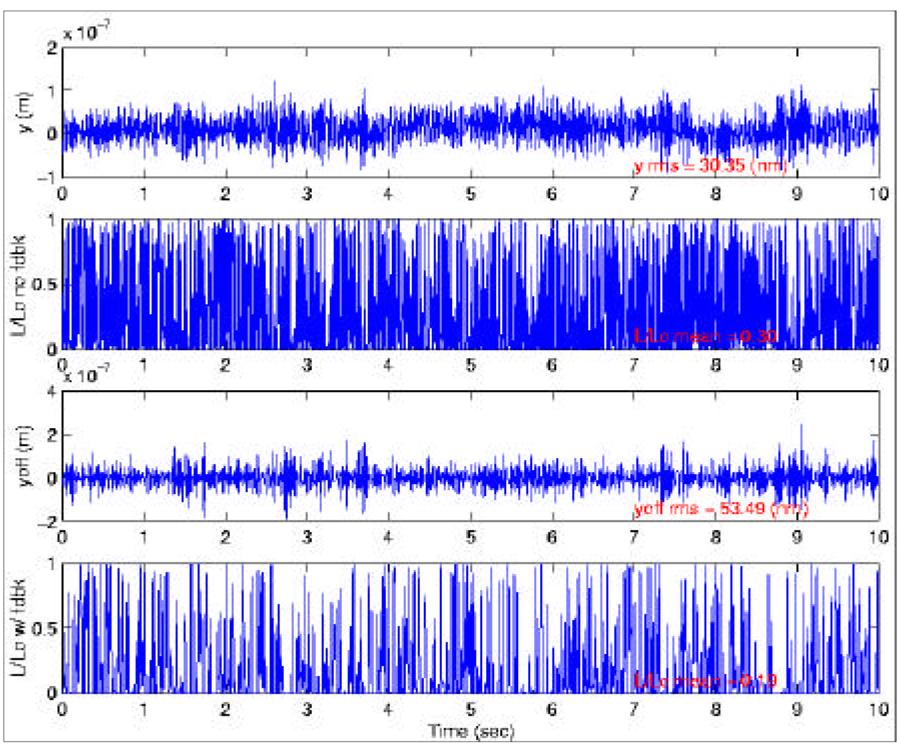

Figure 16. Luminosity plots for QC3 data, assuming incoming electron beam follows the tunnel floor motion

APPENDIX

Figure A.1 plots the integrated power spectrum for vertical vibration measurements using STS-2 Seismometers [16]. Channel 0 is the geophone on QM1B and channel 1 is on the adjacent floor. At 3Hz, the IPS for the difference signal, QM1B-floor, is 3.5 nm. This data was apparently taken on 11/22/95 at 2AM (unpublished).

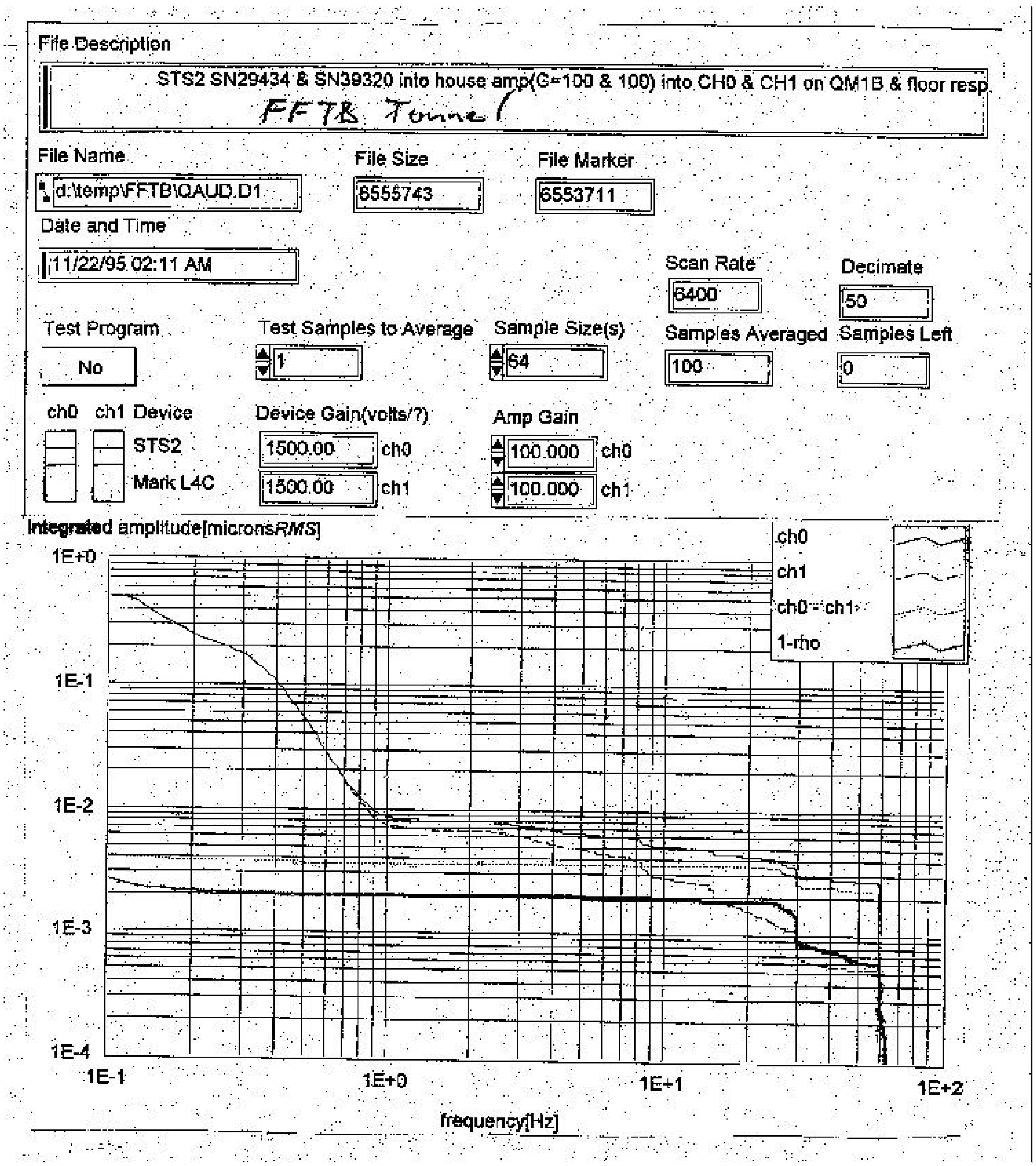

Figure A.1 Online Labview plot of vertical vibration IPS for QM1B in the FFTB tunnel.