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B. Baklakov, T. Bolshakov, A. Chupyra, A. Erokhin, P. Lebedev, V. Parkhomchuk and Sh. Singatulin

Budker Institute of Nuclear Physics
Novosibirsk, Russia 630090

J. Lach and V. Shiltsev

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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B. Baklakov, T. Bolshakov, A. Chupyra, A. Erokhin, P. Lebedev,
V. Parkhomchuk, Sh. Singatulin
Budker Institute of Nuclear Physics, Novosibirsk, Russia, 630090
J. Lach, V. Shiltsev
Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

November 24, 1997

Abstract

Ground motion can cause significant beam emittance growth and orbit oscillations in large hadron colliders due to a vibration of numerous focusing magnets. Larger accelerator ring circumference leads to smaller revolution frequency and, e.g. for the Fermilab Very Large Hadron Collider(VLHC) 50-150 Hz vibrations are of particular interest as they are resonant with the beam betatron frequency . Seismic measurements at an existing large accelerator under operation can help to estimate the vibrations generated by the technical systems in future machines. Comparison of noisy and quiet microseismic conditions might be useful for proper choice of technical solutions for future colliders. This article presents results of wide-band seismic measurements at the Fermilab site, namely, in the tunnel of the Tevatron and on the surface nearby, and in two deep tunnels in the Illinois dolomite which is though to be a possible geological environment of the future accelerators.

1 Introduction

Leading accelerator laboratories mount serious efforts in alignment and vibration studies concerning the stability of future accelerator facilities such as photon and meson factories, future linear colliders, and hadron supercolliders [1, 2, 3, 4, 5]. There are several future collider projects under consideration at Fermi National Accelerator Laboratory, including muon collider [6], linear collider and Very Large Hadron Collider(VLHC) [7]. On-site data on seismic vibration are of interest for all of them.

Besides concerns about orbit or trajectory stability, operation of large hadron colliders is a potential subject of transverse emittance growth due to fast (turn-to-turn) dipole angular kicks $\delta\theta$ produced by fast motion of quadrupoles. The emittance growth rate is equal to [2]:

$$d\epsilon_N/dt = (1/2)\gamma N_q f_0^2 \overline{\beta} S_{\delta\theta}(\Delta\nu f_0)$$

or, for a white seismic noise with rms value of magnet vibrations σ_q

$$d\epsilon_N/dt \simeq (1/2) f_0 \gamma \overline{\beta} N_q (\sigma_q/F)^2, \tag{1}$$

where f_0 is the revolution frequency, $\Delta\nu$ is a fractional part of tune, $S_{\delta\theta}$ is the power spectrum density of kick at a quadrupole $\delta\theta = \sigma_q/F$, F is the focal length of the quadrupole, N_q is a total number of quadrupole focusing magnets, $\overline{\beta}$ is the mean beta-function. The requirement of $d\epsilon_N/dt < \epsilon_N/\tau_L$, where τ_L is the luminosity lifetime, sets a limit on the turn-by-turn noise amplitude which looks extremely tough – of the order of the atomic size.

Table 1 shows main parameters of three hadron collider projects and their tolerances on low frequency vibrations [8]. The comparison of the emittance growth tolerance σ_q with the results of measurements worldwide (see Section 5 below) shows that for all these colliders the effect may have severe consequences.

Last two rows present necessary precision of quad-to-quad alignment in order to keep rms closed orbit distortion within 5 mm over the ring, and the estimated frequency of realignment of the most of focusing magnet.

Table 1: Stability of Hadron Colliders

Parameter		LHC	SSC	VLHC
Beam energy	E, TeV	7	20	50
Circumference	C, km	26.7	87.1	550
Norm. emittance, rms	ϵ_N, μm	4	1	1
Luminosity lifetime,	τ_L, hrs	10	20	5
Betatron frequency,	$f_\beta = \Delta\nu f_0$, Hz	3100	760	90-230
Tolerance on quads jitter at $\sim f_\beta$	rms, σ_q, nm	0.15	0.1	0.3
Measured jitter,	rms, nm	0.01-0.1	0.2	0.1-50
Tolerance on velocity PSD	$S_v(f_\beta),\ \mu m^2$/s	1.5$\cdot 10^{-3}$	1.6$\cdot 10^{-4}$	(0.6-4)$\cdot 10^{-5}$
Alignment tolerance for 5mm, closed orbit distortion	μm quad-to-quad	100	60	30
Realignment frequency,	days	$\sim$200	$\sim$45	$\sim$5

Here we discuss vibration measurements that have been carried out in August-October 1997 for Fermilab Future Collider Projects. The article is organized from several sections. In Section 2 we briefly describe seismic probes we used and our data acquisition system and procedures. Section 3 is devoted to results of surface mesurements at Fermilab. Deep tunnel measurement results are presented in Section 4. Finally, brief overview and conclusion is given in Section 5.

2 Seismic probes and data acquisition system

The data acquisition system used in our measurements were based on IBM PC Pentium 200 computer and two seismic stations [10]. Each station consists of a set of probes and data acquisition module (DAS Module). Backbone of our seismic instrumentation is modified geophone of SM3-KV type (made by collaboration of Special Design Bureau of Institute of Earth Physics (Moscow) and Budker INP, Novosibirsk). The SM3-KV seismometer is a single pendulum velocity-meter to measure (by choice, one of) vertical or horizontal vibration component in the frequency range from 0.05 to 120 Hz. Supplimental data on the ground motion were obtained

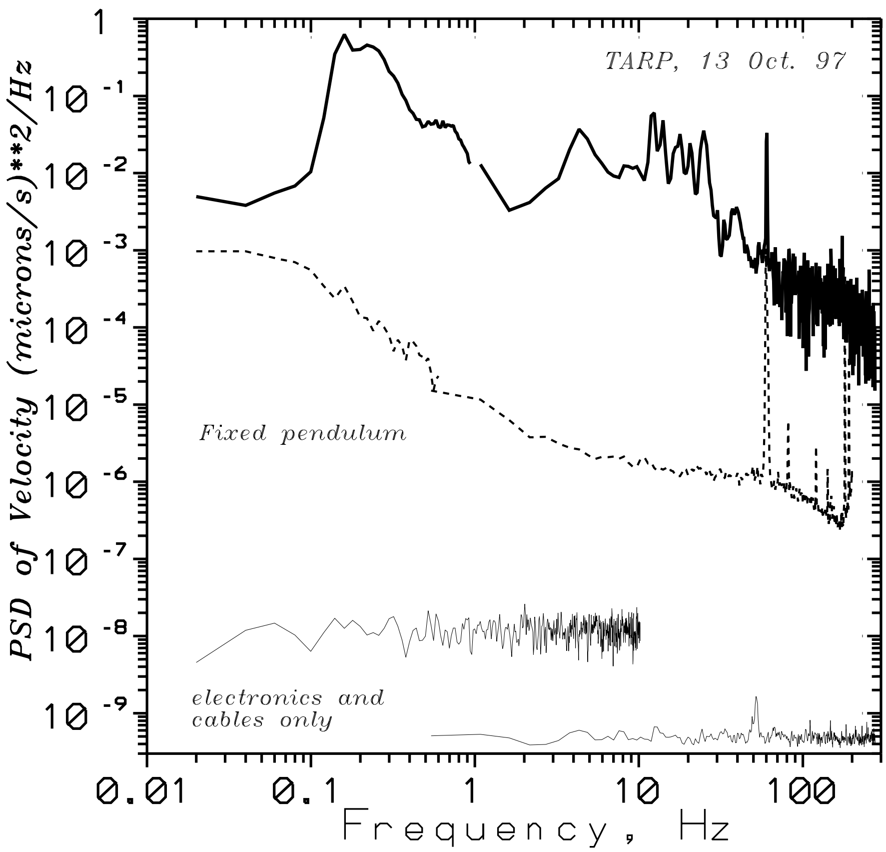

Figure 1: Typical spectrum of ground motion measured by SM3-KV probe in quiet condition (upper line), with fixed pendulum (middle) and equivalent noise of electronics only (two lower curves).

with tri-axial very broad band STS-2 seismometer (Streckeisen AG, Switzerland) and seismic accelerometer 731A by Wiloxon Reasearch (Maryland, USA).

Main parameters of these probes are presented below:

Probe	SM3-KV	STS-2	Wilcoxon 731
Sensitivity	0.083 $V/(\mu m/s)$	0.0015 $V/(\mu m$ /s)	$10^{-6}\, V/(\mu m/s^2)$
$\pm$3dB flat response to	velocity in 0.05-100 Hz	velocity 0.008-50 Hz	acceleration 0.05-500 Hz
Sensors	one inductive	three capacitive	one piezo
Operation frequencies	0.07-120 Hz	0.005-15 Hz	10-400 Hz
Mass	$\simeq$ 8 kg	13 kg	0.54 kg
Size	$24 \times 17 \times 14.5\, cm^3$	23.5cm dia$\times$26cm height	6.2cm dia$\times$5 cm height
Oper. temperature, ^{o}C	-10..+45	-5..+65	0..+40

Fig.1 presents typical power spectral densities of the ground motion at rather quiet deep tunnel of TARP (see below) measured by the SM3-KV probe and noise of the probe if it's pendulum is locked. One can see, that Signal to noise ratio exceeds 6dB at low frequency end of about 0.05 Hz and at high frequency of about 130-200 Hz. Similar conclusions can be made from correlation measurements with two SM30-KV seismometers installed side by side. For comparison, Fig.1 shows equivalent noise due to electronics and cables only, i.e. the probe was disconnected from the DAS module preamplifier. Two curves correspond to rms noise value of 0.5 nm/s with sampling frequencies of 25 Hz and 554 Hz.

The seismic probes are connected to the stations by short 5 m long cables. Maximum 8 analog signals can be processed by DAS Module of each station. The stations can be installed at a relatively large distance because they are connected to the PC operation board by a single RG58 cable up to 300 m long. Usually we supply each station with 24V and about 1.2 A of DC power through additional coaxial cable. By a command from the PC we can change gain and low-pass filters of the DAS Module amplifiers and sampling frequency. To suppress a frequency "aliasing" usual for digital Fourier transformation, we use analog 4th order Butterworth low-pass filters with 3dB frequency of 2, 20, 200 and 2000 Hz. Gain can be changed from 1 to 30. Sample frequencies varies from 2 Hz to 700-900 Hz .

The software to process data delivered to the PC operation board is written on C++ for Windows'95. It provides access to DAS Module sample frequency, filter and gain for each channel. It also allows to view probe signals, calculate and display spectra on the PC monitor on-line and/or store it on the PC hard disk.

For any pair of stationary random processes $x(t)$ and $y(t)$, the correlation spectrum $S_{xy}(f)$ is defined as a limit $T \to \infty$ of following equation:

$$S_{xy} = \frac{2}{T} \int_0^T x(t) e^{i\omega t} dt \int_0^T y(t) e^{-i\omega t} dt \qquad (2)$$

where T is time of measurement, $\omega = 2\pi f$ is frequency. Power Spectral Density(PSD) of signal $x(t)$ is equal to $S_x(f) \equiv S_{xx}(f)$. Normalized correlation spectrum (which we quote everywhere below) is equal to

$$C_{xy}(f) = \frac{< S_{xy} >}{\sqrt{< S_{xx} >< S_{yy} >}} \qquad (3)$$

where $< .. >$ means an averaging over series of measurements.

By the definition, $C_{xy}(f)$ is a complex function. Modulus of the correlation $|C(f)_{xy}|$ is the coherence of two signals at frequency f. It is always positive and less or equal to 1 – for example, if $C_{xy}(f) = 0$ then the Fourier components of signals have no connection to each other, i.e. the phase difference between them varies in time.

During our measurements we used 1024-point Fast Fourier Transformation (FFT) of data from 16 channels of both stations to calculate the PSDs $S_{116}(f)$ and the correlation spectra matrix $C_{xy}(f)$. To reduce statistical errors in the spectra estimate we averaged the spectra up to several hundred times.

As an example of the setup arrangement Fig 2 shows the configuration of measurements in the Tevatron tunnel. Here, "SM3" are the SM3-KV probes (V-vertical and H-horizontal), "piezo" is the piezoaccelerometer, "BPM" and "BLM" are beam position monitor and beam loss monitor, respectively.

3 Measurements at Fermilab

3.1 On-surface measurements at Site E4

Initial measurements and test of seismic equipment have been carried out on the surface at E4 location (building E4R, South-West corner of the Main Ring) near the Tevatron RF building. Fig.2 presents variation of the maximum amplitude of the ground vertical velocity versus time which is presented in units of days (e.g. 19.0

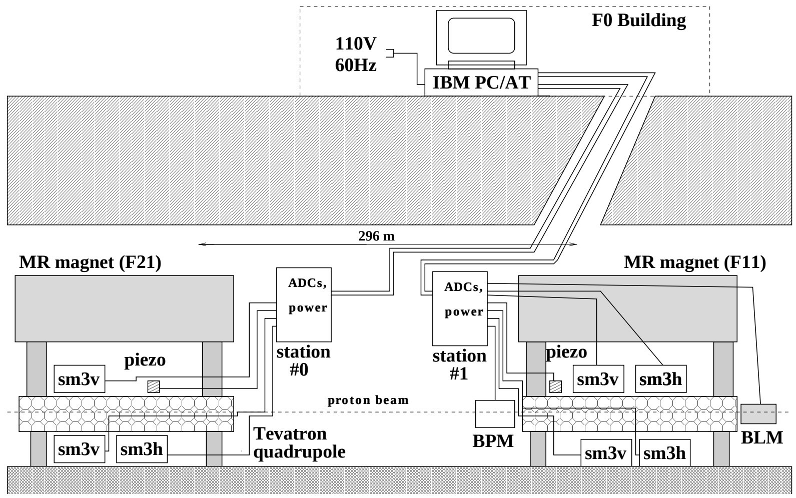

Figure 2: Scheme of measurements in the Main Ring tunnel.
Tevatron ring is located under the Main Ring magnets.

means midnight of 19 September 1997). The record had been done with 5 Hz sampling frequency and 2 Hz low-pass filter. One can see significant increase of the signal around 7 a.m. (or 19.3 in our time units) due to construction activities at the Fermilab Main Injector, traffic noise and operation of equipment within a few kilometers from the detector. The night amplitude is approximately 5-6 times less than that at working time.

Figure 4 shows signals of two SM3-KV geophones separated by 32 m on the night of 17th of September 1997. Both signals are similar, and 5-7 seconds period oscillations are clearly seen. It is well known that this "7 seconds hum" of "microseismic waves" with some dozens km wavelength is produced at the nearest coasts and can be detected almost everywhere on the Earth (see e.g. [1]). The coherence spectrum of these two signals is equal to 1 in a frequency range from 0.1 to 1 Hz – see Figure 5.

Figure 6 shows the power spectrum density of vertical vibrations. Again, the "microseismic waves" demonstrate themselves as a broad peak near 0.2 Hz.

At the working day time (7 a.m.-5 p.m.), human activity significantly increases the vibration amplitudes in frequency range of 2-100 Hz. Fig.7 shows the vertical SM3-KV signal at working time – compare with Fig.4. Now the signal has high frequency components and looks like a white random noise. Consequently, the microseismic peak is seen neither in the data record nor in the spectrum.

Figure 8 presents the coherence of vertical vibration at distances of 0 m and 62 m measured at E4R site. As seen, the correlation between two vertical SM3-KV is very close to 1 in frequency range from 0.1 up to 100 Hz when the probes are placed side by side. At the distance of 62 m the coherence is near 1 only at microseismic and around 0.8 Hz peaks, then it rapidly falls to 0 at 50-100 Hz. For comparison, at the same Figure we present Tevatron tunnel coherence measurement where two SM3-KV probes were placed at the distance of 296 m. In that case the coherence is practically equal to zero for all frequencies higher than 0.1 Hz, except some sharp peaks due to technical noise (rotating parts of machines, etc.).

Except technological noise frequencies, the coherence tends to decrease very fast with increase of a distance between probes. It allows to use a model of multiple uncorrelated sources of plane waves for calculating of the impact of the vibration on accelerators (see e.g. Ref.[11]).

Fig.9 presents the distribution of the displacement amplitudes of ground vibrations at E4R. We divided many hours long record of the ground motion signal on 10 s intervals and calculated maximum amplitude of displacement in each interval (by means of integration of the velocity signal). The distribution of those

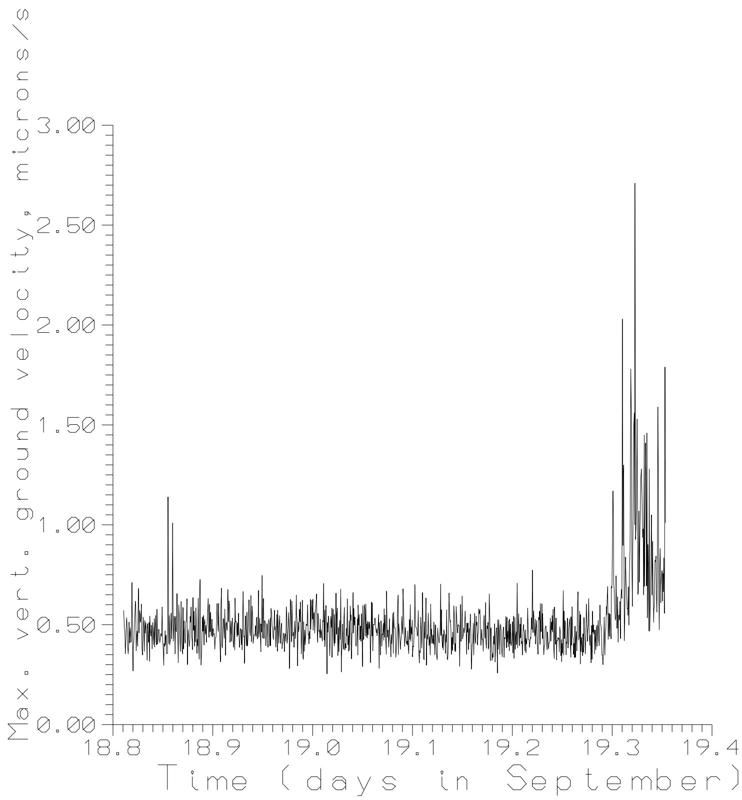

Figure 3: Maximum vertical ground velocity at E4R building recorded from 7:30 p.m. Thursday, 18 September 1997 till 8:30 a.m. 19 September 1997.

maximum amplitudes is practically flat up to the 0.2- 0.3 microns, then it rapidly decreases for vertical signals and somewhat slower for horizontal vibrations. Both distributions are far from the Gaussian and look more power law like.[1] One can fit the probability of the displacement at the E4R building by the function:

$$dW/dx = \frac{\alpha - 1}{\alpha a_{min}} \quad for \quad x < a_{min}$$

and

$$dW/dx = \frac{\alpha - 1}{\alpha a_{min}} \cdot (a_{min}/x)^{\alpha} \quad for \quad x > a_{min}. \tag{4}$$

For horizontal amplitude in Fig.9 we have $a_{min} = 0.3\mu$m and $\alpha \simeq 3$. Corresponding probability that over 10 s interval the displacement will occur with amplitude more than $x > a_{min}$ is equal to :

$$W = \frac{1}{\alpha}(\frac{a_{min}}{x})^{\alpha - 1} \tag{5}$$

For example, predicted probability of the horizontal displacement to be larger than 10 micron is equal to $3 \cdot 10^{-4}$, or, equivalently, it will take place once every 10 hours.

Such a distribution can be very useful for determination of parameters of the feedback system to control the closed orbit in accelerators. These distributions can help to estimate probability of very large relative displacements of the magnets. Using only r.m.s. values without knowledge of the distribution one can not predict

[1]Power law distributions are indicators of fractal arrays and quite natural in geophysics (e.g. for earthquakes) – a lot of examples can be found in Ref.[12]

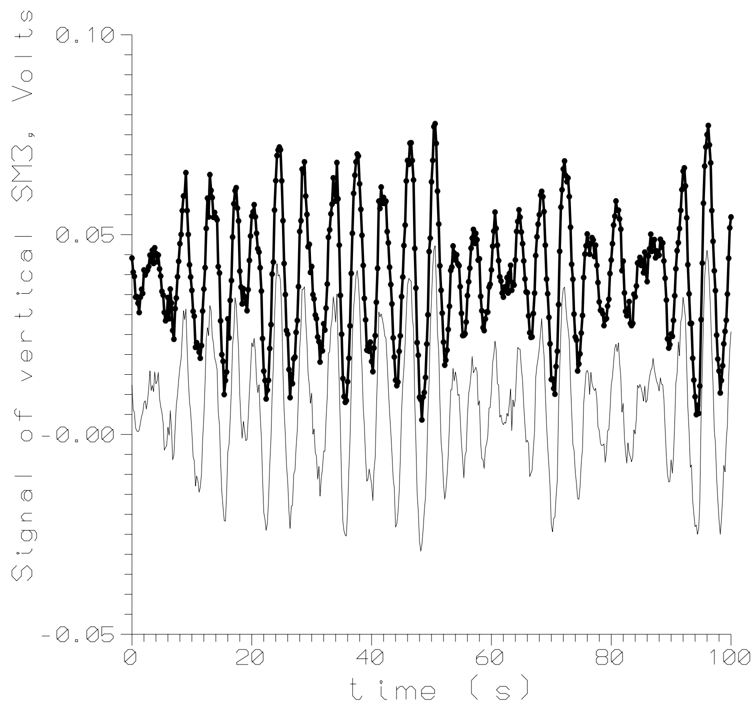

Figure 4: Signals from two vertical SM3-KV geophones separated by 32m.
Measured at night of 17-18 September 1997 at E4R building.

these large amplitude events. Extrapolation of the Eq.(5) beyond range of our measurements, give us that the vibration amplitude of about 1 mm within period of 10 s may happen in Fermilab every 3.5 years – that does not seem ridiculous.

3.2 Main Ring tunnel measurements

The vibration measurements in the Tevatron tunnel have been done at Sectors F11 (near the Tevatron RF station) and F21. Computer was located on the surface in the F0 building. Seven SM3-KV probes (four vertical and three horizontal) and two vertical piezoaccelerometers were used. The layout of experiment is shown in Fig.1.

Station 0 is placed at a distance 296 m from station 1. The station 0 digitizes the signals from one vertical and one horizontal SM3-KV probes on the floor of the tunnel at F21, and from vertically oriented piezoaccelerometer and vertical and horizontal SM3-KVs on the Tevatron quadrupole magnet.

Station 1 digitizes the signals from four SM3-KV geophones (vertical and horizontal on the quadrupole magnet at F11 and vertical and horizontal on the tunnel floor nearby), one piezoaccelerometer placed on the same magnet, and additionally from a beam position monitor (BPM) and a beam loss monitor (BLM).

Technological noise at the Tevatron tunnel performs little day-night variation of the maximum vibrations amplitude – see Fig.10 measured from 3:30 pm September 3, 1997 until about 7:30 am next day, and compare it to similar Fig.7 for E4R site.

PSDs of the F11 magnet and on the tunnel floor are compared in Figure 11. They are almost the same at frequencies of 5–20 Hz. At frequencies below 5 Hz and above 20 Hz, the magnet spectrum is 1-2 orders of the floor spectrum. For comparison, the PSD measured on the surface at the E4 site at night time is also shown in

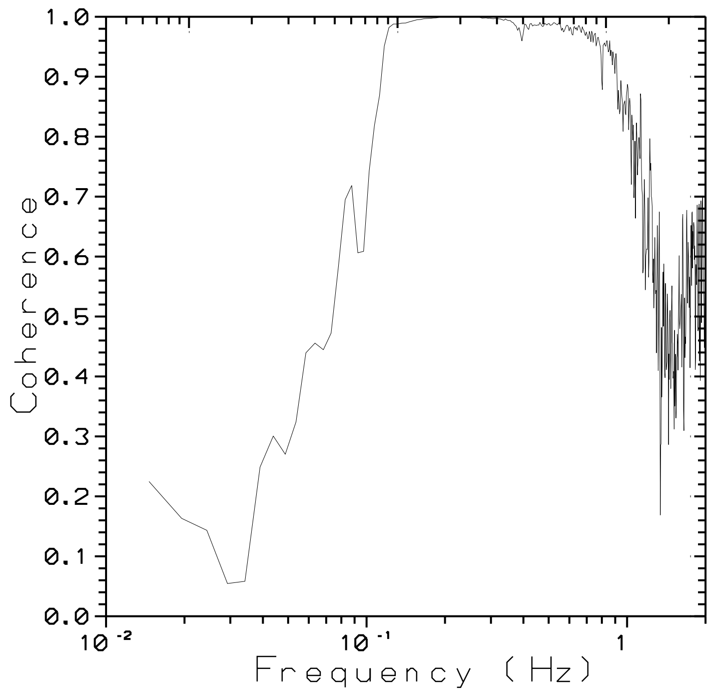

Figure 5: Coherence of vertical ground motion at distance 32 m.Night time of 09/17/97 at E4R building.

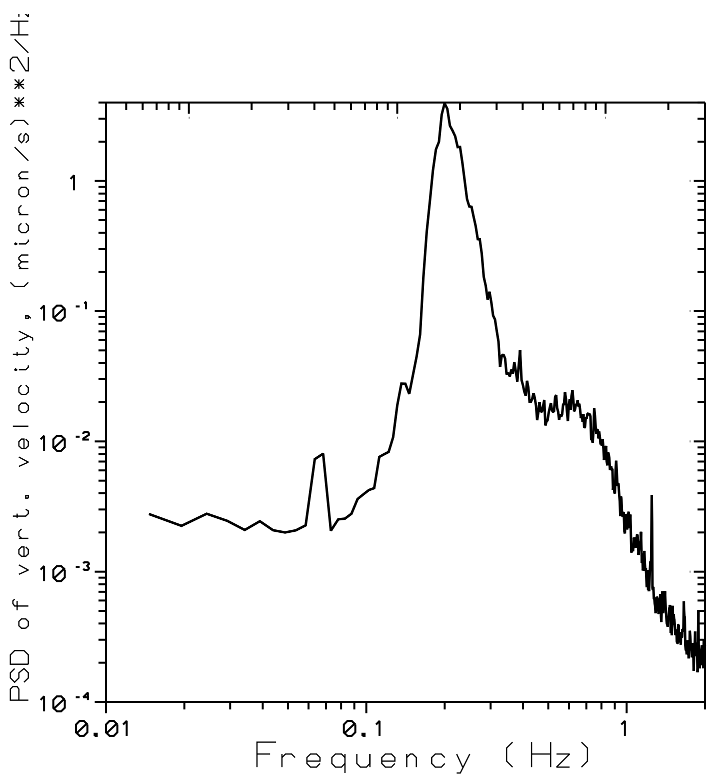

Figure 6: Power spectral density of vertical ground motion at night time.

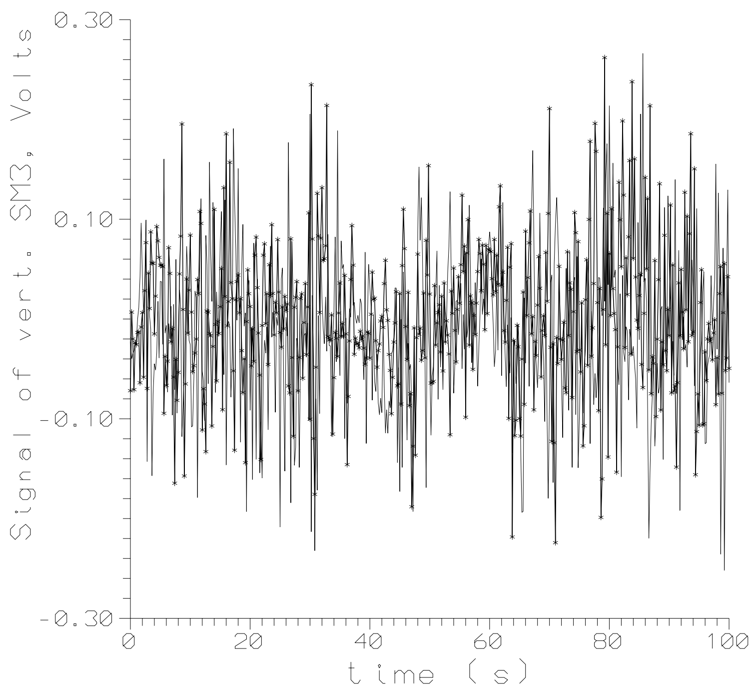

Figure 7: Signal of SM3KV at working time

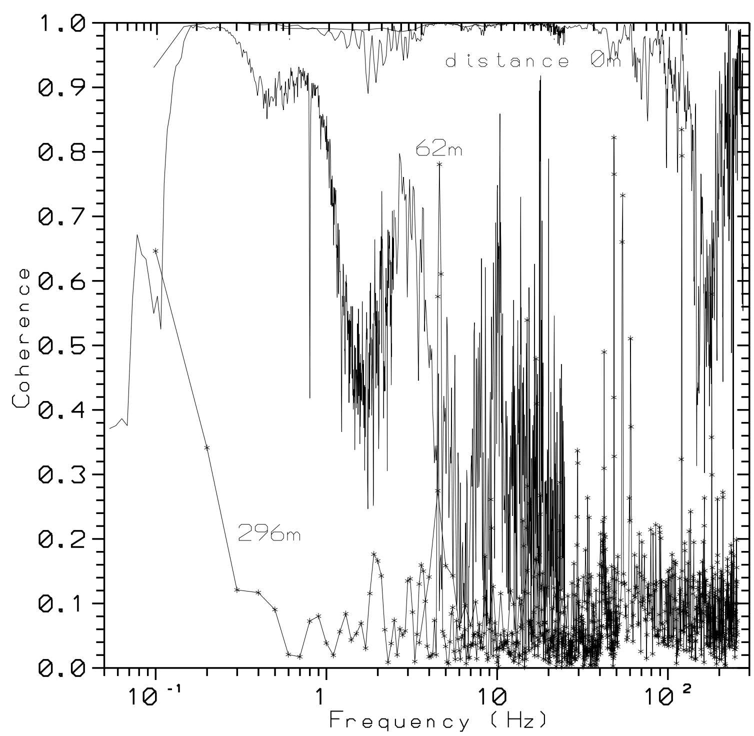

Figure 8: Coherence of vertical ground motion signals measured by probes 0 m and 64 m apart in E4R, and 296 m apart in the Tevatron tunnel.

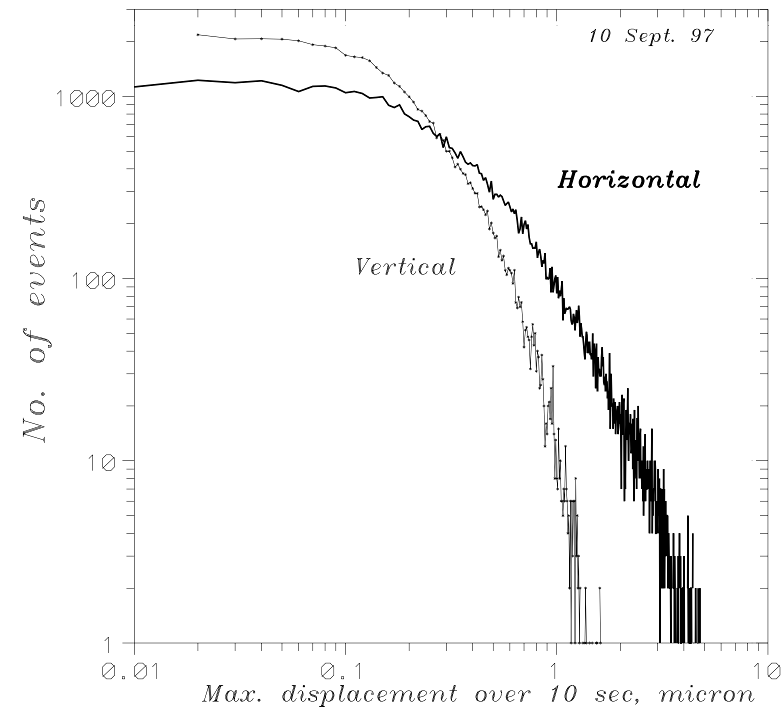

Figure 9: Distribution of maximum ground displacements over 10 s interval.

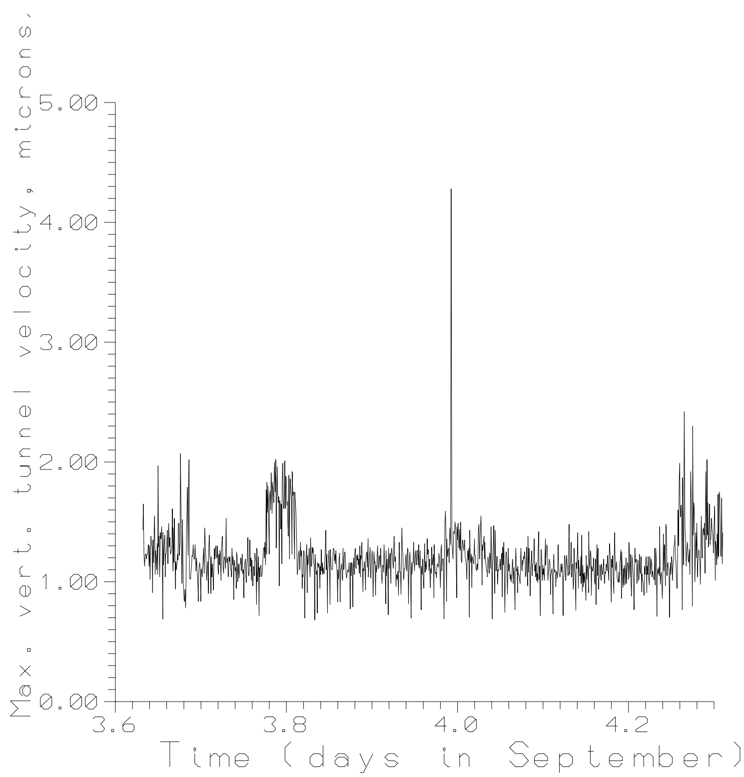

Figure 10: Vibration amplitudes in the tunnel of Tevatron over 16 hours starting 3:30pm 09/03/1997. The Main Ring and the Tevatron ring are under operation.

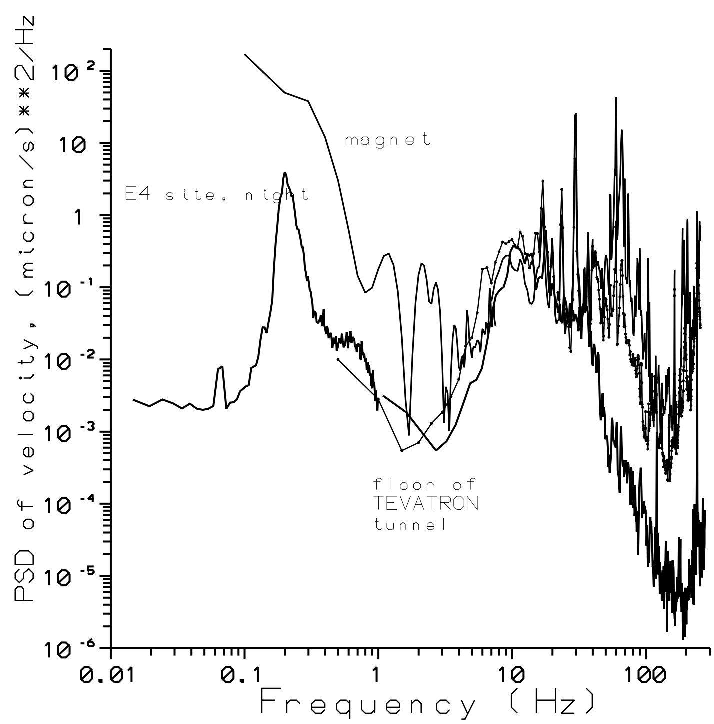

Figure 11: Power spectral densities of vertical vibrations of the Tevatron quadrupole magnet (upper curve), the tunnel floor (middle line with marks) and on the surface at E4 (lower curve).

Fig.10. One can see, that again, below 5 Hz and above 20 Hz the vibration amplitude at the tunnel is higher than on the surface at night. Supposedly, at high frequencies the amplitude is higher due to the technical equipments under operation inside the tunnel (water and helium pipes, power cables, magnets themselves, etc.). At frequencies around 1 Hz and lower the main contribution is possibly due to strong mechanical distortions of the magnets during the Main Ring cycle (about 3 s) and the Tevatron acceleration cycle (about 60 s in fixed target operation).

Simultaneously measured spectra of the vertical orbit velocity [2], the F11 magnet and the tunnel floor velocities are compared in Figure 12. The coherence spectra between the beam orbit and the magnet and between the beam orbit and the tunnel floor motion are presented in Figure 13. One can see that the orbit correlates well with the floor only at low frequency 0.1 Hz, while some excessive but small coherence exists at 2-4 Hz. On the other hand, the beam orbit correlates very well with the quadrupole magnet motion at frequencies of 0.2-2 Hz. One of possible origin of such coherence may be related to 3 s accelerating cycle of the main Main Ring which mechanically affects closely located Tevatron magnets and produce impact on the Tevatron beam via straw magnetic fields at harmonics of 1/3 Hz.

The closed orbit distortion is caused by the displacements of all magnetic elements along the circumference of Tevatron. The strong coherence between the magnet and beam vibrations means that there is a common source of vibration along the whole accelerator ring. For example, several remarkable peaks in the orbit-magnet coherence occur at 4.6 Hz, 9.2 Hz, 13.8 Hz, etc., at the Fermilab site specific frequencies caused by Central Helium Liquefier plant operation [13].

[2] calculated as the PSD of the BPM signal multiplied by ω^2

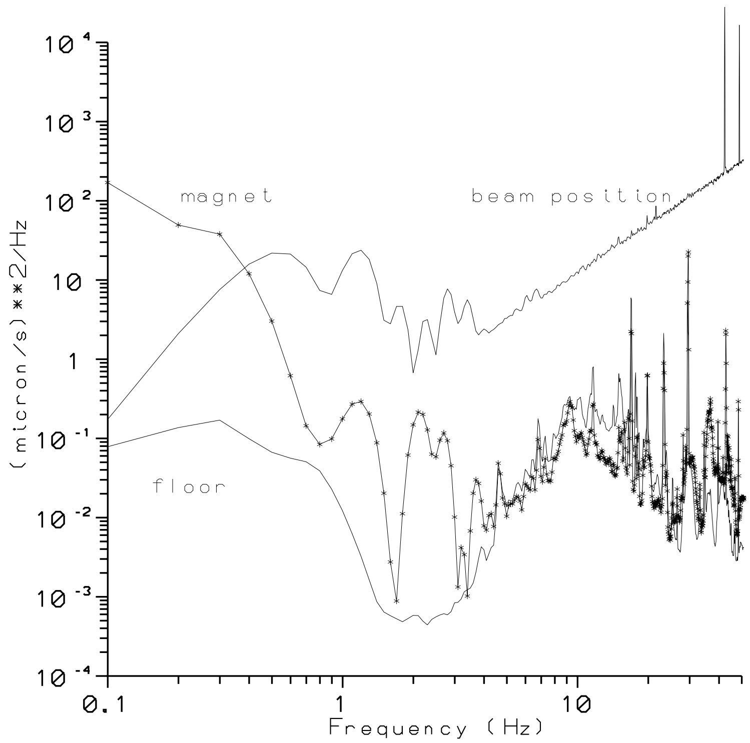

Figure 12: Spectra of the Tevatron beam orbit vibrations, tunnel floor motion and the Tevatron quadrupole vibrations at F11.

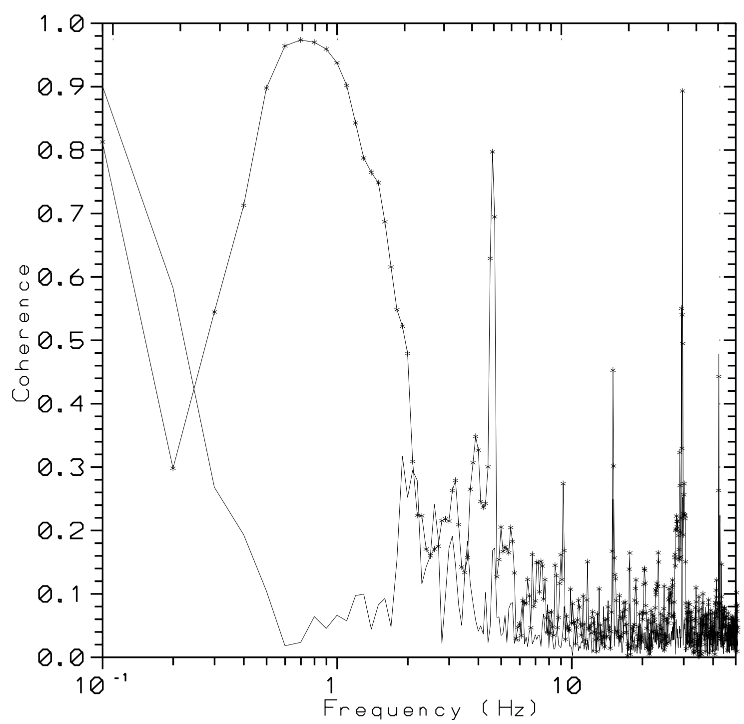

Figure 13: Coherence between signals of the vertical Tevatron beam orbit motion and the F11 magnet vibrations (marked line) and between the orbit and the tunnel floor.

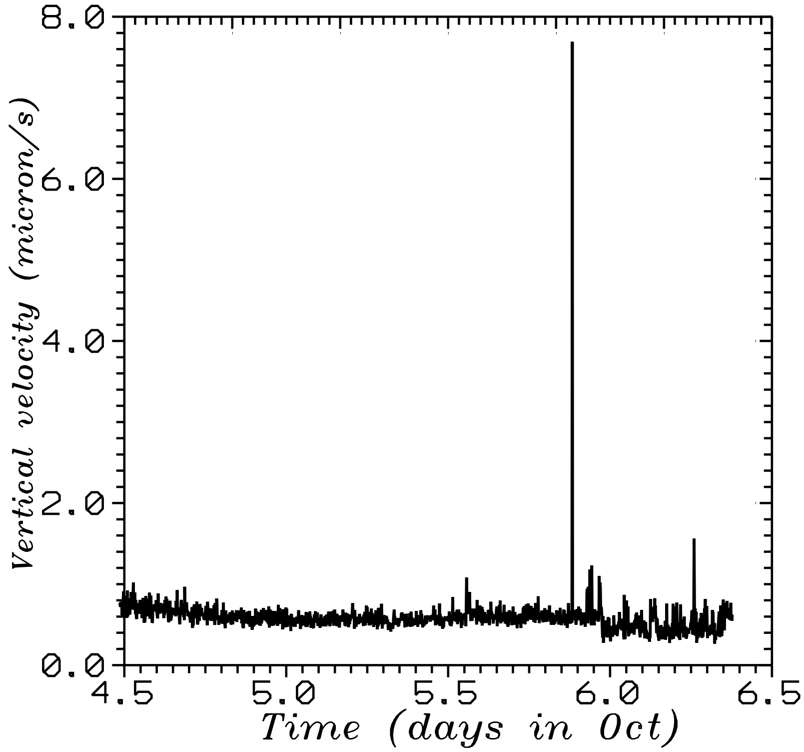

Figure 14: Maximum ground velocity in Aurora mine.

4 Measurements in deep tunnels

Future Colliders at Fermilab yet have no specific locations. There is also no definite requirement to be located within the FNAL site. For the purposes of radiation safety and tunnel stability, deep tunnels in the Illinois dolomite layer are alternative. This several hundreds feet thick layer is considered as moderately hard and stable. Details of the Illinois geology can be found elsewhere (see, e.g. [14]).

We studied seismic vibrations at two points of the Illinois dolomite layer. The first is 250 ft deep mine[3] (Conco Mine - Western Stone Co., 105 Conco street, North Aurora, IL) located about 5 miles North-West of Fermilab. We carried out measurements there in period of October 3 - October 6, 1997. We denote everywhere below data from that mine as "Aurora".

The second place is 300 ft deep Dewatering Station tunnel of Metropolitan Water Reclamation District of Greater Chicago (MWRDGC). The station is located about 30 miles East of the FNAL in the Chicago suburb of Hodgkins, IL, less than 0.5 mile away from rather noisy I-55 interstate highway, and very close to a stone quarry. The tunnel was digged as a part of the Tunnel and Reservoir Project (TARP) of the MWRDGC, and we will mark data taken there as "TARP". Our measurements there took 9 days from October 8 to October 17, 1997.

Despite restricted access to the both tunnels (due to blasting and stone production in the Aurora mine and operation schedule of the Mainstream pumps of the MWRDGC), data acquisition was almost continuous, except occasional few hours periods for the data control, primary analysis and relocation of the seismic probes for various experiments, e.g. for correlation measurements at different distances.

Figs.14 and 15 show long term records of the maximum velocity detected in Aurora and TARP respectively. Both are made with 10 Hz sampling frequency and 2 Hz low-pass filters. One can see, that the amplitude did not vary too much in the Aurora mine from noon of Saturday Oct.4 till Monday morning of Oct.6.

[3] about 500ft elevation above sea level

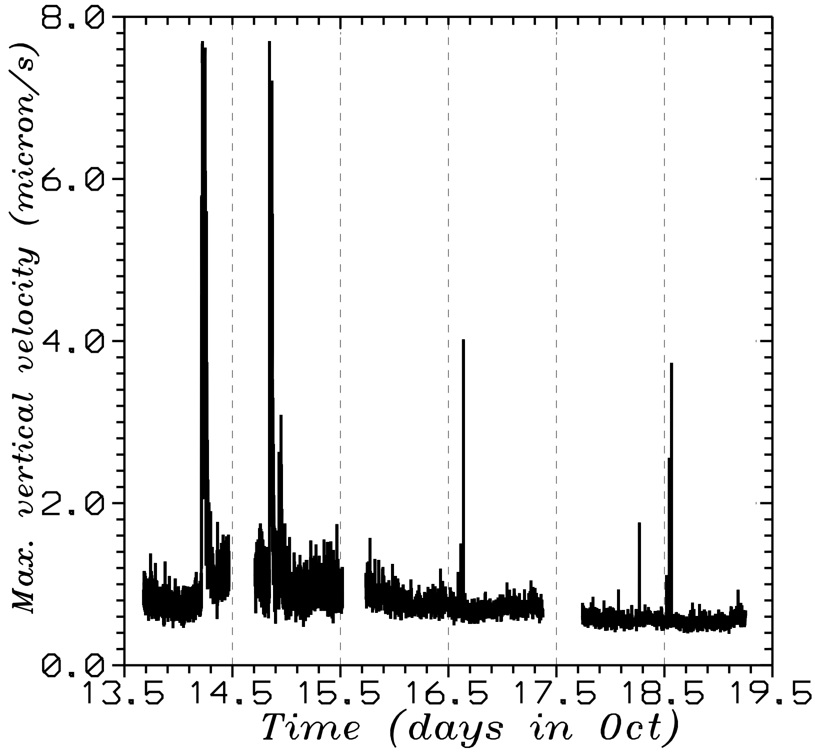

Figure 15: Maximum ground velocity in TARP shaft.

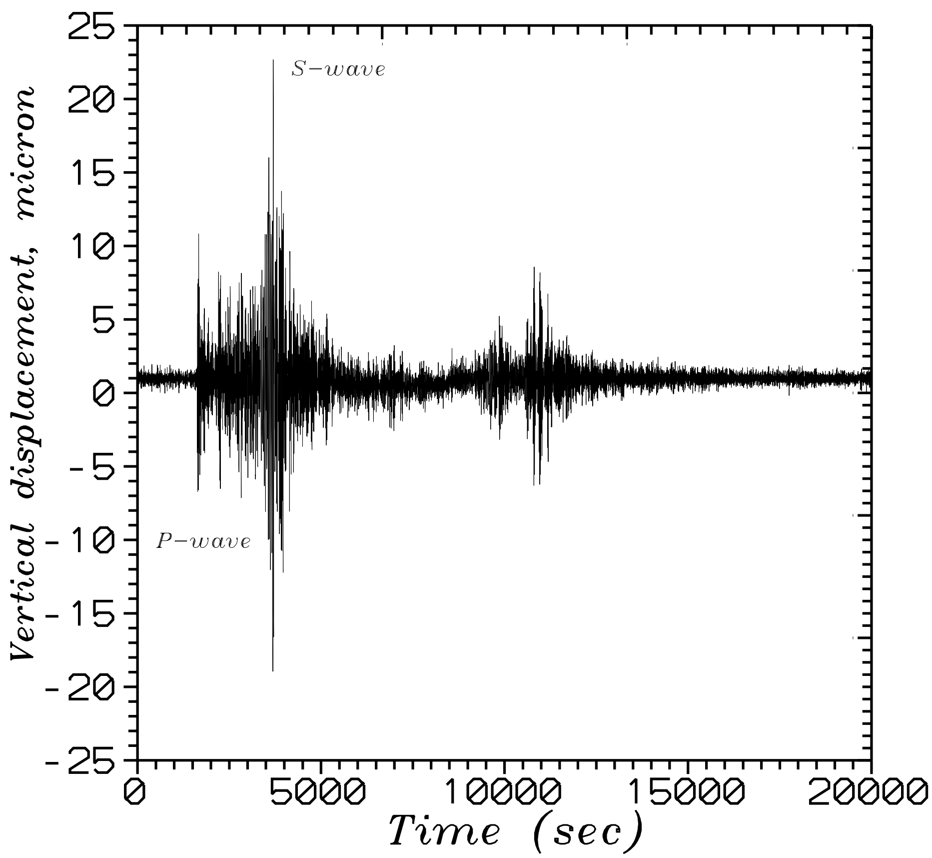

Figure 16: Earthquake waves. Record starts at 7:45 pm 10/14/97.

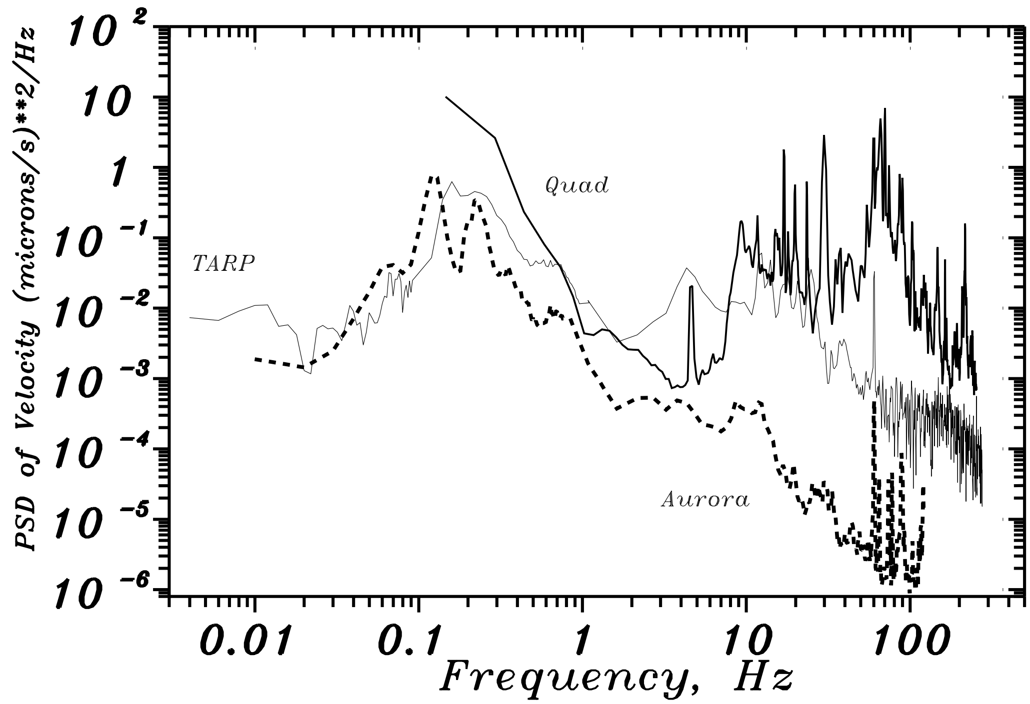

Figure 17: Spectra of ground motion in Aurora mine, TARP tunnel,and the Tevatron magnet vibrations

The main component of the signal is due to the microseismic waves performed slight changes. Contribution of man-made noises was small because of the depth of the mine, low-pass filtering and quiet weekend time when no powerful machinery worked in the mine. Alone peak at about 10 pm of Oct.5th appeared when a superintendent of the mine came to check the equipment and passed nearby.

In opposite, the record made in the TARP shaft shows significant variations over several days. First of all, two long lasting and significant perturbations are seen at about 5 am in the morning of October 14, 1997, and at about 8:15 pm evening of the same day. They are identified as 20-40 second period waves from powerful distant earthquakes: magnitude 6.5 event at Fiji island region and 6.8 quake near coast of central Chile. These waves traveled about 20-30 minutes before reaching the Chicago. Figure 16 demonstrates the second of the quakes in more detail. One can see that the ground motion amplitude is of the order of 10-25 microns. The wave does not look as a sharp shock, instead it is long lasting (few hours) series of primary and secondary waves, and aftershocks.

Blasting in the quarry near the TARP shaft produces short (about minute long) pulses of high-frequency (5-15 Hz) waves with relatively small amplitudes of about 0.1 micron or about 4 micron/s maximum velocity. Two of these events are seen in Fig. 15 at about 4:00 pm of October 16 and at 1:40pm of October 18. Other short peaks in Fig. 15 are probably due to man-made activity in the TARP shaft (from time to time workers went down on an heavy elevator and worked not far from our detectors). It is interesting to note, that the background level of the maximum ground velocity in Fig.15 substantially varies – it is much larger Monday, October 13th and smaller at evening of Friday, October 17th, and Saturday, October 18th. We think the reason can be residual excitation from on-surface sources (high-ways, roads, quarry operation, etc.) which are usually less active at weekends.

Power spectral densities of the ground velocities measured in the Aurora mine, in the TARP shaft are presented in Fig.17 in comparison with the Tevatron quadrupole magnet vibration PSD. These spectra cover five decades of frequency band from 0.005 Hz to 280 Hz and are obtained with different probes and with different sampling rates (besides different places and different times). For example, the TARP curve (solid line) con-

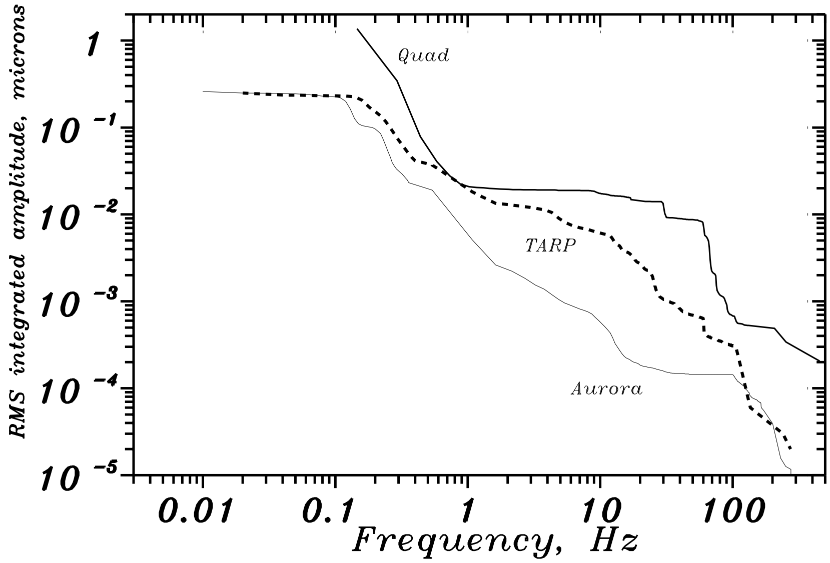

Figure 18: Integrated rms ground motion amplitude.

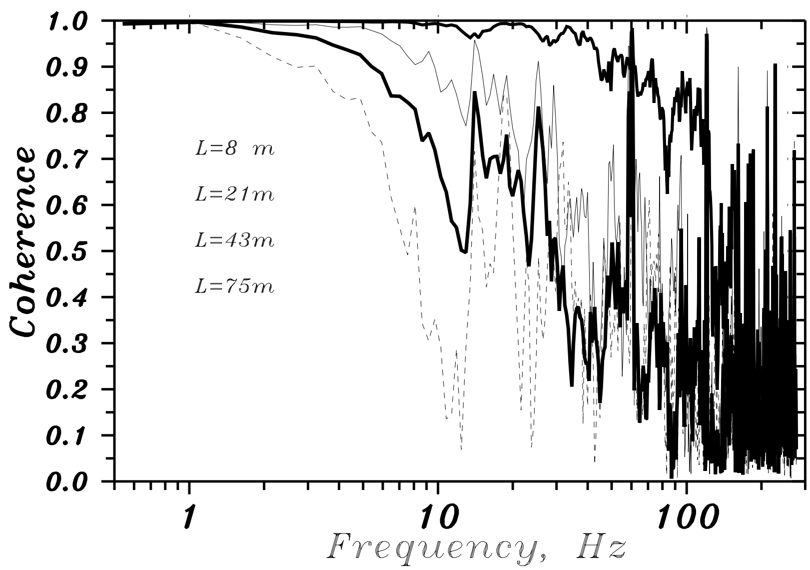

Figure 19: Coherence of the ground motion vs distance. TARP measurements.

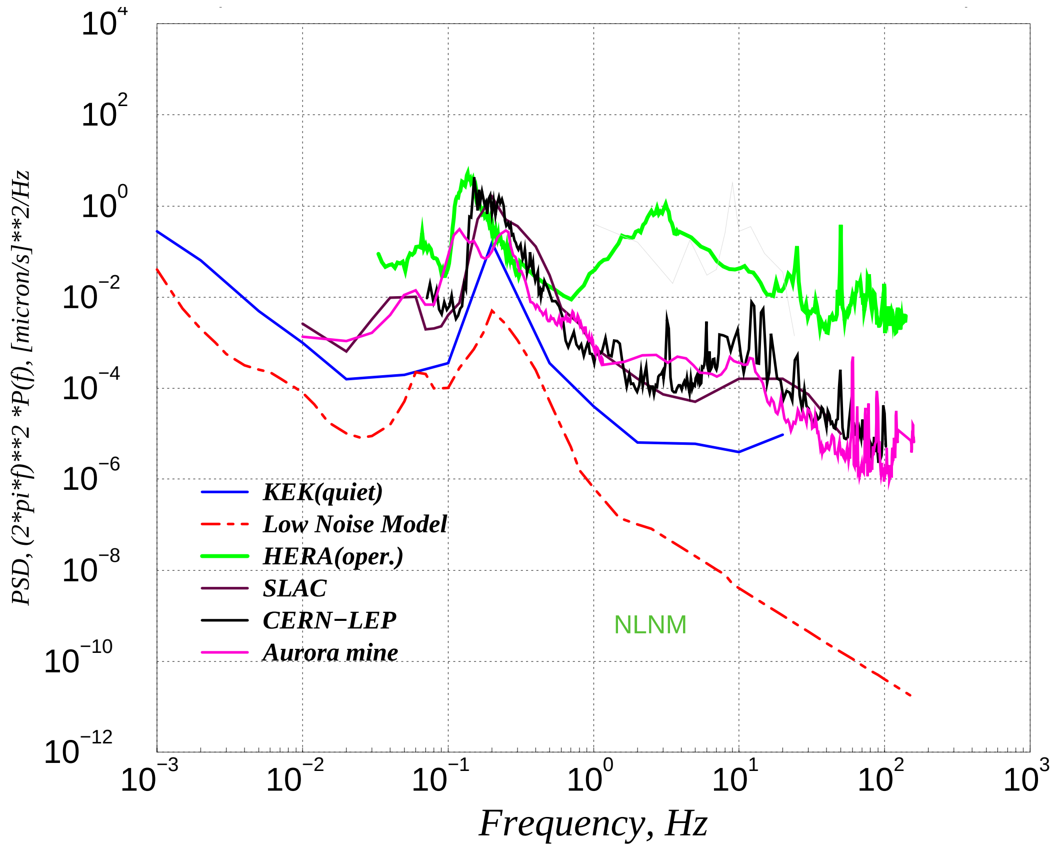

Figure 20: Ground motion spectra at different accelerator sitesand the USGS New Low-Noise Model.

sists of spectrum measured by the STS-2 vertical probe (from 0.005 Hz to 0.1 Hz), by the SM3-KV geophone (from 0.1 Hz to 120 Hz) and by the Wicoxon piezoprobe (from 120 to 280 Hz). The Aurora data (dashed line) showed high frequency vibrations above 120 Hz too small to be detected by the piezoaccelerometer.

One can see that the Aurora mine is the quietest place of the three. Some technologically related peaks are seen in the "Aurora" PSD only at 60-120 Hz range. We believe that it is due to lightning transformers in the tunnel, weak humming of which can be heard there. Below 0.5 Hz the spectral density in Aurora mine and in the TARP tunnel are about the same. Above 2 Hz, the TARP PSD is 20-800 times the PSD of the Aurora. Nosier environment on the surface and more technological equipment in the tunnel itself are probable reasons for two very broad peaks in the TARP spectrum at 5 Hz and around 25 Hz, respectively (as damping decrement of the ground grow with frequency). Finally, the Tevatron quadrupole spectrum consists of many peaks (4.6Hz, 9.2Hz, 20Hz, 60Hz, etc.) and is much noisier (as we discussed above - due to the Tevatron equipment) than the others above 10 Hz.

Now, we can compare measured PSD of velocity with the VLHC requirement of (0.6-4)$\cdot 10^{-5}$, $\mu m^2/s$ – see Table 1 (the first value is for tune of $\Delta\nu$=90 Hz/554 Hz=1.16, the second - for Δnu =230Hz/554Hz=0.42, 554Hz is the VLHC revolution frequency). The "Aurora" data are below the tolerance, the TARP result is 40 times above at 90 Hz and about 1.5 times above at 230 Hz, and the quadrupole vibration PSD is 2000 times the tolerance at 90 Hz and 25 times at 230 Hz. It is useful to add that accordingly to the data presented in Fig.11, the Tevatron tunnel floor vibrations PSD is 2 times the tolerance at 90 Hz and somewhat smaller at 230 Hz.

Integration of these spectra accordingly to

$$\sigma_x(f) = \int_f^\infty S_x(f)df = \int_f^\infty S_v(f)\frac{df}{(2\pi f)^2}, \tag{6}$$

(here $S_v(f)$ is the PSD of velocity, $S_x(f) = S_v(f)/\omega^2$ is the PSD of displacement. gives us the rms amplitudes of vibrations presented in Fig.18. One can see that the amplitudes in the deep tunnels are about 0.3 micron at frequencies $\sim$0.5 Hz and below, while above 100 Hz they are less than 0.1 nm = 10^{-4} micron. Motion of the quadruple is several times larger.

In Fig.19 we present spectra of coherence between two SM3-KV vertical probes in the TARP tunnel separated by 8, 21, 34 and 75 meters. Each of the curves is an average over 200 measurements that gives an estimate of the statistical error of less than 0.07. One can make general conclusion that the coherence goes down with increase of frequency and distance between two points. In particular, the tunnel vibrations of two points 75 m apart at frequencies of 90-230 Hz can be considered as uncorrelated since the coherence is less 0.2 (i.e within few statistical errors). Note, that at frequency of 60Hz the coherence is high due to powerful and correlated noise contribution.

5 Discussion and conclusion

The results of measurements allow us to make following conclusions for the VLHC:

1.The amplitude of vibration at frequencies of 50-200 Hz performs large variation in time due to man-made activity. Neither location at the Fermilab site satisfies the tolerance of 0.3 nm (see Table 1) at the day time. But at night time vibrations outside the Tevatron tunnel becomes about or less than required by the VLHC. In deep tunnels of the Illinois dolomite we observed vibrations below the tolerance. As the amplitudes of ground vibrations are smaller at higher frequencies, we propose to operate the machine at higher fractional part of the tune, because it concludes in higher resonance betatron frequencies.

We have to remark that accelerators are relatively 'noisy'. For example, Fig.20 from Ref.[8] compares the PSDs of velocity $S_v(f) = S_x(f)(2\pi f)^2$ for the "New Low Noise Model" [15] – a minimum of geophysical observations worldwide – and data from accelerator facilities of HERA [4], UNK [5], VEPP-3 [16], KEK [17], SSC [18], CERN [19], our measurements in the Aurora mine (marked as FNAL), APS [20], and SLAC[11].

That comparison tells us that if during the design and construction of the VLHC some proper attention is paid to decrease the level of technical vibration, than it will be possible to obtain vibrations by 10-100 times lower that at the Fermilab site now and close to what we detected in the deep tunnels. For that, it is necessary to place potential sources of vibrations as far as possible from the accelerator ring or/and to dump vibrations at their origin. From these point of view it seems very useful to have a seismic monitoring system at the VLHC site.

2.Thorough investigations of a spatial characteristics of the fast ground motion have shown that above 1-4 Hz the correlation significantly drops at dozens of meters of the distance between points. Therefore, the displacements of different magnetic elements of the accelerator (which will be spaced by hundreds of meters) can be regarded as uncorrelated except characteristic frequencies of technical devices producing the vibrations along the whole ring (electric power, water, Nitrogen and Helium systems etc.)

3. Careful engineering of mechanical supports, of vacuum, power and cooling systems should be an important part of R&D efforts to decrease the level of vibrations in the VLHC as well as in any other future collider.

4. Comparison of on-surface and underground sites have shown that levels of vibrations are typically smaller in deep tunnels. Effects due to on-surface noise sources is less seen in the deep tunnels, though visible.

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