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MEASUREMENTS OF CROUND MOTION AND MAGNETS VIBRATIONS AT THE APS

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НОВОСИБИРСК

Measurements of Ground Motion and Magnets Vibrations at the APS

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Abstract

This article presents results of ground motion and magnets vibrations measurements at the Advanced Photon Source. The experiments were done over wide frequency range 0.05 – 100 Hz with use of SM-3KV type seismic probes from Budker Institute of Nuclear Physics (Russia). Spectral power densities of vertical and horizontal motions of the APS hall floor and quadrupoles on regular supports were obtained. There were also investigated magnets vibrations induced by designed cooling water flow and spectral characteristics of spatial correlation of the quads vibration at different sectors of the ring. Influence of personnel activity in the hall and traffic under the ring on slow motion of storage ring elements were observed. Amplitudes of vibrations at the APS are compared with results of seimic measurements at some other accelerators.

1 Introduction

The Advanced Photon Source (APS) is a synchrotron radiation facility under construction at Argonne National Laboratory. It is based on 1.1 kilometer circumference 7 GeV positron storage ring [1]. To obtain high brilliance of X-ray radiation of positron beam from dipole magnets and insertion devices at each of 40 sectors of the ring, the transverse beam sizes and angle divergencies should be rather small all around the circumference. Special kind of magnetic focusing lattice and design values of horizontal and vertical beam emittances $\epsilon_H = 10 \quad nm$ and $\epsilon_V = 1 \quad nm$ allow to get following rms beam parameters: $\sigma_H \approx 300 \quad \mu m$, $\sigma'_H \approx 25 \quad \mu rad$ and $\sigma_V \approx 100 \quad \mu m$, $\sigma'_V \approx 10 \quad \mu rad$. These tiny dimensions result in high sensitivity of the beam position to vibrations of magnetic elements that produce jitter of the positron beam closed orbit and corresponding instability of synchrotron radiation beam angle and position. The issue arises from the fact that closed orbit distortion (COD) is a summation of all disturbances around the ring, i.e. many times larger than amplitude of the distortion caused by single magnet. For example, in the case when every i-th quadrupole with focal length equal to F_i is displaced on δ_i from its ideal position then total COD X at the point of the ring characterized by beta function β is equal to :

$$X = \sum_i \frac{\delta_i \cdot \beta^{1/2}\beta_i^{1/2}}{2F_i \sin(\pi\nu)} * \cos(\Delta\phi_i - \pi\nu), \qquad (1)$$

here β_i) is beta function at the point of i–th quad, $\Delta\phi_i$ is the betatron phase advance from the quad to the point of observation, ν is tune of the storage ring.

In the realistic case of uncorrelated displacement of different quads (see results of measurements below) the summation over the APS lattice gives factor of COD magnification in comparison with amplitude of vibration about 50 for horizontal and about 40 for vertical distortions [1]. If one assumes that 10%-jitter of effective beam emittance is not dangerous for the purposes of X-ray users then maximum allowable amplitudes of quads horizontal and vertical vibrations are $\delta_H \approx 0.34$ μm and $\delta_V \approx 0.12$ μm respectively [1, 2].

Corresponding criteria for amplitude of single quadrupole vibration amplitude gives its maximum values $\Delta_H \approx 2.2$ μm and $\Delta_V \approx 1.3$ μm - i.e much weaker than restrictions mentioned just above.

We'd like to attract attention to other source of beam jitter. Tilt of the APS dipole (across the beam orbit) $\delta\theta$ produces vertical kick acting on the beam equal to:

$$\Delta\theta_{beam} = \delta\theta \cdot \theta_0 \tag{2}$$

here θ_0 is bending angle of positrons' orbit by main field of the dipole (about 80 mrad for the APS). It's easy to calculate that angular vibration $\delta\theta \approx (\delta_V/F)/\theta_0 \approx 0.25$ μrad will also cause 10% effective emittance increase. If one takes dipole-to-floor distance about 1.2 m then such angular amplitude corresponds to maximum allowable horizontal (across the beam orbit) vibration of dipoles about $1.2 * 0.25 = 0.3\mu m$ - even a little smaller than for quads.

If amplitudes of vibrations are above these conditions then some feedback system of beam position steering is necessary to keep X-ray beam positions over all the ring. The frequency band of the system should be larger than the band of concerned vibrations. Therefore it's very important to have following information about magnets vibrations: (1) its' spectral characteristics (power spectral densities), (2) spectral characteristics of spatial correlation of the vibrations (spectrum of correlation).

These characteristics are taken from statistical analysis of noises while, generally speaking, ground motion and vibration are noises. Just to remind to a reader we give definitions of these characteristics. The power spectral density (PSD) $S(f)$ which we calculated have the following relation to rms value of signal $X_{rms}(f_1, f_2)$ in frequency band from f_1 to f_2:

$$\delta X_{rms}(f_1, f_2) = \sqrt{\int_{f_1}^{f_2} S(f)df}. \tag{3}$$

The spectrum of correlation $K(f)$ of two signals $X(t)$ and $Y(t)$ (or, mutual correlation spectrum) is defined as:

$$K(f) = \frac{\langle X(f)Y^*(f)\rangle}{\sqrt{\langle X(f)X^*(f)\rangle\langle Y(f)Y^*(f)\rangle}} \tag{4}$$

here the brackets $< .... >$ mean averaging over different measurements (usually 63 in this work), and $X(f), Y(f)$ are Fourier transformations of $X(t), Y(t)$. *Coherence* of the two signals is equal to modulus of complex function $K(f)$. By the definition the value of the coherence does not exceed 1.0. During our experiments wee took these signals from two similar seismic probes distanced from each other. If the value of the coherence is close to zero in some frequency band then it means absence of any correlation between the vibrations; if two signals are well-correlated then the value of the coherence is close to 1.0. As we mentioned above, COD in the APS is rather sensitive to spatially uncorrelated motion of magnets.

2 Description of the Experiment

The place of measurement was chosen at the hall of the APS building. Vibrations of quadrupoles were measured mainly at Sector 39 where the magnets were installed on regular girders and connected with pipes for cooling water. Some measurements were done at the floor Sector 19 just above the tunnel under the APS building. We investigated there the effect of traffic under the ring. At the time of experiments (19-26 of May 1994) there were installed no girders and magnets.

As the main probes for slow ground motion we used the SM-3KV type velocity meters which allow to obtain data in 0.05 - 200 Hz frequency band. Two SM-3KV probes No.1112 and No.1140 were carried from the Budker Institute of Nuclear Physics (Novosibirsk, Russia) and had been previously tested in vibrational studies for linear collider VLEPP, in the UNK tunnel (Protvino, Russia), for Novosibirsk B-Factory VEPP-5 and electron storage ring VEPP-3, and for Superconducting Super Collider (Dallas, TX).

A commercial velocitymeter SM-3KV was modified to extend the frequency band to 0.05-200 Hz. The proper pendulum period of the probe is 2

Table 1: Parameters of SM-3KV Type Probe

Frequency band without EFS, Hz	1-40
Frequency band with EFS, Hz	0.05-200
Sensitivity, mV s/μm	83
Free pendulum period ,s	2.0
Pendulum inertial moment, $kG \cdot m^2$	$8.5 \cdot 10^{-3}$
Effective pendulum length, m	$3.4 \cdot 10^{-2}$
Coil sensitivity, V s/m	135
Sizes, cm	$17.0 \times 14.5 \times 23.0$
Mass, kG	8.0

s. A special electrical feedback system (EFS) modifies the raw signal from the coil of the pendulum, which vibrates in the magnetic field system; thus, the output signal is proportional to the velocity of vibrations without resonance, emphasizing the proper period. At frequencies above 200 Hz the feedback system gain is small and it doesn't improve probe characteristics. The probe allows to measure vertical as well as horizontal vibrations after some simple mechanical transformations. Probes were calibrated in the working frequency range. It was done through the special calibrated coil installed in the probes and by using a special vibrating table in Novosibirsk INP. The difference in the sensitivities of the two probes is less than 10%. Results of calibration are presented in Fig. 1. Signal-to-noise ratio for SM-3KV probe with the smallest observed ground vibration signals is less than 2 above 1000 Hz and below 0.05 Hz. Under usual and noisy conditions this ratio becomes many times more.

Table 1 summarizes main characteristics of the SM-3KV probes.

Electrical signals from probes were digitized and developed by a CAMAC-based experimental set-up named ASSA (also from Novosibirsk INP), which includes [3]:

- CAMAC crate
- CAMAC crate controller
- Two 10-bit, 4-channel CAMAC ADC ZIIS-4 type
- CAMAC differential amplifiers (this allows us to change the total gain from 0.1 to 10^2 and low-pass frequency filters from 0.5 Hz to 2000 Hz)

- Two 256-K, 24-bit word CAMAC memories
- CAMAC timer
- Interface CAMAC (IBM PC)
- IBM 486 personal computer.

The ASSA set-up is fully autonomous and needs only a 110-V outlet.

Signals from both probes were digitized simultaneously by ADCs with a sampling frequency (changeable by timer from 0.1 Hz to 32 kHz) and then were sent to memory for storage. The maximum memory available for one channel is 64-K 24-bit words. It corresponds to 17.8 h of permanent measurement time with a sampling rate of 1 Hz or about 1 min with 1 kHz. For long measurements we used low-pass filters at 2 Hz or 20 Hz; for fast analyses 2000-Hz filter were applied.

The software used allows us to analyze data in both the time and the frequency domain, to transform raw signal data to vibration amplitudes (i.e., transform volts to micrometers), to change all variable parameters of hardware (sampling frequency, gains, filters), to calculate power spectral densities of all signals and spectra of correlation between all pair of channels, and to present results graphically and produce hard copy on a printer.

For calculations of spectra we used the optimized 512-point Raider-Brenner algorithm based on a 16-point Winograd algorithm for discrete Fourier transformation. On an IBM PC/486, the algorithm works twice as fast as the usual Fast Fourier Transformation (FFT) technique of Cooley and Tukey. This algorithm is very useful because in order to reduce statistical errors we can average over a greater number of spectra (usually 63).

3 Results of Measurements

Let us consider vertical motion of the APS quadrupole magnet AQ-1 installed on regular girder in Sector 39. Fig. 2 presents 80-sec record of the quad displacement since 11:20am 20 of May 1994. This figure shows two remarkable features: during the first 40 seconds of observation the motion looks like irregular oscillations with amplitude about 0.1 μm. This motion with periods 5-14 sec is due to micro seismic waves produced by ocean waves at the closest coastal line and is called often "7-second hum". Due to small attenuation such waves (few dozens kilometers wavelength) are clearly seen even in central parts of continents. In the PSD of the ground motion it will correspond to a wide "microseismic" peak at 0.07-0.2 Hz (see below).

The last 40 seconds of Fig. 2 illustrate the motion of the quadrupole while a man was passing beside. One can see that it caused 2.6 micron down displacement of the quad (together with the floor). This is twice above the allowable level for the APS. Of course, during the machine operation there will be no staff inside the hall, but any relocation of an equipment heavier than 80 kG may cause the same static effect.

Another point of trouble is traffic under the ring, in a tunnel under Sector 19. The measurement of floor motion was done when a compact car drove in, stopped for a few seconds and drove out the tunnel. It resulted in 1.5 micron displacement as it shown in Fig. 3

Vibrations with higher frequencies (say, more than 1 Hz) are mostly due to technical noises and the strongest one is pressure fluctuations in flow of cooling water. Usually rms vertical amplitude of the quadrupole vibrations (frequency band 2-50 Hz) during our measurements was about 0.015 – 0.02 micron without water flow and as big as 0.06 – 0.09 micron with 200 g/sec cooling water flow. This is under the allowable levels for the APS mentioned in the Introduction and in rather well coincidence with previous measurements with S-500 vibroprobes by *Teledyne Geotech* [4]. Fig. 4 shows power spectral densities of the quadrupole vibration with cooling water on and cooling water off.

To compare spectral properties of different signals *an amplitude ratio* $R(f)$ is often used which is equal to square root of corresponding PSDs ratio:

$$R(f) = \sqrt{\frac{PSD_1(f)}{PSD_2(f)}}. \quad (5)$$

Fig. 5 shows the amplitude ratio for PSDs from Fig. 4 (PSD_1 - water on, PSD_2 - water off). One can see that the biggest effect - about factor of 40 - the water flow gives at frequency about 32 Hz. In the absence of water flow mechanical properties of the girder gives 8-10 times amplification of vibrations at frequencies about 46 Hz and 67 Hz as it is shown in Fig. 6 (PSD_1 - spectrum of the quadrupole vibration, PSD_2 - spectrum of the floor vibration).

Horizontal vibration of the AQ-1 quadrupole have the rms value in band 2-50 Hz about 0.02 – 0.04 micron in the absence of water flow - it is practically the same as for vertical motion. But situation was cardinally changed when 200 g/sec water flow was switched on. In Fig. 7 one can see 4-sec record of the quad vibrations. The maximum double amplitude of observed 10 Hz oscillations is up to 3 micron. 10 Hz frequency is determined by resonance of girder support structure that is mechanically driven by coils and pipes

vibrations due to the water flow.

Fig. 8 presents PSD of horizontal quad vibrations with cooling water on (solid line), how the spectrum was changed after installation of wooden stick between the quad and the wall of the hall (it improves rigidity and decreases the rms amplitude four times from 0.84 micron to 0.22 micron, see dashed line). PSD of horizontal movement of the floor is marked by stars. One could conclude that something similar to additional wooden support may be used to obtain horizontal vibration below the level of acceptability (0.25-0.34 micron) or other measures to damp the dangerous 10 Hz resonance should be applied.

Inasmuch as correlation properties of quads vibrations are important for estimation of positron beam orbit jitter the corresponding experiments were carried out. The results of measurements of vertical motion coherence are shown in Fig. 9. The dashed line shows that in the case when two SM-3KV type probes are close to each other (0 meters distance) both of them produce the same signal and coherence is very close to 1.0 in frequency band 0.08 – 70 Hz as it should be in the case when probes' internal noises are much less than useful signal. The marked line corresponds to coherence of motions of two AQ-1 quadrupole magnets in different sectors of the APS ring (namely Sector 39 and Sector 37, distance about 60 meters). One can surely say that quads motions are practically uncorrelated at frequencies above 1-2 Hz because the degree of coherence is less than 0.5. Below 1 Hz and down to 0.07 Hz the coherence is close to 1.0 because at this frequencies the microseismic waves (correlated over large distances, at least over 20 km wavelength) give main contribution to motion of the ground and quadrupoles. Frequencies below 0.05 Hz are in fact out of range of SM-3KV type probes and in next section we will discuss uncorrelated slow ground motion on the basis of other investigations.

4 Discussion and Conclusions

It is interesting to compare the spectra of vertical vibrations of the APS floor (this work), at KEK [5], in the SSC tunnel [6] and in the hall of VEPP-3 storage ring (Novosibirsk) [7]. All data were obtained under "quiet" conditions (night or weekend). One can mention that all the spectra look rather similar, contain "microseismic" peak at 0.07 – 0.2 Hz, demonstrate same "falling" character. Valuable difference occurs at frequencies 1 – 100 Hz where technical noise plays main role. One can see that the APS spectrum is more close to the VEPP-3 one (that storage ring was under operation during measurements) than to data from KEK and SSC sites which were far of additional sources of vibrations.

Slow ground motion which is off consideration in this experiments may be separated on two parts: at first, ground motion that is generated by local sources such as winds, temperature gradients, ground water, etc. It cannot be adequately treated as waves propagated in the ground. Amplitudes of such movements sometimes may caused significant influence on the accelerators operation, but nevertheless, this motion of ground is regular - it doesn't take place in absence of the origin (wind, temperature fluctuations, etc.).

The second kind of low frequency motion has principally inevitable character and leads to diffusive wandering of ground. There is experimental law that states that diffusion of *relative* positions of two points of the ground takes place in accordance with ATL formula [8]:

$$dX^2 = A \cdot T \cdot L, \quad A \approx 10^{-4} \mu m^2/(s \cdot m), \qquad (6)$$

here T is time of observation, L is distance between the points, dX is the rms value of the displacement.

Due to small value of the coefficient A in (6) this diffusion often exists as a background for large regular processes but was properly measured in long term observations in geophysics laboratories and in accelerator tunnels (see, for reference [9]). The rms value of the close orbit distortion ΔX during time period T in storage ring with circumference C may be roughly estimated as [9]:

$$\Delta X \approx 2\sqrt{ATC} \qquad (7)$$

Taking the APS parameter $C = 1100$ m, one may estimate that after 2 years rms COD (without correction) will be about 0.5 cm. This value is not acceptable for the dynamical aperture of the ring.

Finally, let's count some results of the work:

- measurements of ground motion and magnet vibrations were done in frequency band 0.05 – 100 Hz;

- correlation measurements have shown that motion of magnets may be treated as uncorrelated in high frequency part of spectrum (above 1-2 Hz);

- rms values of uncorrelated vertical and horizontal magnets vibrations under quiet conditions are about 0.015-0.04 micron, i.e. below allowable level for the APS;

- cooling water flow rate about 200 g/sec doesn't cause dangerous vertical vibrations of quadrupoles;

- 10 Hz mechanical resonance of system "quadrupole-girder" driven by the water flow fluctuations leads to some 3 times above acceptable amplitudes of quadrupole vibration and additional damping support is needed;

- relocations of heavy masses inside the ASP hall or traffic in the under the ring may cause to unacceptable large single quadrupole magnet vertical displacements.

5 Acknowledgments

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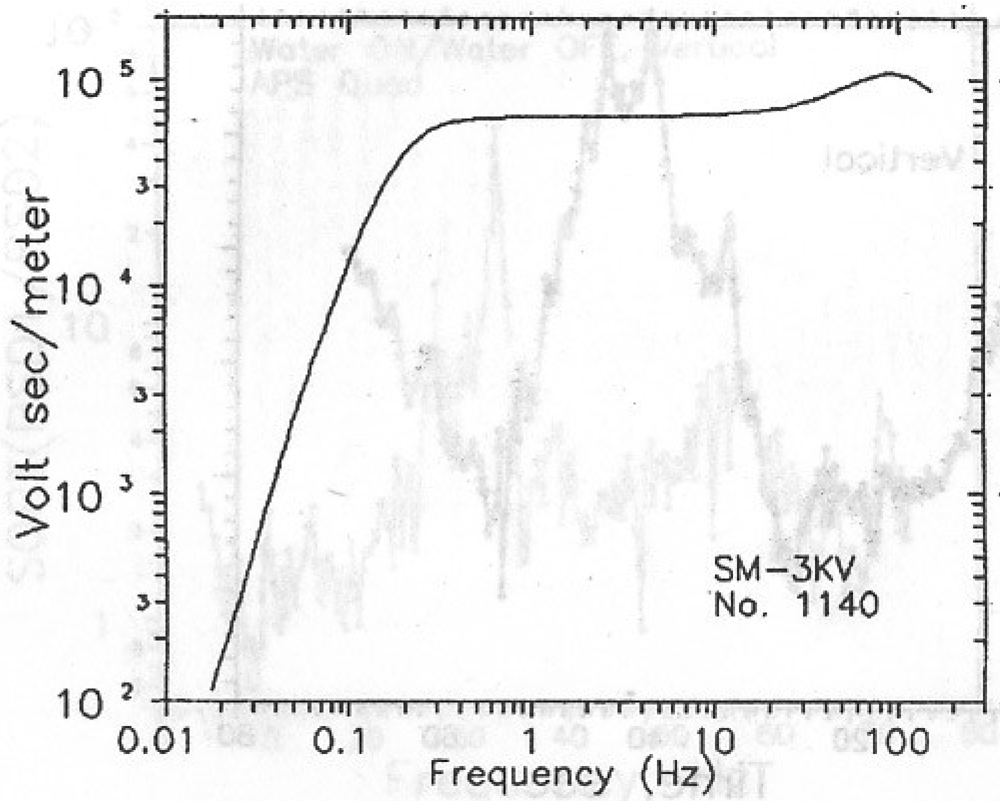

Figure 1. Calibration data for SM-3KV type seismometer.

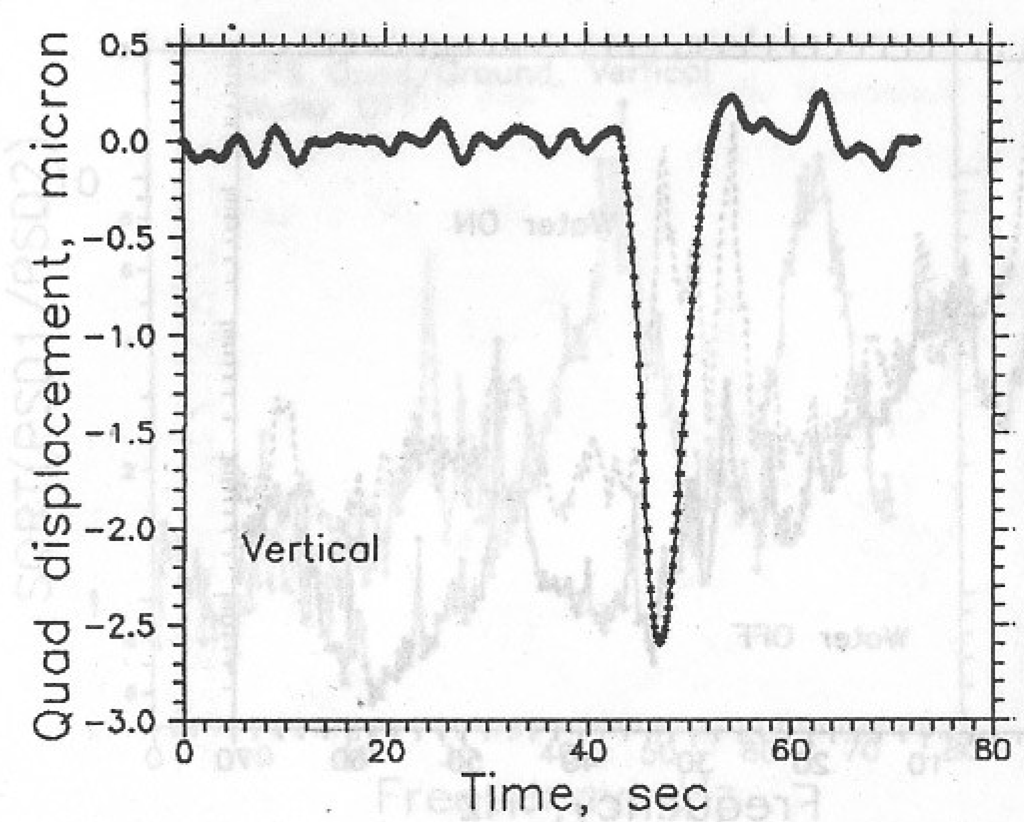

Figure 2. Low frequency vertical motion of the APS quad and effect of a man passing closely.

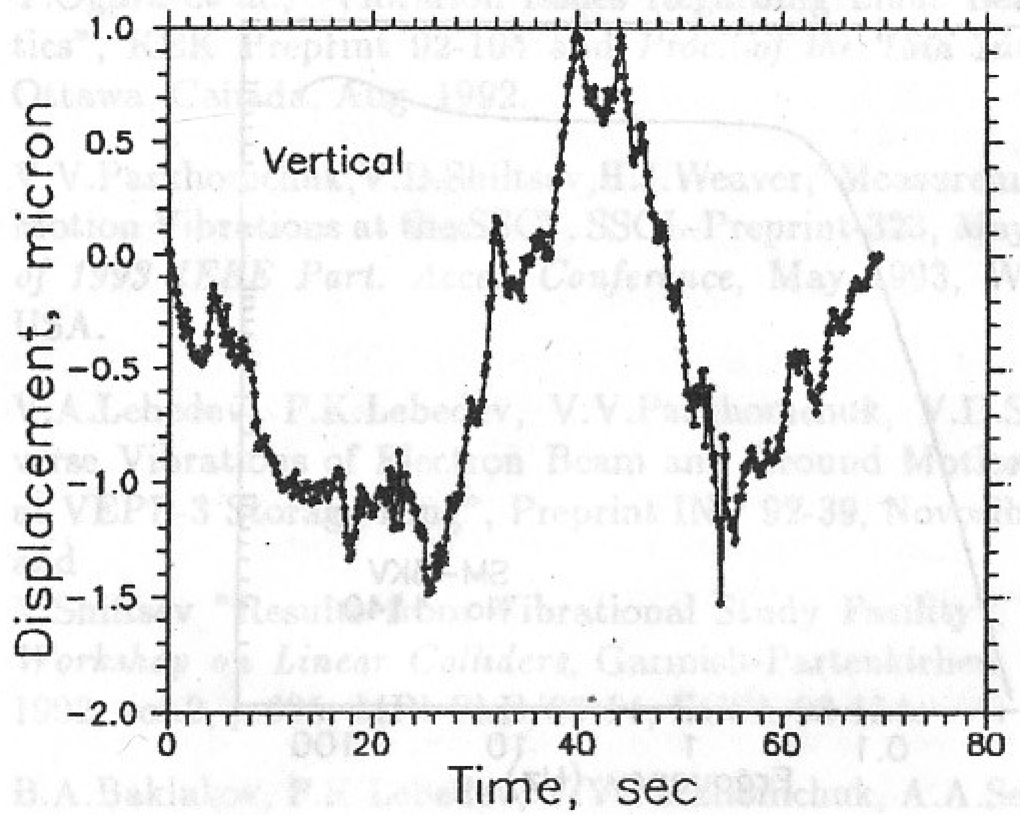

Figure 3. **Vertical motion of the APS hall floor just above the tunnel while a compact car passing tunnel.**

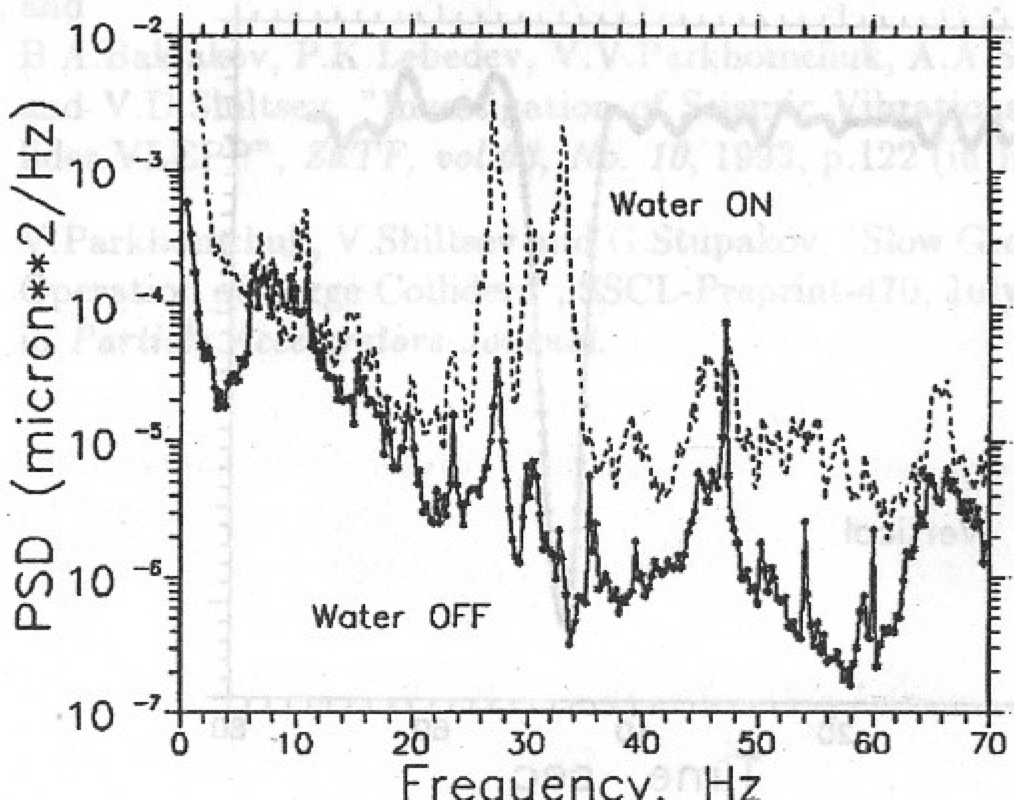

Figure 4. PSD of vertical vibration of the APS quad with cooling water on and off.

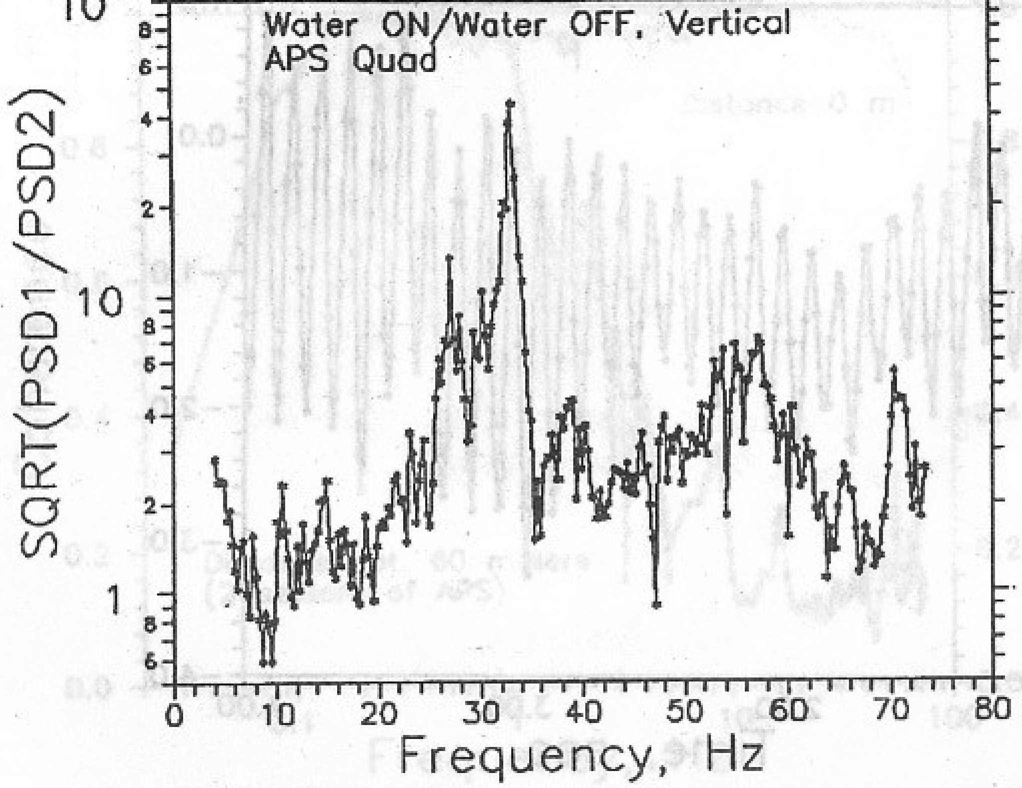

Figure 5. Spectral amplitude ratio: effect of cooling water flow 200 g/sec on vertical vibration of the APS quadrupole.

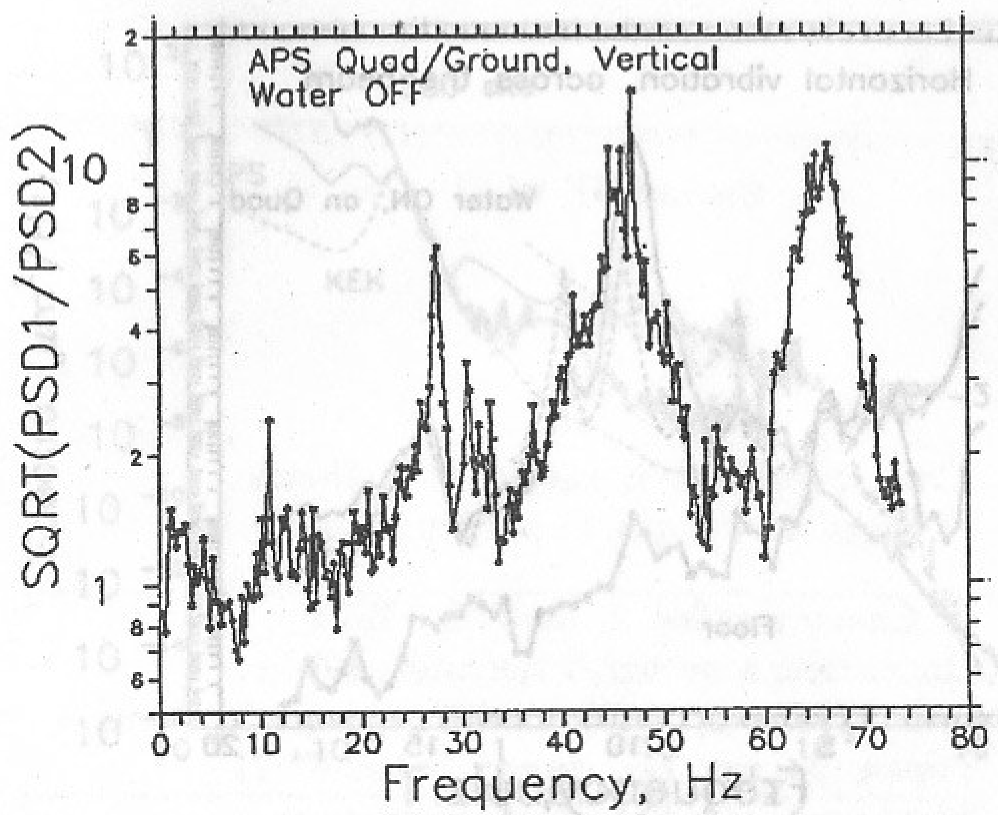

Figure 6. Horizontal vibration of the APS quad with cooling water flow rate 200 g/sec.

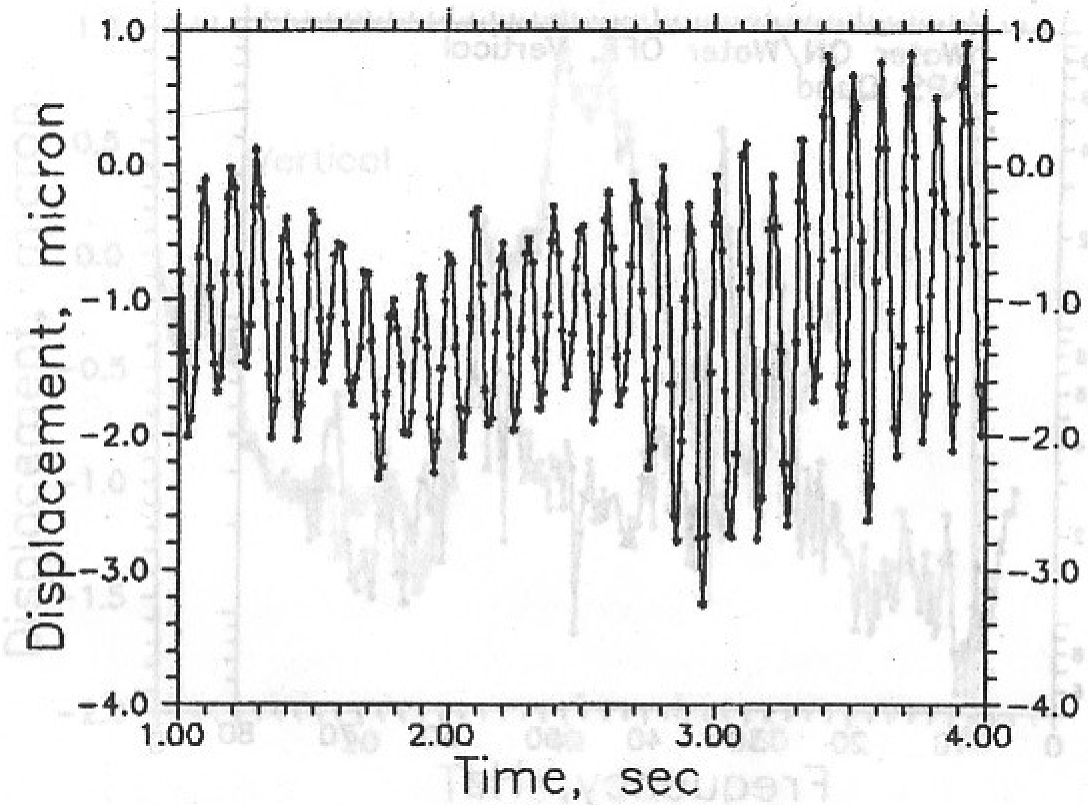

Figure 7. Horizontal vibration of the APS quad with cooling water flow rate 200 g/sec.

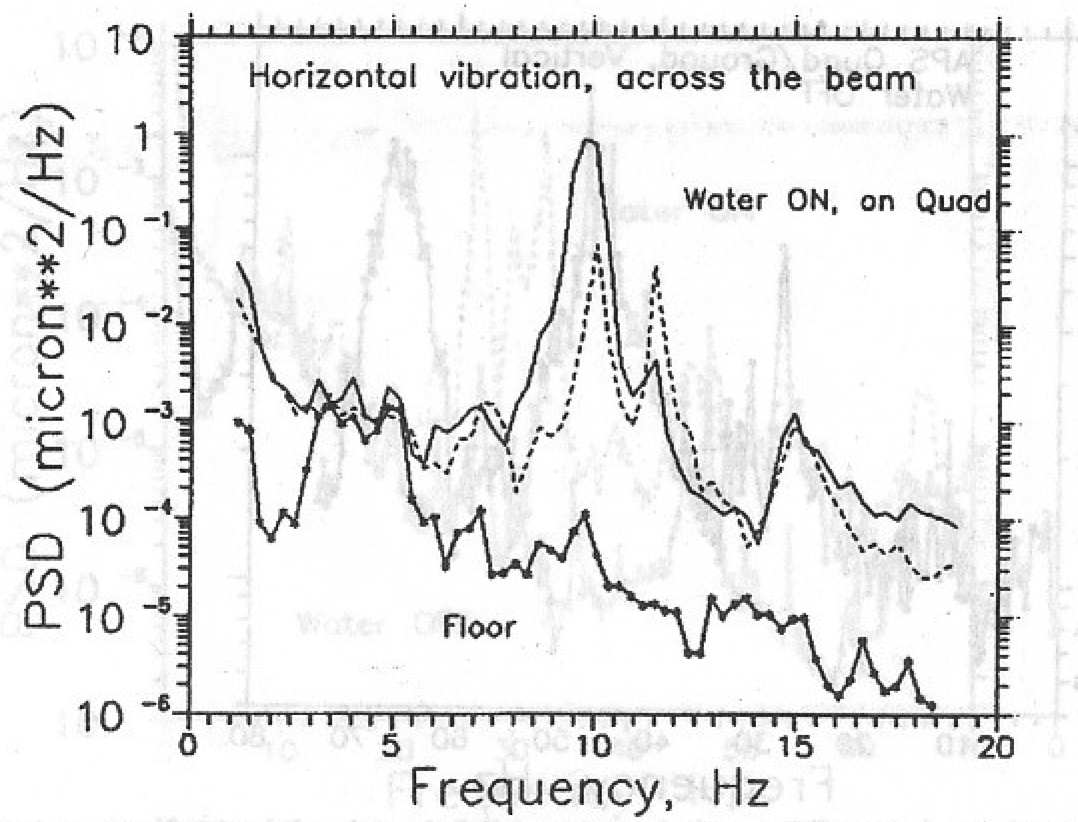

Figure 8. PSD of horizontal vibration of the APS floor (marked line), the APS quad with cooling water on (solid line) and the same quad with installed additional wooden support(dashed line).

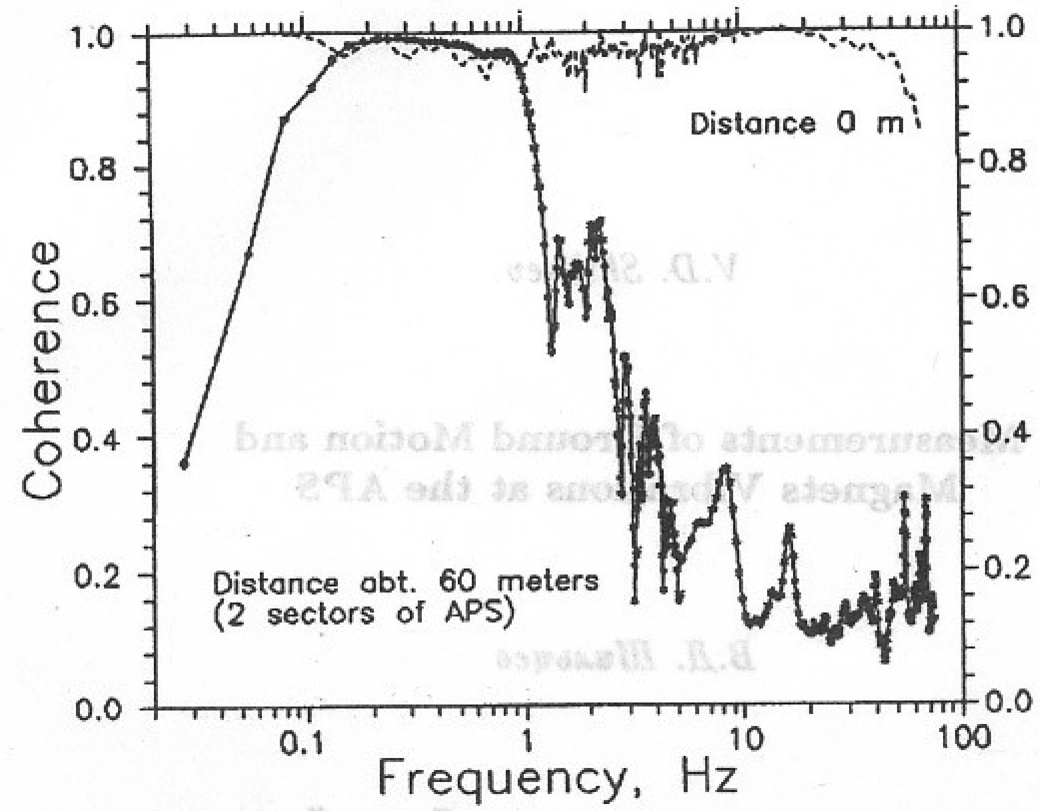

Figure 9. Coherence spectra of vertical motions of two APS quadrupoles distanced by two APS sectors (about 60 meters).

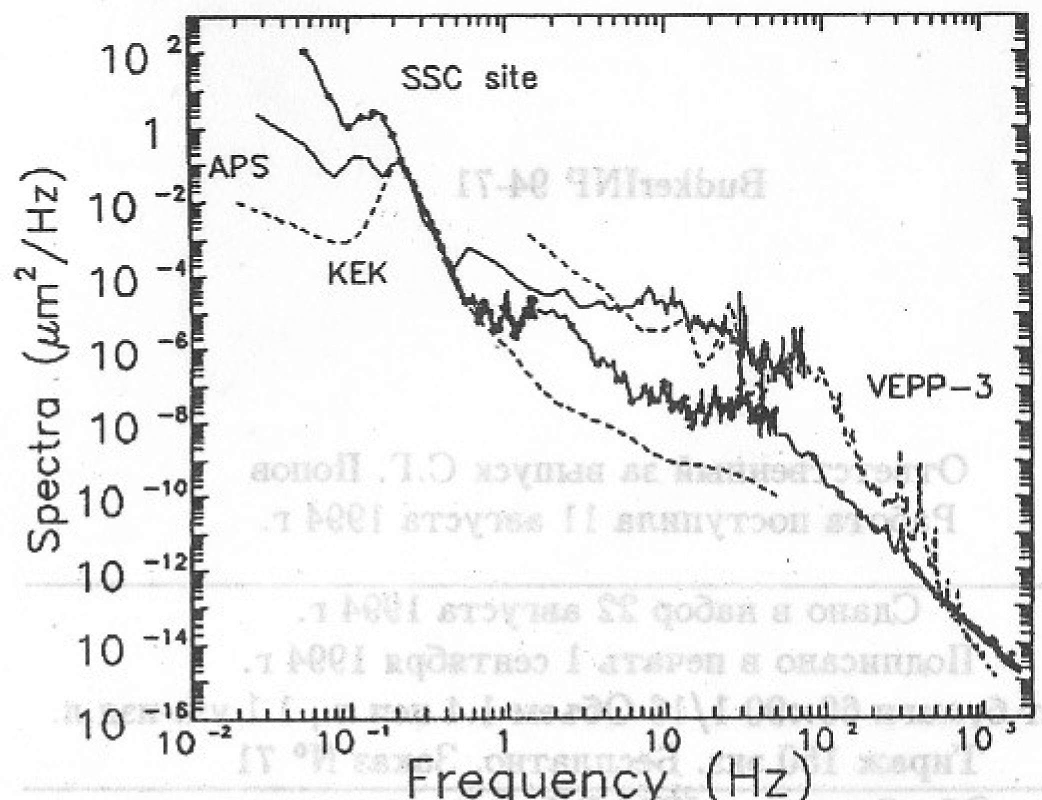

Figure 10. Power spectral densities at the APS and other accelerator tunnels: SSC, VEPP-3, KEK (see comments in text).

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Измерение движения земли и вибраций магнитов на накопителе APS

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