GROUND MOTION MEASUREMENTS IN HERA

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Abstract

This article presents the results of ground motion measurements at DESY. Power spectral densities of vertical and horizontal ground motion were obtained in a frequency range from 0.003 Hz up to 140 Hz at some points of the HERA tunnel. The spectra of correlation were measured at a 30 m distance between seismic probes. Amplitudes of measured uncorrelated vibrations are compared with Linear Colliders tolerances.

I. Introduction

Vibrations of magnetic elements of particle accelerators due to the ground motion cause the distortion of beam orbits. At modern colliders with separated beam optics systems for each beam species (e.g. HERA, Linear Colliders), the cumulative effect of numerous perturbations produced by microscopic vibrations of quadrupoles manifest itself as beam-beam separation at the interaction point (in contrast to the majority of existing machines where both beams share the same guiding magnetic fields).

While the orbit distortions in the accelerators are sensitive to the uncorrelated quadrupole motion, the goals of the experiments at DESY were to investigate the spatial correlation and measure the amplitudes of the HERA tunnel vibrations under conditions of a working accelerator. A very broad frequency band of almost 5 decades from 0.003 Hz to 140 Hz is a distinctive feature of these experiments.

These measurements were done in the HERA Hall North (H1 detector area) and in the HERA Hall West at a depth of about 25 m. The measurements are described in detail in [1].

II. Instruments and Methods

Sensors for the ground motion were four SM-3KV type velocity meters (a pair of vertical and a pair of horizontal) which allow us to obtain the data in a 0.1 – 140 Hz frequency band with a sensitivity of about 80 mV/($\mu m/s$); and a pair of three component CMG-3T geophones made by *Guralp Systems Co.* with a flat velocity response of 0.75 mV/($\mu m/s$) in the band 0.003 Hz – 50 Hz.

The electrical signals from all the probes were digitized and developed by a CAMAC-based experimental set-up which includes two 10-bit and 4-channel ADCs, four 20-bit ADCs, differential amplifiers with low-pass frequency filters, and an IBM 486 personal computer. The signals were digitized simultaneously by the ADCs with a sampling frequency (variable by a timer from 0.1 Hz to 32 kHz) and then sent to the memory for storage. The maximum memory available for one channel is 64-K 24-bit words. It corresponds to 18 h of permanent measurement time with a sampling rate of 1 Hz or about 3 min with 400 Hz. For long-term measurements we used the low-pass filters at 0.5 Hz, 2 Hz or 20 Hz, for fast analyses the 200-Hz filter was applied.

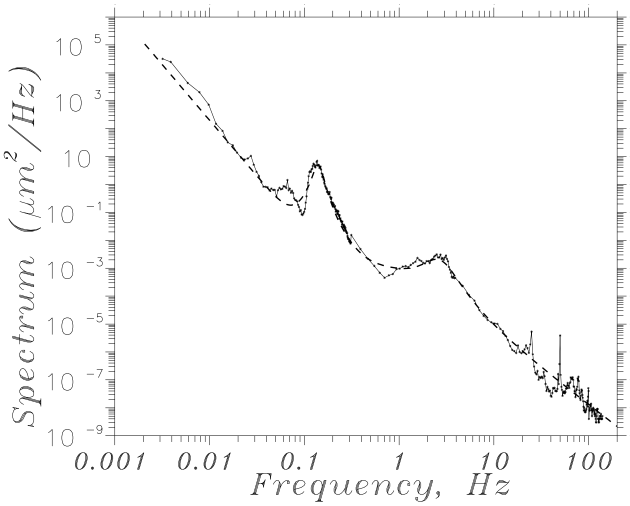

Figure. 1. Spectrum of vertical vibrations.

As the ground motion is $noise$, its properties can be described by *the power spectral density (PSD)* $S_x(f)$. The dimension of the PSD is *power in a unit frequency band*, i.e., m^2/Hz for the PSD of displacement. The value of $S_x(f)$ relates to the rms value of the signal $X_{rms}(f_1, f_2)$ in frequency band from f_1 to f_2 as $X_{rms}(f_1, f_2) = \sqrt{\int_{f_1}^{f_2} S_x(f)df}$. The *normalized spectrum of the correlation* $K(f)$ of two signals $x(t)$ and $y(t)$ is defined as

$$K(f) = \frac{\langle X(f)Y^*(f)\rangle}{\sqrt{\langle X(f)X^*(f)\rangle\langle Y(f)Y^*(f)\rangle}}, \qquad (1)$$

where the brackets < .... > mean the time averaging over the different measurement data, and $X(f) and Y(f)$ are the Fourier transformations of $x(t)$ and $y(t)$. Note, that correlation $K(f)$ is a complex function. The coherence of the two signals is equal to the modulus of $K(f)$. By the definition, the value of the coherence does not exceed 1.0.

III. Results

The PSD of the vertical ground motion measured 20-21.09.1994 in HERA Hall West at the tunnel depth is shown in Fig. 1 in a log-log scale. The spectrum can be approximated by the formula (see dashed line)

$$S_x(f)[\mu m^2/Hz] \approx \frac{2\cdot 10^6}{(\frac{f}{0.001})^4} + \frac{10^{-3}}{1+f^{5/2}} +$$

$$+ \frac{5}{(1+(\frac{f-f_m}{0.14\cdot f_m})^2)^{3/2}} + \frac{2\cdot 10^{-3}}{(1+(\frac{f-f_c}{0.45\cdot f_c})^2)^{3/2}}. \qquad (2)$$

The first term in (2) fits the spectrum of the slow ground motion noise in a frequency range of 0.003 – 0.1 Hz, the second one describes a continual part of the spectrum from 4 Hz to 140 Hz, the third one represents *the microseismic waves* with the frequencies about f_m=0.14 Hz, and the last one corresponds to a broad peak around f_c=2.5 Hz, which is often referred to the manifestation of the resonances in an upper crust. Clearly visible peaks in the PSD at about 25 Hz and 50 Hz are not described in (2) because of their definitely technological origin. The horizontal ground motion was also measured simultaneously, and its amplitudes are the same as the vertical ones within a factor of 3.

During almost two months of observation in Hamburg the rms amplitude of the microseismic waves (the square root of integral of PSD around f_m) varied smoothly within the range of 0.1 $\div$ 2 μm, and their mean frequency f_m varied from 0.1 Hz up to 0.25 Hz. To determine the direction toward the sources of these waves, we set side by side a pair of the horizontal SM-3KV type geophones, so that their pendula were perpendicular to each other. Their signals passed through a 0.07 Hz – 0.5 Hz filter and were recorded for further processing [1]. Figure 2 presents the angular distribution of the 0.07-0.5 Hz signals for Sept. 2, 1994 data record when the probes were installed on the bottom of the H1 pit. The length of each ray in this Figure is proportional to the squared amplitude (energy) of waves which propagate in the direction of the ray. The main ”leaf” of the diagram points to the North-North-West (the North-West coast of Denmark, or the southern coast of Norway) while a pair of smaller ones are directed to the closest coastal lines of the North Sea and the Baltic Sea. The ground motion at higher frequencies, that can not be properly treated as waves, shows practically uniform angular distribution.

The spectra of the coherence $Co(f)$ were measured in a frequency range of 0.01 – 140 Hz by a pair of the vertical SM3-KV probes and in the band of 0.003 – 20 Hz by the CMG-3T geophones. Usually, we made 63 FFTs of the signals (for 1$\div$1000 s long records) because this allows us to reduce the statistical error of the coherence measurement down to $\approx$10%.

Initially, the probes were set together in a certain point of the HERA Hall West at the tunnel depth, and it was found that $Co(f)$ $\approx$1.0 over the whole frequency range (see solid line in Fig.3). Being displaced by L =15 m, the same probes showed a significant drop in the coherence at the frequencies higher than 5 Hz and below 0.05 Hz (see dashed line). The further increase in the distance up to L =30 m (maximum available distance in the Hall West pit) led to a larger decrease of the coherence as it is presented by a marked line in Fig.3.

It is seen that inspite of the tendency of smaller coherence at longer distances, there are some frequency regions with good coherence, namely, around 100 Hz, 50 Hz, 2 Hz and 0.2 Hz. As for the frequencies above 1 Hz, the decrease in the coherence at 30 m is well understood and was always observed earlier. Below 0.05 Hz, the fall of the coherence is somewhat surprising. While the internal noises of low-frequency CMG-3T type probes are smaller than a signal (it is proven experimentally because the coherence at L =0 m is close to 1.0), some external noises can explain the lack of the coherence (”floating” of the ground potential, fluctuations of pressure and temperature at different tunnel

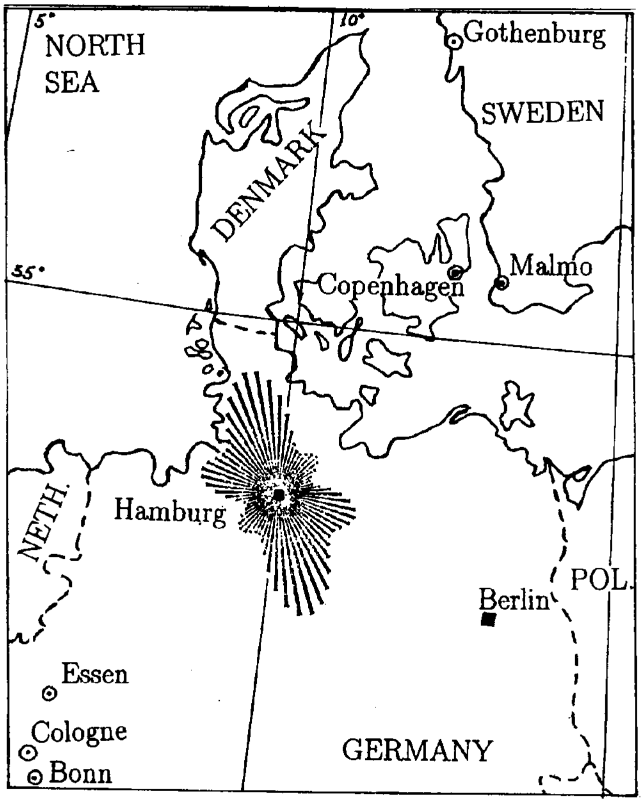

Figure. 2. Directions of 0.07–0.5 Hz ground waves.

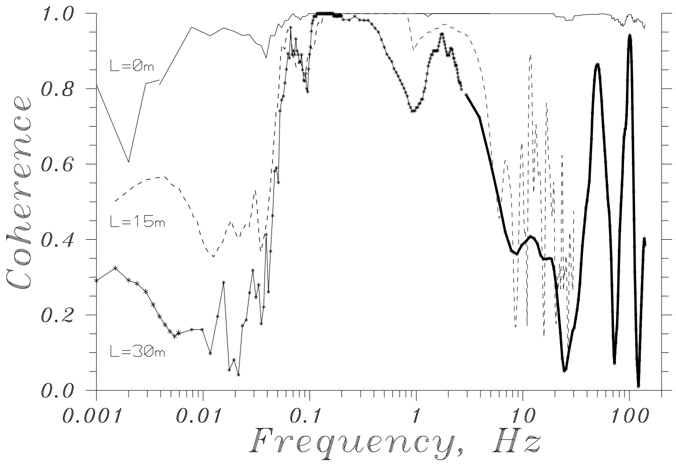

Figure. 3. Spectra of coherence at 0, 15 and 30 meters.

points, cracks in the concrete, etc). Further investigations of the issue are necessary.

During almost two months of these experiments, we observed some dozen events with the amplitudes far above the ordinary ones. As Hamburg is rather quiet seismic site, these events were mostly the waves from remote earthquakes. Typically, they had 20 – 400 μm amplitude, a period of about 10-30 s, and their durations were up to 2000 s. The statistics of the events with large amplitudes allows us to approximate the mean time $T(A)$ between the events with amplitude more than A as $T(A)[days] \approx 10 * (A/100\mu m)$. Having a very large wavelength of about a hundred of km, the earthquake waves can not produces beam orbit distortions in the accelerators built in elastic media, and we did not see any beam orbit distortions in the HERA collider during the quakes [1].

IV. Discussion and Summary

The quadrupole vibrations result in the beam degradation in Linear Colliders. These vibrations arise from the motion of the ground amplified by support systems, vibrations due to cooling flow turbulence, etc. Tolerances on uncorrelated jitter of the quadrupoles in the main linac vary for the different LC projects [2]: for vertical motion it is about 10 – 30 nanometers for small emittance designs (CLIC, VLEPP, JLC, NLC – X-band machines) and 50 – 100 nanometers for S-band and TESLA designs. Tolerances on the quads motion in a final focus system are about 10 times more severe. To reduce the effect of the ground motion, one can either use a beam-based feedback system or measure and correct the actual quad motion. The experience of using the SLC beam-based feedback has shown that the system operates effectively at the frequencies below $f_{rep}/30$ where f_{rep} is the repetition frequency of the linac. Therefore, the vibrations above that frequency are not correctable by the beam-base technique.

The data obtained in the HERA tunnel allow us to estimate the amplitudes of the vibrations at the frequencies above certain frequency f. Figure 4 shows the rms amplitudes $U_{30m}(f)$ of the uncorrelated ground motion at L=30 m in comparison with the rms amplitude of the absolute ground motion at both points $A(f)$ (dashed line) vs. the frequency f. These values were obtained according to the formula

$$U_{30m}(f) = \sqrt{\int_f^{\infty} (1 - Co_{30m}(f)) \cdot S_x(f) df} \tag{3}$$

and

$$A(f) = \sqrt{\int_f^{\infty} S_x(f) df}, \tag{4}$$

where $Co_{30m}(f)$ is the coherence spectrum at L =30 m as shown in Fig.3 and $S_x(f)$ is the PSD of the vertical ground motion in the HERA tunnel (presented in Fig.1). One can see that the incoherent motion is noticeably smaller than the coherent motion only in a frequency range of 0.05 Hz – 2 Hz. It should be emphasized that the increase in the uncorrelated motion at the frequencies less than 0.05 Hz is due to the lack of coherence $Co_{30m}(f)$ in this range which should be checked more carefully.

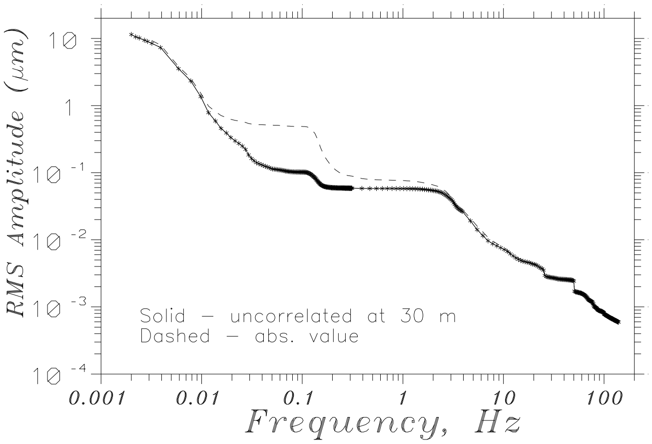

Figure. 4. RMS amplitude of vertical vibrations at frequencies higher than f vs. f

Table I

	f_{rep}/30, Hz	Jitter toler.,nm	U_{30m}, nm
X-band	4-10	10-30	15-5
S-band	0.3-2	70	60

Finally, Table I compares our results on the uncorrelated ground motion with the requirements for the two groups of the LC projects.

From the Table I one can see that for all the projects the ground motion amplitudes measured in HERA are over or close to the tolerable levels.

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References

[1] V. Shiltsev *et. al*, to appear as DESY HERA Report, 1995; see also this conference.

[2] *Proc. of Int. Workshop* ”Linear Colliders’95”, KEK, 1995.