

CLOSED-ORBIT DRIFTS IN HERA IN CORRELATION WITH GROUND MOTION

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Abstract

This article describes the results of orbit motion measurements in HERA $e-p$ collider. Power spectral density of vertical drifts of HERA proton beam orbit was obtained in a frequency range from $6 \cdot 10^{-5}$ Hz up to 250 Hz. The slow closed-orbit drifts were found to have diffusive character and to grow as the square root of time interval. Simultaneous measurement of ground vibrations at HERA tunnel has shown significant correlation of the orbit drifts with the ground motion. It was observed that the orbit motion substantially affects the proton loss rate.

I. INTRODUCTION

Quadrupole vibrations due to ground motion cause distortion of beam orbits in HERA and beam-beam separation at the interaction point. The goal of these measurements was to reveal directly the correlation between the HERA tunnel vibrations and the closed orbit distortions (COD). To do this, the signals of beam position monitors (BPM) and seismometers were recorded with high precision. The search was performed in a very broad frequency band of almost 7 decades from $6 \cdot 10^{-5}$ Hz to 250 Hz. At the same time, the dependence of the particle loss rate in the ring on the orbit motion is a point of keen interest, therefore, we recorded and took in processing the signal from a proton loss monitor. During the measurements, most of the data on beams were obtained under luminosity run conditions of HERA with the typical parameters: proton current of 30-45 mA at 820 GeV, electron (positron) current of 10-25 mA at 28 GeV. 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 data in 0.1 – 140 Hz frequency band with a sensitivity of about 80 mV/($\mu\text{m}/\text{s}$); and a pair of three component CMG-3T geophones made by *Guralp Systems Co.* with a flat velocity response of 0.75 mV/($\mu\text{m}/\text{s}$) in the band 0.003 Hz – 50 Hz. The noises of the probes were found to be much less than the ground motion signals in the corresponding frequency ranges [1]. The vibration detectors were set in the HERA Hall North (H1 detector area) and in the HERA Hall West at the depth of about 25 m.

The transverse proton beam closed orbit was detected by a pick-up BPM at WR35 sector of HERA ($\beta_h = 227\text{m}$, $\beta_v = 25\text{m}$). The BPM sensitivity was 1.5 mV/ μm in respect to $\beta = 1\text{m}$. (Further, the orbit motion will be normalized to the point of a lattice with $\beta = 1\text{m}$. It is about the HERA interaction point values of $\beta_v^* = 0.7\text{m}$ and $\beta_h^* = 1.4\text{m}$). The rms BPM noises are

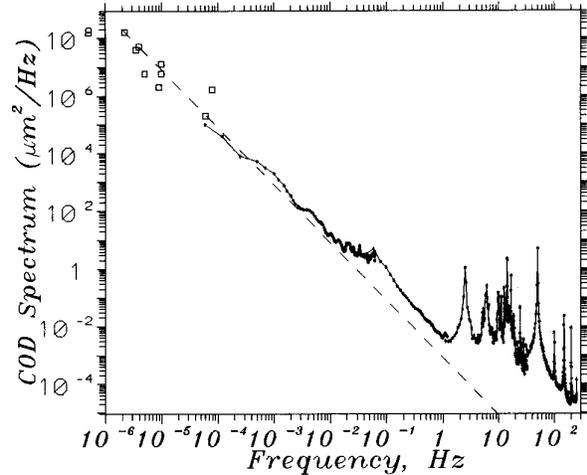


Figure 1. Spectrum of vertical COD of proton beam (normalized to $\beta=1\text{m}$). Squares are for the data from Ref. [3].

about 0.1 μm in a frequency band of 0.5 Hz and about 0.5 μm for a 100 Hz band.

The HERA proton loss monitor detects the beam halo particles scattered in the material of a collimator. Note, that the loss rate variation depends on beam shaking as well as on the beam shape (cross section) deformations because the collimator "jaw" was from the only side of the beam. The monitor is described in detail in [2].

The signals from all the monitors were digitized simultaneously by ADCs with variable sampling frequency (from 0.1 Hz to 1 kHz) and then were sent to the memory for storage. To get information in different frequency ranges, the low-pass filters at 200 Hz, 20 Hz, 2 Hz, and 0.5 Hz were applied.

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

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

where the brackets $\langle \dots \rangle$ 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 is a complex function $K(f) = Co(f) \exp(-i\Delta\phi(f))$. The coherence $Co(f)$ 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.

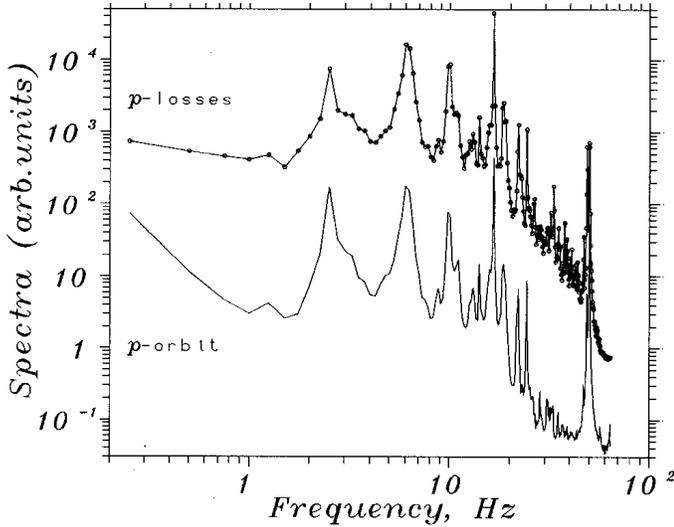


Figure 2. Spectra of proton loss rate and p -BPM signals.

The value of $\Delta\phi(f)$ reflects phase advance between the corresponding Fourier harmonics of the two signals.

III. RESULTS

The power spectral density of the vertical motion of the HERA proton beam closed orbit (scaled for $\beta = 1$ m) from $6 \cdot 10^{-5}$ Hz up to 250 Hz (almost 7 decades in frequency) is shown in Fig.1. In order to get better estimation of the PSD at the lowest frequency three-day data record (29.09 – 01.10.1994) were processed. It is interesting to note that the measured PSD is well consistent with the analysis of weekly orbit drifts all over the HERA- p ring [3], those data are marked by squares in Fig.1. The spectrum can be divided in two parts: continuum below 1 Hz and a series of peaks at frequencies above 1 Hz. The continuous part can be approximated by the formula (see dashed line in Fig.1)

$$S_{COD}(f) = \frac{1.2 \cdot 10^{-3}}{f^2} [\mu\text{m}^2/\text{Hz}], \quad (2)$$

This part of spectra describes the slow drift of the HERA proton orbit that looks like a “random walk” process, and its PSD corresponds to the rms orbit displacement proportional to the square root of the time interval of observation \sqrt{T} .

The Fourier processing of the proton loss signal (see Fig.2) shows that at frequencies above 1 Hz the spectrum of proton orbit vibrations (solid line in Fig.2) and the spectrum of proton losses variations (solid line marked by points) follow each other. For example, the spectral lines at 2.5 Hz, 6.25 Hz, 9.8 Hz, 12 Hz, 16 Hz, 18 Hz, 19 Hz, 22 Hz, 24.4 Hz, 48.8 Hz, 50 Hz, etc, are clearly seen in both PSDs. This coincidence points to certain connection (correlation) of the particle losses and orbit motion. Results of direct correlation measurements allow us to conclude that below 50 Hz the most of these peaks are caused by mechanical vibrations (for, example, 24.4 Hz and 48.8 Hz harmonics are due to mechanical pumps in HERA), and above 50 Hz they are due to the multiples of 50 Hz in magnet power supplies.

The spectrum of the coherence between the vertical ground motion (detected by CMG-3T and SM3-KV probes at the tun-

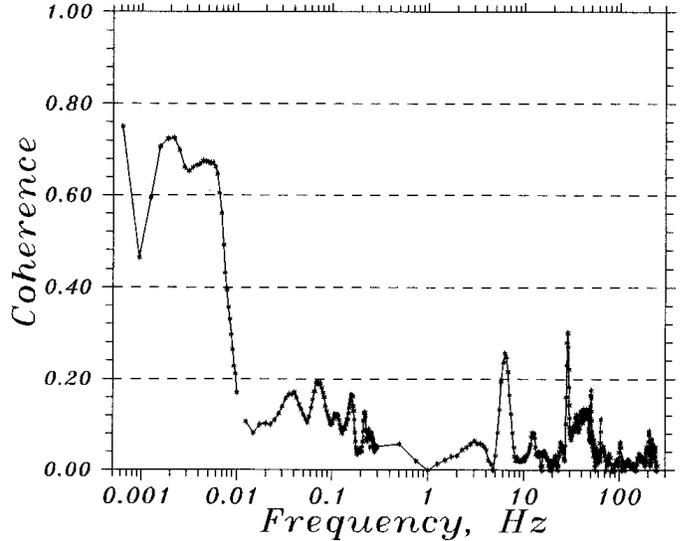


Figure 3. Spectrum of the coherence between vertical ground motion and vertical closed-orbit drifts of p -beam.

nel depth in the Hall West pit) and proton closed orbit vibrations measured by the BPM is shown in Fig.3. The measurements were performed during 5 days (September 16 – 21, 1994), and the spectrum covers a frequency band of 0.001 Hz – 200 Hz. A number of FFTs of the data records was about 60 – 90, and it allowed us to reduce the statistical error of the coherence measurement down to $\sigma \approx 0.1$. As it is seen in Fig.3, the significant coherence (above 2σ) was detected at frequencies 24.4 Hz and 6.25 Hz. There is no valuable correlation at frequencies of the *microseismic ground waves* which occupy a band of 0.1–0.3 Hz in the PSD of the HERA tunnel motion, and their amplitudes are about $2 \mu\text{m}$ [1]. The reason is that their wavelength of 20–30 km is much longer than the betatron wavelength in HERA (about 200 m). In spite of the PSD of the tunnel vibrations, there is no peak due to these waves in the COD PSD which is shown in Fig.1.

It is hard to conclude definitely on the COD–ground correlation at frequencies of 0.02 – 0.3 Hz, where the value of $C_o(f)$ is about $1-2 \sigma$. The remarkable phenomena in this frequency region are the waves from the remote earthquakes that happened some dozen times during the period of the experiments. In spite of their large amplitude (up to $400 \mu\text{m}$) these seldom events produced no effect on HERA beams because their wavelength is above hundreds of km.

Below a frequency of 0.01 Hz, the coherence is as big as 0.6 – 0.7, what is above 3σ limit. This allows us to consider the slow tunnel motion to be a governing source of the closed orbit drifts in HERA.

Fig.4 demonstrates that the proton losses are due to the orbit motion at the frequencies of 0.01 – 0.3 Hz and 1–30 Hz. The harmonics observed in the PSD of the proton losses (Fig.2) are clearly seen in the coherence spectrum. Nevertheless, this connection is not still fully understood. For example, there is no a reasonable model to describe fast changes of the phase shift $\Delta\phi(f)$ between the BPM and the p -loss monitor signals over a frequency range of 0.01–30 Hz – see Fig.5.

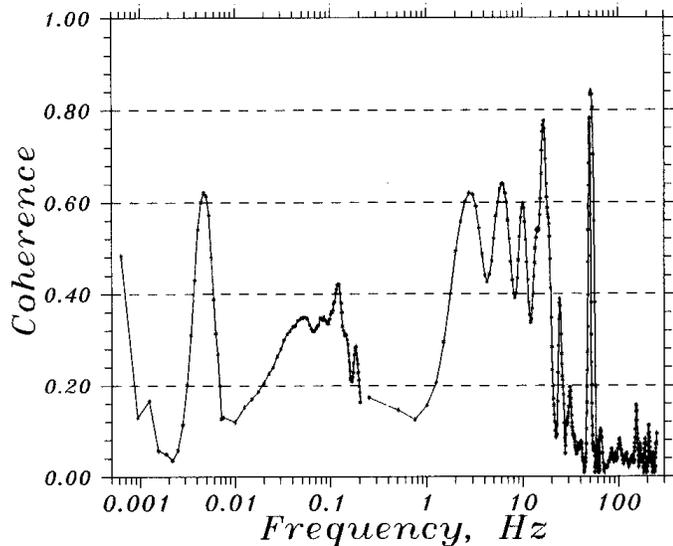


Figure 4. Spectrum of coherence between proton orbit motion and proton loss rate.

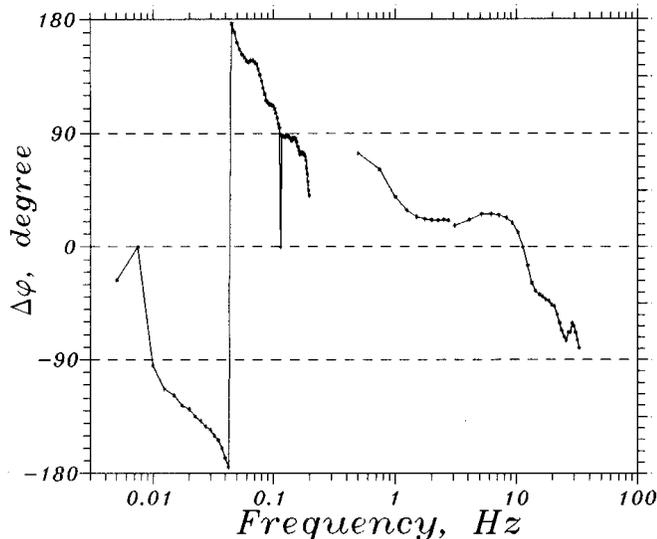


Figure 5. Phase advance between p -orbit motion and proton loss rate signals vs. frequency.

IV. DISCUSSION

The observed orbit drifts in HERA and the conclusion on their ground motion origin are in agreement with predictions of *the ATL law* [4]. This empirical rule states that besides the regular correlated ground motion there is a diffusion of *relative* positions of two points of the ground. The rms value of the displacement dX depends on the distance between the points L and the observation time interval T as $dX^2 = A \cdot T \cdot L$, where the constant somewhat depends on the site and typically $A \approx 10^{-5} \div 10^{-4} \mu\text{m}^2/(\text{s} \cdot \text{m})$. Due to a small value of the coefficient A , this diffusion usually takes place as a background for the large regular processes; however, it was properly measured in long-term observations in geophysics laboratories and in accelerator tunnels [4]. At present time, the interval of distances $L=7 - 2000$ m and the corresponding time interval from

some hours to 17 years are considered to be within the limits of validity of the law.

The ground diffusion leads to the closed orbit distortion $X_{COD} \propto \sqrt{ATC}$, where C is the accelerator circumference (6.3 km for HERA). Thus, the PSD of the COD is inversely proportional to the squared frequency $S_{COD} = A \cdot P/f^2$. The factor P contains machine lattice parameters and is derived analytically in [4]. For the HERA proton ring with vertical tune $\nu_y=33.298$, this parameter is about $P \approx 60$. Finally, from the approximation (2) of measured HERA proton COD spectrum $S_{COD}(f) = 1.2 \cdot 10^{-3}/f^2[\mu\text{m}^2/\text{Hz}]$, one can get the value of the ground diffusion constant $A = 1.2 \cdot 10^{-3}/P \approx 0.2 \cdot 10^{-4} \mu\text{m}^2/(\text{s} \cdot \text{m})$. It is within the range of previous results on the ATL diffusion and close to the HERA- e data [3].

V. ACKNOWLEDGEMENTS

We express our acknowledgement to Y. Soloviev, I. Shevyakov, S. Herb, M. Seidel, W. Radloff, M. Lomperski, S. Kazaryan (DESY), N. Dikansky, V. Parkhomchuk, S. Sigmatuulin, A. Chupira (INP) for their assistance in preparing the measurements in DESY. We would like to thank G.-A.Voss, F.Willeke (DESY) and A.Skrinsky (INP) for useful discussions.

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