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DESY HERA 94-04
SW 9425

DESY HERA 94-04
April 1994

Observation of Closed Orbit Drift at HERA Covering 8 Decades of Frequency

R. Brinkmann and J. Rossbach

Deutsches Elektronen-Synchrotron DESY
Hamburg, Germany

Submitted for publication in Nuclear Instruments and Methods A.

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Deutsches Elektronen-Synchrotron DESY
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Abstract

Experimental data for closed orbit motion in both rings of the HERA e-p collider are presented for a time scale ranging from 0.01 s to 10^6 s.

The frequency spectrum derived from the data below 1 Hz exhibits a $\propto \nu^{-2}$ dependence, as expected if the orbit motion is caused by diffusive ground motion governed by the so-called *ATL* rule. Analysis of the data in terms of this model yields for the diffusion constant $A = (4 \pm 2)10^{-6}(\mu\mathrm{m})^2\mathrm{s}^{-1}$.

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1) Introduction

In colliding beams facilities, intense high energy beams move in opposite directions and are brought into collision at certain interaction regions (IR). In order to achieve high collision rates, it is essential to have very small transverse beam sizes. Beam sizes at the IR are typically $\sigma_x{}^*\sigma_x{}^* = 0.3\times 0.1\,\mathrm{mm}^2$ for the HERA electron-proton collider, and, in the future, even smaller values are envisaged at HERA and elsewhere. Thus, good transverse stability of beam positions is required to permanently guarantee optimum beam collision conditions. With storage rings for particle - antiparticle collision, this is not an issue, because antiparticles move on the same closed orbit as the respective particles of same energy, as long as the guide fields are purely magnetic. Thus, beam separation at the IR due to unintentional changes in the guide fields is automatically avoided. This is, however, not the case for double ring colliders like HERA [1] and LHC, and it is a key problem for linear colliders [2].

For large storage rings and linear colliders, the dominant reason for beam orbit motion is most likely to be the mechanical motion of magnetic quadrupole lenses [3-8]. It is the purpose of this paper to prove that this is true for HERA at least in the frequency range between $5\cdot 10^{-7}$ Hz to 10 Hz. Because, in most cases, the vertical beam size is much smaller than the horizontal one, the vertical motion is most critical. Therefore, this paper mainly deals with analysis of vertical orbit motion.

2) Quasi - Continuous Measurements

As an example, Fig. 1 shows the closed orbit motion of the HERA electron ring during a period of 6 seconds. Most of the spectral components have been allocated to vibration modes of quadrupole supports and to the ground motion in the HERA tunnel [1]. Similar measurements have been taken at the HERA proton ring, showing analogous behaviour.

While the orbit motion shown in Fig. 1 has been recorded at a sampling rate of 100 Hz (resulting in a Nyquist frequency of 50 Hz) a much smaller sampling rate had to be used to cover a larger time interval.

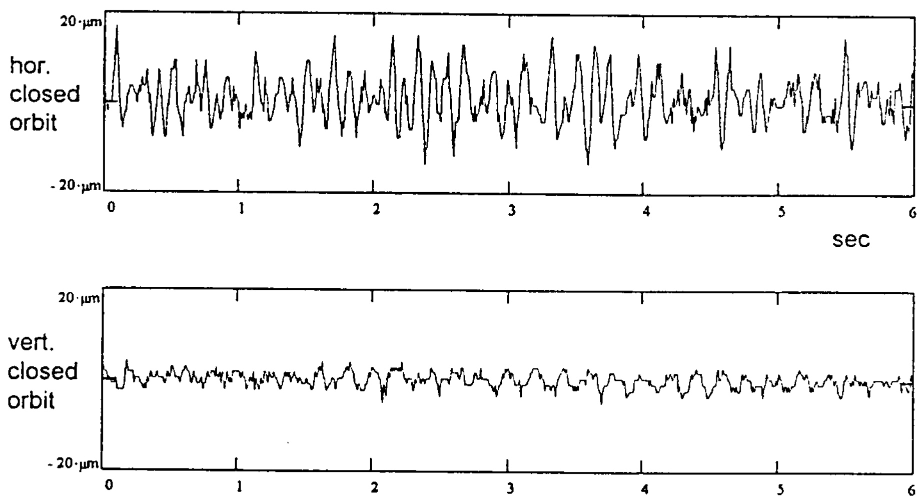

Fig. 1: Closed orbit motion of the HERA electron ring at one beam position monitor (BPM) [9] on July 12, 1991, during a time period of 6 seconds. The orbit position has been normalized for a beta function of $\beta = 1\,\mathrm{m}$. The beam energy was 26.6 GeV. The effective resolution of the BPM has been improved considerably using an averaging technique [10, 11].

Therefore, another set of measurements has been taken using a sampling rate of 1 Hz. Taking 2600 samples results in a total measuring time of T = 3/4 hours, corresponding to a bandwidth of $1/T = 4 \cdot 10^{-4}$ Hz. The power spectrum density (PDS) of this measurement of the vertical motion of the HERA electron ring is displayed in Fig. 2.

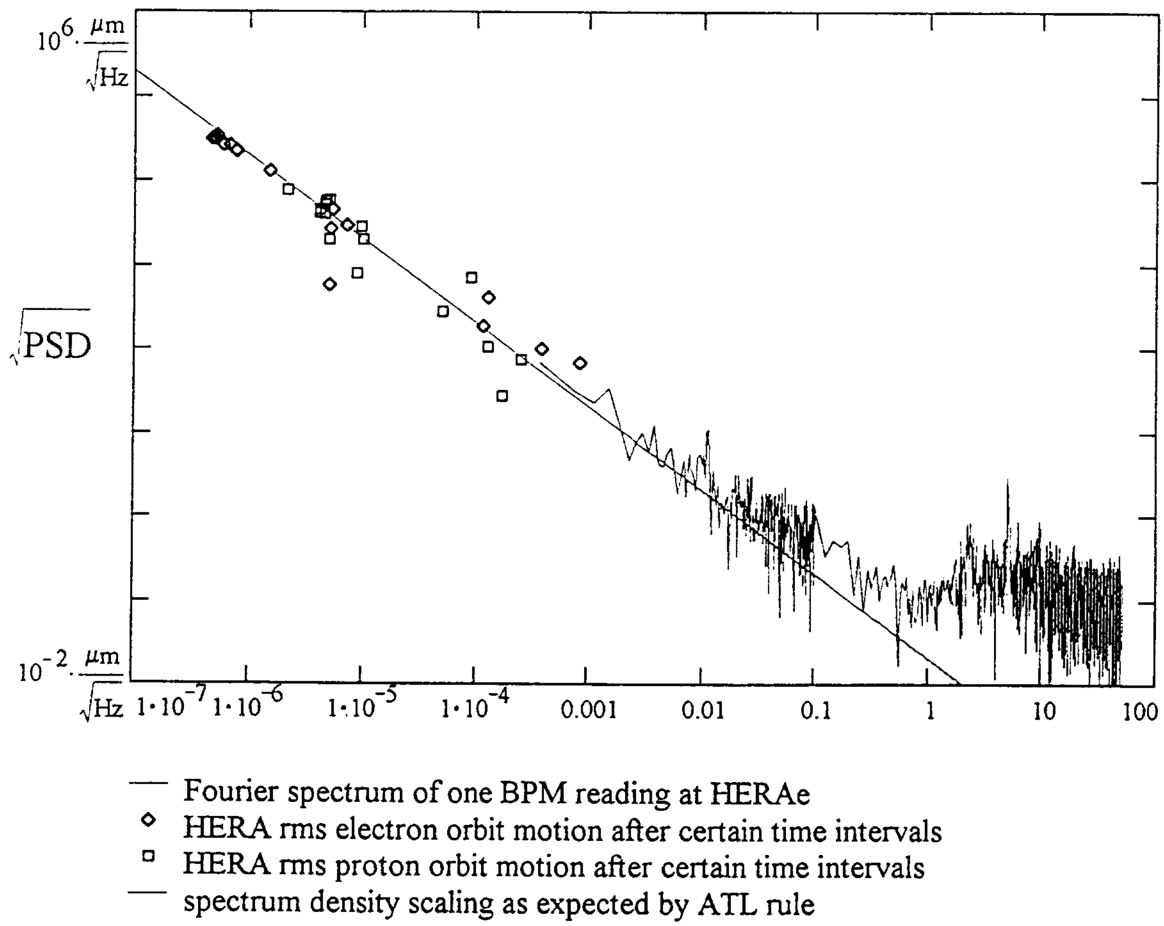

Fig. 2: Power spectrum density PSD of vertical orbit motion in HERA, normalized for $\beta = 1\,\mathrm{m}$. While the (quasi-) continuous spectrum is from the HERA electron ring at 26.6 GEV, the dots are from both HERA-e and HERA-p observations (see Figs. 3 and 4). A constant noise contribution has been subtracted in accordance to the fit Eq. (1). Also, the proton ring data have been scaled by the *FODO* cell length to account for the different sensitivities of the lattices, see text.

In this plot, it has been combined with the PSD of the vertical motion shown in Fig. 1, so that, in total, the frequency range from $4 \cdot 10^{-4}$ Hz up to 50 Hz is covered by these quasi-continuous measurements. Fig. 2 also includes results of so-called difference orbit measurements as described in the next section, which extend the frequency range to even smaller values.

3) Long-Term vertical Orbit Drifts in HERA

Because of the limited storage time (of the order of hours), it is practically impossible to extend the quasi-continuous observation of orbit motion to much smaller values of bandwidth. Instead, one has to include orbit measurements from different fills of the storage rings. The procedure is to occasionally measure the closed orbit position at all 288 beam position monitors (BPM) in HERA-e (or 131 BPMs in HERA-p, respectively). If the result is subtracted from a previous one, a so-called difference orbit Δz is obtained, indicating any eventual orbit drift.

From orbit data stored during the 1993 Luminosity run, it is possible to extract the drift of the closed orbit in the HERA electron and proton ring on a relatively long time scale. Assuming that this orbit drift is essentially determined by the displacement of quadrupoles due to ground motion, the drift constant for ground motion itself can be estimated (we only consider vertical ground motion here). The evaluation of difference orbits from the data stored at different points in time during four months of luminosity operation involves some complications. First, orbit corrections have been occasionally applied by changing the setting of correction coils. In the case of the electron ring, the corrector settings are included in the closed orbit data files and with the known optics of the ring, different corrector settings can be subtracted from the calculated difference orbits. For the proton ring, the corrector data are in general not available so that the analysis of difference orbits is limited to time intervals during which (according to the control room logbook) no intentional change of the closed orbit occurred. The maximum useful time interval for p-ring difference orbits is about five days.

Secondly, the orbit in HERA was on several occasions changed by known influences other than ground motion or corrector settings. Examples are the failure of one of the experiment solenoids or the opening/closing of the H1 experiment leading to non-negligible deformation of the interaction region quadrupole supports. This limits the maximum useful time interval in the case of the electron ring to about one month.

Furthermore, some of the stored orbit data are not useful because of lack of accuracy, e.g. due to poor beam intensity, falsely set monitor operation mode, excitations of the beam, etc. In any case, when there was doubt about the quality of the data, the orbit was excluded from the analysis. It is clear though, that every difference orbit unavoidably contains a certain amount of noise which adds incoherently to the "real" orbit drift.

The results for the mean square vertical orbit drift $(dz)^2 = \langle(\Delta z)^2\rangle$ in HERA are shown in Figs. 3 and 4.

Averaging is over all BPMs. An increase of dz with $t^{1/2}$ (t = time), as predicted by the ATL rule, is observed, see next section. A linear fit of $(dz)^2$ *vs.* t yields

$$\langle(\Delta z)^2\rangle = a+bt \qquad (1)$$

with $a = 0.02$ mm^2, $b = 8\cdot 10^{-8}$ mm^2 s^{-1} for HERA-e

and $a = 0.025$ mm^2, $b = 3\cdot 10^{-7}$ mm^2 s^{-1} for HERA-p, respectively.

Here the constant, a, accounts for the above mentioned noise of the orbit measurement, including orbit fluctuations which occur on a time scale shorter than the averaging time of the monitor system (about 2 ms).

Finding the best way to extract PSD values from orbit drift data is not trivial. It is discussed in the next section.

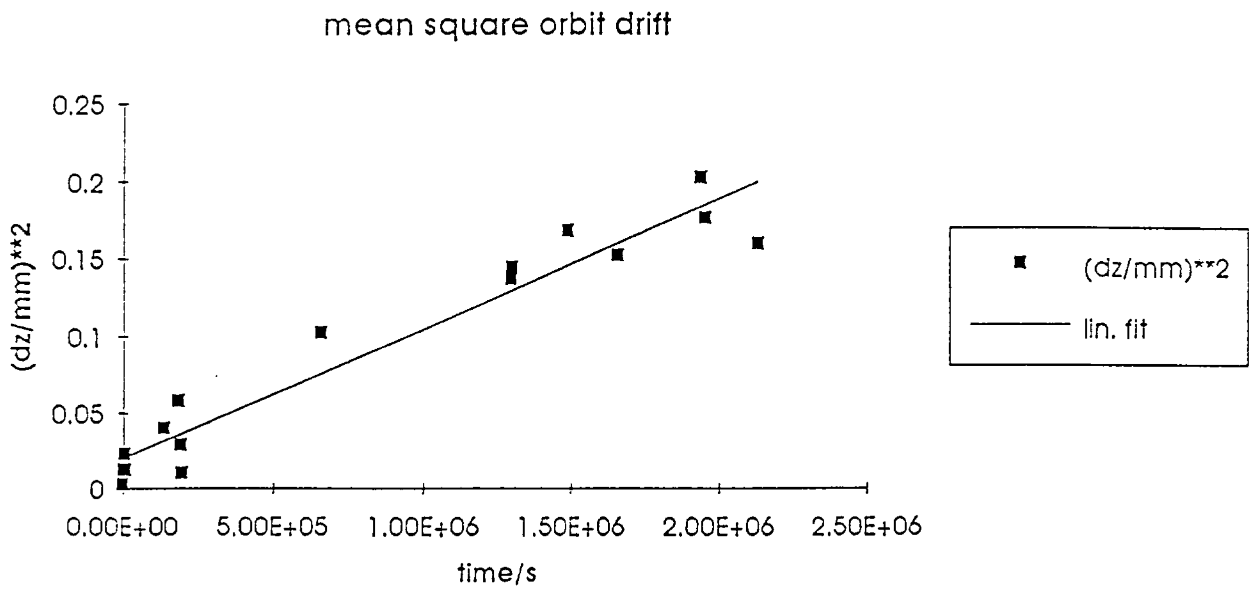

Fig. 3: Mean square difference of closed orbits in the HERA electron ring vs. time obtained from data stored during 1993 luminosity operation.

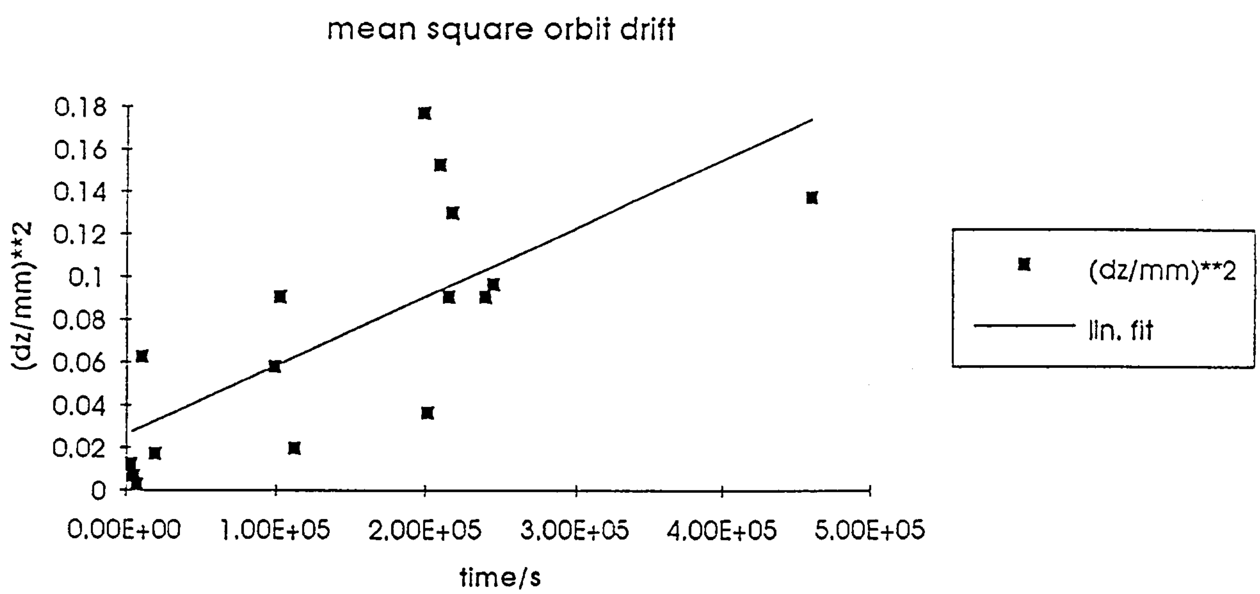

Fig. 4: Mean square difference of closed orbits in the HERA proton ring vs. time obtained from data stored during 1993 luminosity operation.

4) **Discussion**

In general, it is not possible to allocate a single difference orbit measurement (taken at a time difference Δt) to a certain frequency ν_0. However, if an α / ν^2 scaling of the PSD is assumed, the constant α that can be extracted from a single measurement depends in a unique way on the frequency ν_0 allocated.

The scaling

$$\mathrm{PSD}(\nu) \propto \frac{1}{\nu^2} \tag{2}$$

is what one expects if the ground moves in accordance with the ATL rule [12]. This rule has been proposed to describe experimental data on relative displacement of two points, a distance L apart, on the ground surface. According to this rule, the relative rms displacement σ of two points grows with time T and distance L:

$$\sigma^2 = \mathrm{ATL} \tag{3}$$

A is a constant that, according to many measurements, does not depend too much on the site. Several ways to numerically simulate a surface moving in accordance with Eq. (3) have been discussed in ref. 8.

If L is fixed, a possible realization is given by a displacement that changes after each time step δT by a small amount $V \delta T$. After j time steps the displacement is given by

$$z_j = \sum_{i=1}^{j} V_i \, \delta T \tag{4}$$

If the velocities V_i are uncorrelated and independent of time, this stochastic process is called a Wiener process:

$$[V_i \cdot V_{i'}] = V_i^2 \, \delta_{ii'} = V^2 \, \delta_{ii'} \tag{5}$$

$\delta_{ii'}$ is the Konecker Symbol, and [ ] denotes ensemble averaging.

The rms displacement after time $T = j \delta T$ is

$$[z^2] = \sigma^2 = V^2 \delta T T \tag{6}$$

Using the definition

$$A = \frac{V^2 \delta T}{L}, \tag{7}$$

Eq. (6) assumes the form of Eq.(3).

Now we want to relate the quantity $\sigma^2 / T = AL = V^2 \delta T$ to the PSD. By definition, the integral of the PSD over a frequency interval gives the time averaged variance σ_t^2 of the displacement contained in this frequency range. Thus, we have to consider the time average of the displacement described by our model. If $\langle \, \rangle$ denotes time averaging, the time average after N steps can be written

$$\langle z\rangle = \frac{1}{N}\sum_{j=1}^{N} z_j = \frac{1}{N}\sum_{j=1}^{N}\sum_{i=1}^{j} V_i \delta T \tag{8}$$

Note that the (time) average value $\langle z\rangle$ contributes to neither the variance nor the PSD. The *ensemble* average of $\langle z\rangle$ is zero, but its ensemble variance $[\langle z\rangle^2]$ is not, because for each individual realization there is a significant mean value. This is illustrated in Fig. 5, where 40 different realizations with 100 time steps each are shown.

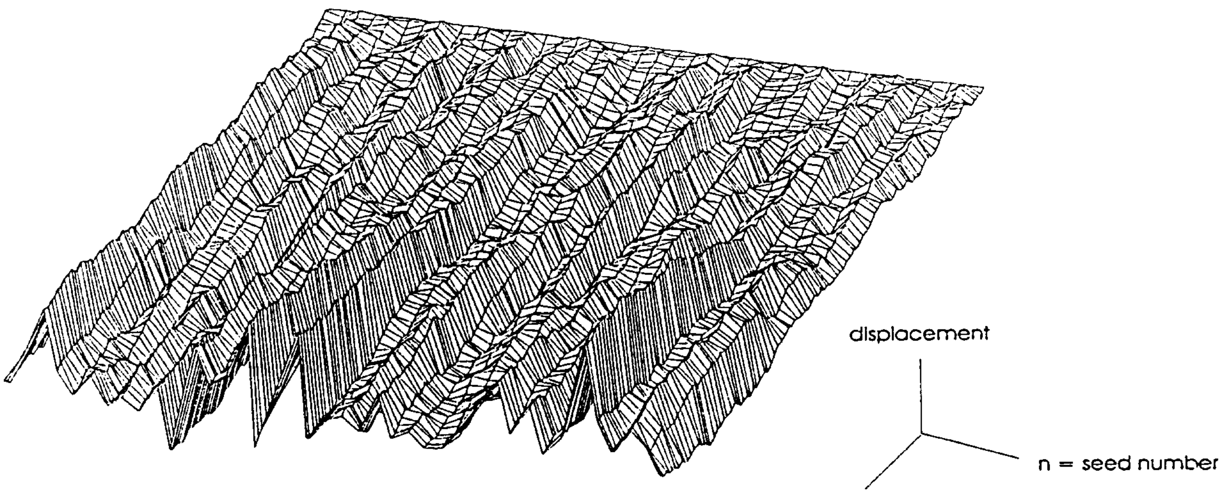

Fig. 5: 40 different realizations of one-dimensional diffusive ground motion with 100 time steps each. Note that the mean value (described by Eq. (11)) is significant in each individual realization. It does not contribute to the power spectrum density PSD.

The variance of an individual realization is

$$\sigma_t^2 = \left\langle (z - \langle z\rangle)^2 \right\rangle = \left\langle z^2 \right\rangle - \langle z\rangle^2$$

The ensemble average of this quantity is

$$\left[\sigma_t^2\right] = \left[\left\langle z^2\right\rangle\right] - \left[\langle z\rangle^2\right] \tag{9}$$

The first term can easily be related to Eq. (6) if we change the order of ensemble and time averaging (with $N\delta T = T$):

$$\left[\left\langle z^2\right\rangle\right] = \left\langle\left[z^2\right]\right\rangle = V^2(\delta T)^2\langle j\rangle = V^2(\delta T)^2\frac{N}{2} = \frac{1}{2}ATL \tag{10}$$

The second term yields, using Eqs. (5) and (8):

$$\left[\langle z\rangle^2\right]=\left[\left(\frac{\delta T}{N}\right)^2 \sum_{j=1}^{N}\sum_{j'=1}^{N}\sum_{i=1}^{j}\sum_{i'=1}^{j'} V_i V_{i'}\right]$$

$$=\left(\frac{\delta T}{N}\right)^2 \sum_{j=1}^{N}\sum_{j'=1}^{N}\sum_{i=1}^{j}\Theta(j'-i)V_i^2$$

$$=\left(\frac{\delta T}{N}\right)^2 \sum_{j=1}^{N}\sum_{j'=1}^{N} V^2 \min(j,j')$$

$$=\left(\frac{V\delta T}{N}\right)^2 \sum_{j'=1}^{N}\left(\frac{1}{2}j'^2+j'(N-j')\right)$$

$$=\left(\frac{V\delta T}{N}\right)^2\left(\frac{N^3}{6}+\frac{N^3}{2}-\frac{N^3}{3}\right)=\frac{N}{3}(V\delta T)^2=\frac{1}{3}ATL \qquad (11)$$

Θ is the stepfunction.

Using Eqs. (10) and (11), Eq. (9) yields

$$\left[\sigma_t^{\,2}\right]=\frac{1}{6}\,\mathrm{ATL}=\frac{1}{6}\,\sigma^2, \qquad (12)$$

i.e. the rms displacement after time T is six times the integral of the PSD measured during that time. Because of the PSD scaling Eq. (2), we get

$$\sigma^2=6\int_{\nu_0}^{\infty}\mathrm{PSD}(\nu)\,d\nu=6\nu_0\cdot\mathrm{PSD}(\nu_0) \qquad (13)$$

The minimum frequency ν_0 to be considered is the bandwidth of the Fourier Spectrum, namely $\nu_0=1/T$. We conclude that each isolated rms difference orbit measurement taken at time difference Δt can be allocated to

$$\mathrm{PSD}\left(\nu=\frac{1}{\Delta t}\right)=\frac{\sigma^2\cdot\Delta t}{6}=\frac{AL}{6\nu_0^{\,2}} \qquad (14)$$

if the scaling law Eq. (2) is assumed. This has been done in Fig. 2 (after normalization for $\beta=1\,\mathrm{m}$ and correction for noise contribution).

As indicated by the straight line in Fig. 2, the HERA orbit motion follows the *ATL* scaling quite well within a frequency range between $5\cdot10^{-7}$ Hz and 1 Hz. This is in agreement with direct observation of ground motion, see e.g. ref. 6. With measurements presented in Fig. 2, however, we have a much more direct access to what really matters for colliding beams facilities: the spectrum of orbit motion. This eliminates all uncertainties related to magnet support resonances, correlation properties of quadrupole motion and the like. It should be stressed again that the HERA electron and proton rings have completely different magnet lattices but yet fit nicely into the same plot.

Finally, we want to determine the constant A from our measurement. To this end, we have to evaluate the role of the distance L of Eq. (3) on the beam orbit. The orbit response to elastic ground waves exhibits resonance-like behaviour if the ground wave length equals the betatron wave length λ_β or the *FODO* cell length of the storage ring [13, 14], respectively. A similar result has been obtained for linear collider lattices [2]. The response to wave lengths much larger than λ_β is effectively suppressed for either kind of accelerator. Since for most magnetic lattices, λ_β is considerably smaller than 1000 m, and assuming a phase velocity of ground waves of 300 m/s, one concludes that frequency components below 1 Hz are not expected in the beam spectrum, as long as elastic waves are considered. If dissipative ground drift following the ATL rule is taken into account, the average orbit response of a regular *FODO* lattice is equal to *uncorrelated* quadrupole motion if the *FODO* cell length L_{FODO} is adopted for L [8]. For the HERA electron ring, $L^e{}_{FODO}$=23.5 m, while for the proton ring, $L^p{}_{FODO}$=47 m. Deviations of the HERA lattices from a periodic *FODO* structure in the straight sections do not have a significant effect on our analysis. Thus, for the same PSD of ATL ground motion one expects the HERA-p orbit PSD two times larger than the HERA-e PSD. Therefore, to relate all data included in Fig. 2 to the same lattice sensitivity (namely that of HERA-e), HERA-p PSD data was divided by two before plotting in Fig.2.

The sensitivity of the HERA-e luminosity optics to random uncorrelated vertical motion of the quadrupoles σ_q is given by

$$\sigma_{c.o.} = 31.3\,\sigma_q \tag{15}$$

A satisfactory fit of the measured PSD is given by

$$\mathrm{PSD}_{orbit} = \frac{(4\pm 2)\cdot 10^{-16}\,\mathrm{m}^2\cdot\mathrm{Hz}}{\nu^2}$$

Taking the average beta function $\beta = 38\,\mathrm{m}$ and Eqs. (14, 15) into account, we get

$$A = \frac{6}{23.5\,\mathrm{m}}\cdot\frac{38}{31.3^2}\cdot(4\pm 2)\cdot 10^{-16}\,\mathrm{m}^2\cdot\mathrm{Hz} = (4\pm 2)\cdot 10^{-6}\,\frac{\mu\mathrm{m}^2}{\mathrm{m}\cdot\mathrm{s}}$$

Compared to the "typical" value of $10^{-4}\,\frac{\mu\mathrm{m}^2}{\mathrm{m}\cdot\mathrm{s}}$ quoted in Ref. [8], our value is quite small. This is remarkable the more so since it has been assumed in our analysis that the orbit motion is exclusively due to diffusive ground motion. In any case it suggests that the ground noise spectrum is quite favourable at Hamburg with respect to large accelerator stability, at least as long as frequencies below 1 Hz are considered.

As indicated by Fig. 2, above 1 Hz the orbit motion PSD exceeds the level expected from the diffusive ground motion model (ATL). In this frequency range, elastic ground waves may have a large impact on orbit motion and can easily explain the observed spectrum [1]. As an origin of these waves, so-called cultural noise plays an essential role which is naturally quite large in a big city like Hamburg.

Acknowledgements

The authors gratefully acknowledge the help of the HERA operation staff in gathering the experimental data. They are also indebted to V. Shiltsev and H. Mais for valuable discussions.

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