GROUND MOTION IN THE INTERACTION REGION

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Abstract

Ground motion and according quadrupole vibration is of great importance for all Linear Collider schemes currently under study, since these effects lead to orbit jitter and therefore luminosity degradation. To estimate the effects of final focus quadrupole jitter for the Linear Collider TESLA, ground motion measurements were performed in one interaction region of the electron-proton collider HERA, which is considered a realistic environment to study vibrations.

1 Introduction

Future linear colliders require beam sizes at the interaction point (IP) of roughly $\sigma_x = 100\,\mathrm{nm}$ width and $\sigma_y = 10\,\mathrm{nm}$ height to achieve the high design luminosities of some $10^{34}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$. Since beam orbit vibrations due to ground motion and according quadrupole jitter lead to beam offsets at the interaction point and therefore luminosity degradation, beam-based feedback systems are essential to keep the beams in collision. In the case of TESLA a fast bunch-to-bunch feedback system is foreseen, taking advantage of the very long bunch trains (2820 bunches) and the large bunch spacing (337 nsec) [1]. As simulations show, this system is capable of compensating an initial vertical relative beam offset of $100\sigma_y$ within just 3% of the bunch train.

Nevertheless, it would be desirable to be able to bring beams with shorter bunch trains into collision, for example during the commissioning phase. As experience at the SLC shows, pulse-to-pulse feedback systems are capable of maintaining collisions in the frequency band below some 1/25 of the repetition rate of the linac. In the case of TESLA with $f_{\mathrm{rep}} = 5\,\mathrm{Hz}$ pulse-to-pulse feedback would be applicable below some 0.2 Hz. Therefore it must be ensured that the final focus quadrupoles on both sides of the interaction point do not vibrate with rms amplitudes higher than some fraction of the IP beam size in the frequency band above these 0.2 Hz.

To relax these tolerances, one could increase the beam sizes at the interaction point for this purpose. As a rule of thumb, displacements Δx, Δy of the final focus quadrupoles translate roughly into the same orbit displacement at the interaction point.

Ground motion measurements have been performed in one HERA interaction region in order to estimate final focus quadrupole vibration amplitudes in the future TESLA Linear Collider which is planned to be built at DESY. For this purpose two seismometers were installed in the accelerator tunnel on both sides of the interaction point, each of them at a distance of about 17 m from the IP, see Figure 1.

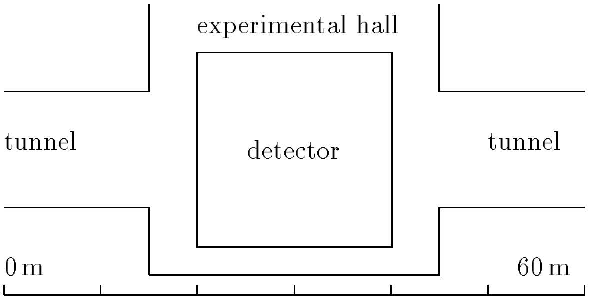

Figure 1: Schematic side view of HERA Hall East with the detector and the accelerator tunnel ends. For the measurements presented in this paper, the seismometers were placed in the two tunnels, each of them at a distance of roughly 17 m from the interaction point.

2 Instrumentation

For all measurements presented in this paper GURALP CMG-3T broadband seismometers [2] have been used. While the mechanical resonance frequency of these instruments is 0.5 Hz, the transfer function is modified by an internal PI feedback loop, thus resulting in a transfer function equivalent to a mechanical resonator of 360 sec period length, or 2.78 mHz resonance frequency. The upper frequency limit is determined by an analog 50 Hz filter.

In order to prevent signal contamination between the sensors and the readout electronics, the primary analog outputs are converted to digital signals by 16 bit A/D converters attached directly to the seismometers, thus avoiding the necessity of signal transfer on long cables. The internal sampling rate of these ADCs is 2 kHz in order to avoid aliasing. This sampling rate is reduced to 50 Hz by means of digital filters. An additional digital lowpass filter can be set to cutoff frequencies of 5 Hz, 10 Hz, or 20 Hz, respectively.

The internal noise level of these instruments was measured by placing them side-by-side, so both of them mesured the same input ground motion signal. Since only the frequency range above 1 Hz was of interest, no attempt was made to thermally insulate the probes. An example of the primary velocity output signals is depicted in Figure 2.

The obviously nice agreement of the corresponding sensor signals can be quantified using the coherence function

$$|\gamma(\omega)| = \frac{|\langle X_1(\omega) X_2^*(\omega)\rangle|}{\sqrt{\langle X_1(\omega) X_1^*(\omega)\rangle \langle X_2(\omega) X_2^*(\omega)\rangle}}. \qquad (1)$$

Here $X_1(\omega)$, $X_2(\omega)$ denote the Fourier transforms of the two respective input signals $x_1(t)$, $x_2(t)$, while the asterisk indicates the complex conjugate. The brackets $\langle \ldots \rangle$ indicate averaging over different data samples.

The resulting coherence function for all three directions is shown in Figure 3. The sharp drop at some 12 Hz occurs due to the internal digital filter set to 10 Hz. Between roughly 0.1 Hz and 12 Hz the coherence is close to unity, while below 0.1 Hz it decreases due to lack of thermal insulation.

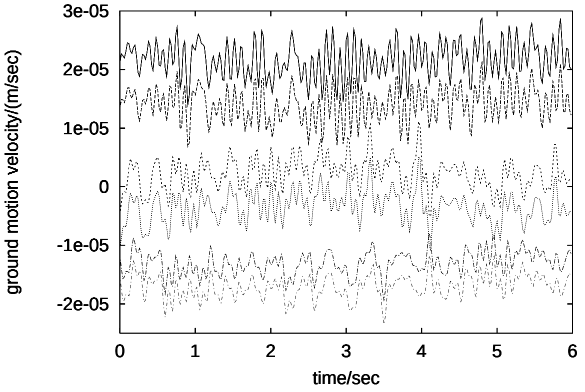

Figure 2: Primary velocity output signals of the two instruments when placed side-by-side. The two upper curves show the signals of the two vertical sensors, the 3rd and 4th line correspond to the motion in one transverse ("North-South") direction, while the two lower lines show the signals in the perpendicular direction ("East-West"). In order to get clearly distinguishable lines in this plot, a certain offset has been added to each signal here.

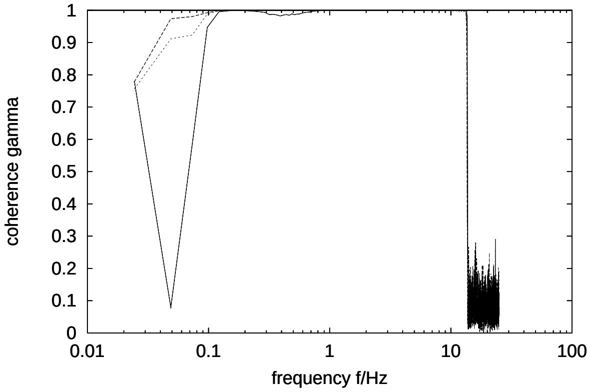

Figure 3: Measured coherence functions $|\gamma(\omega)|$ in all three directions for the sensors placed side-by-side.

The rms value of the difference signal $x_1(t) - x_2(t)$ in the frequency band from f_0 to infinity can be determined from the corresponding power spectrum $\Phi_{1,2}$ as

$$\sigma(f_0) = \sqrt{\int_{2\pi \cdot f_0}^{\infty} \Phi_{1,2}(\omega)\, \frac{\mathrm{d}\omega}{2\pi}}. \qquad (2)$$

The resulting rms difference signal as a function of the lower cutoff frequency f_0 is depicted in Figure 4. Though the coherence function is very close to unity in the frequency region above 1 Hz, the rms value of the difference signal for the same frequency region is roughly 10 nm.

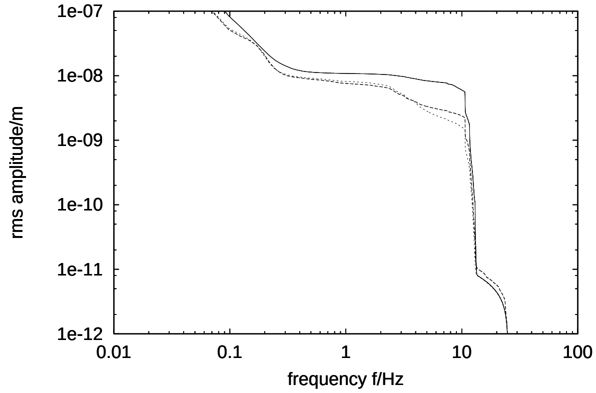

Figure 4: rms value of the difference signal of each pair of corresponding sensors placed side-by-side. In the vertical direction (upper, solid line), the rms difference signal is significantly larger than in the two horizontal directions.

3 Measurements

Since the beams in a Linear Collider are flat with an emittance ratio of typically $\epsilon_y/\epsilon_x \approx 10^{-2}$ vertical ground motion is much more severe in terms of orbit motion and accordingly luminosity degradation due to beam offsets at the interaction point. Nevertheless, ground vibration in all three dimensions, vertical, horizontal, and longitudinal along the beamline, has been measured.

Any kind of seismometer basically consists of a pendulum with a certain resonance frequency. Therefore these instruments respond to acceleration of the ground. When the sensor is tilted by an angle ϕ with respect to the vertical direction, an additional acceleration $a = g \cdot \sin(\phi)$ acts on the horizontal pendulum, where $g = 9.81\,\mathrm{m} \cdot \mathrm{sec}^{-2}$ denotes the gravitational acceleration. Therefore measured amplitudes of ground motion in the horizontal direction tend to over-estimate the real ones.

In order to study the relative motion of the two tunnel ends around the interaction point with respect to each other, two seismometers were installed in the HERA tunnel at a distance of 17 m on either side of the interaction point. Output data of both instruments were simultaneously recorded for 12 hours.

3.1 Vertical motion

With the setup described above, the spectrum of vertical ground motion in a single point was obtained from the output signal of one probe. To determine the effect of cultural noise like traffic on a nearby main road and other human activities, two data sets were analyzed – one measured during the night from 2:00 to 3:00 a. m., and the other one obtained during the rush hour between 8:00 and 9:00 a. m. The corresponding power spectra of vertical ground motion are shown in Figure 5.

The effect of cultural noise occurs clearly in the frequency region above roughly 1 Hz, leading to an enhancement of the corresponding rms amplitudes in this frequency region by roughly a factor of two, see Figure 6 (upper graph).

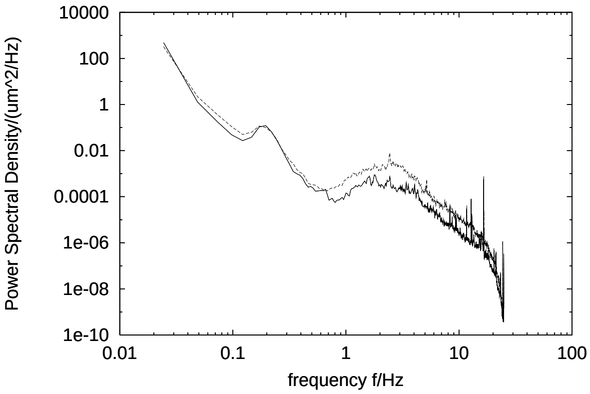

Figure 5: Vertical ground motion spectra obtained in a single point under quiet conditions during the night (solid line) and during the rush hour (dashed curve).

The lower graph of Figure 6 shows the rms value of the relative vertical motion of the two tunnel ends, as measured by the two seismometers. As a comparison to the upper part of Figure 6 shows, the

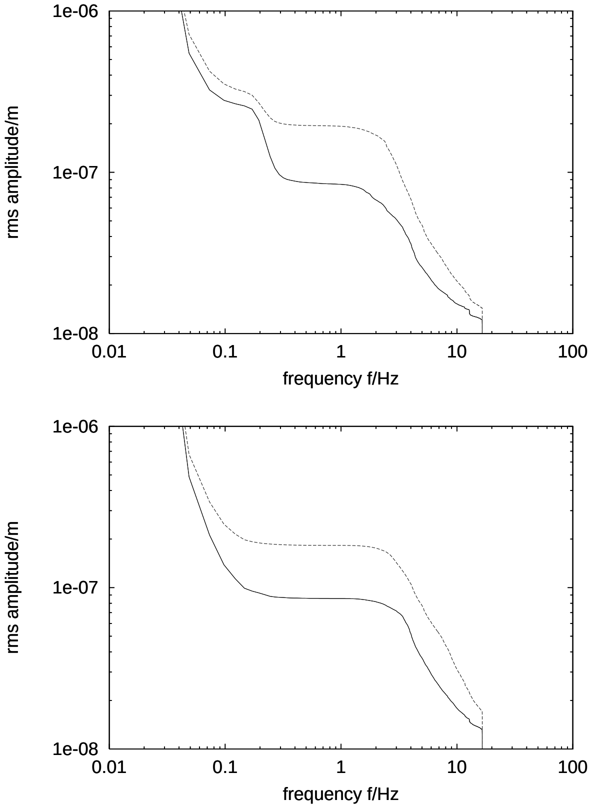

Figure 6: rms vertical ground motion amplitudes in the frequency band from f_0 to 25 Hz as a function of the lower frequency limit f_0 under quiet (solid line) and noisy conditions (dashed curve). The upper plot shows the rms value in a single point as calculated from the spectra shown in figure 5. In the lower plot, the rms value of the relative motion of the two tunnel ends over a distance of 34 m is given.

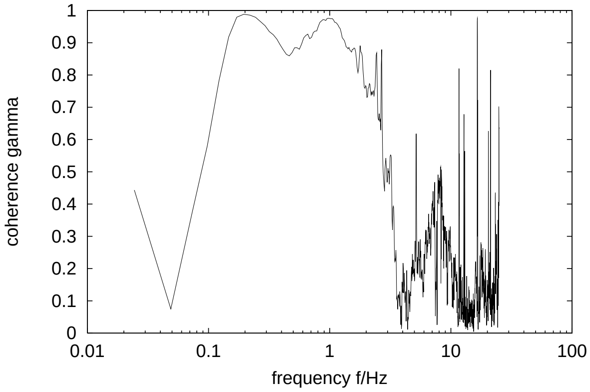

Figure 7: Coherence $|\gamma|$ of the vertical motion of the two tunnel ends over a distance of 34 m.

rms amplitude of the relative motion above roughly 1 Hz is approximately equal to the corresponding value obtained in a single point.
In the case of completely independent motion of the two tunnel ends, the rms value of the relative motion would be a factor $\sqrt{2}$ larger than the corresponding value in a single point. This is indeed the case for frequencies above some 4 Hz. This fact is also reflected in the coherence of the two signals, Figure 7. Above roughly 3 Hz to 4 Hz the coherence drops to values close to zero. Therefore the increase in the rms value of the relative motion in the frequency band between 1 Hz and 4 Hz is smaller than the corresponding value for a single point. In the overall effect, the larger increase above 4 Hz and the smaller increase between 1 Hz and 4 Hz in the case of the difference signal just cancel, leading to similar values at 1 Hz as compared to the motion in a single point.
As expected, the microseismic peak around 0.14 Hz vanishes in the difference signal due to the very long wavelength (about 20 km) of this motion.

3.2 Horizontal motion

Data analysis of the relative motion in the horizontal direction, perpendicular to the beam direction, gives similar results as for vertical motion, see Figure 8. Under quiet conditions during the night the rms value of the relative motion is roughly 80 nm in the frequency band above some 0.1 Hz. This value increases to some 200 nm during the rush hour between 8:00 a. m; and 9:00 a. m.

3.3 Longitudinal motion

Though beam dynamics in a Linear Collider is quite insensitive to longitudinal motion of quadrupoles, even in the interaction region, relative motion of the two tunnel ends in the direction of the beamline has also been studied. Figure 9 shows the primary velocity output signals of the two seismometers at 34 m distance. Both signals are rather similar, thus

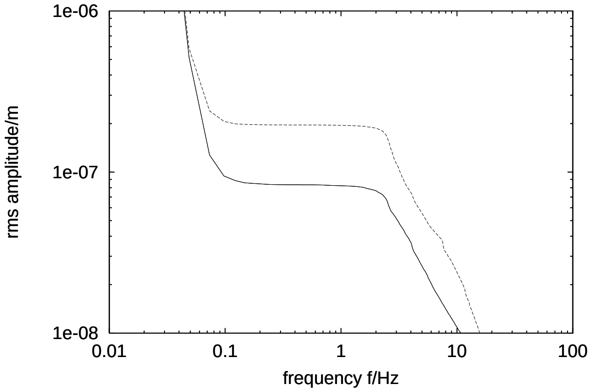

Figure 8: rms amplitudes of the relative horizontal motion of the two tunnel ends over a distance of 34 m under quiet (solid line) and noisy conditions (dashed line).

indicating coherent, synchronous motion. This fact is also reflected in Figure 10 which depicts the coherence function of the two longitudinal motion signals. Compared to the coherence in the vertical direction, Figure 7, the coherence stays high at frequencies up to 4 Hz.
Possible explanations for this phenomenon are cooling water pressure waves in the longitudinal direction, as well as a stronger mechanical coupling of motion along the accelerator tunnel.

4 Conclusion

Since the motion of the two tunnel ends around the interaction point is uncorrelated at frequencies above roughly 3 Hz, and rms amplitudes of relative motion of the two ends with respect to each other exceed the nominal IP beam size of the TESLA Linear Collider by far, active stabilization of mechanical final focus element vibration is necessary for operation modes without fast orbit feedback [3].

5 Acknowledgements

I would like to thank R. Brinkmann for useful discussions, and S. Herb for help with the HERA network environment.

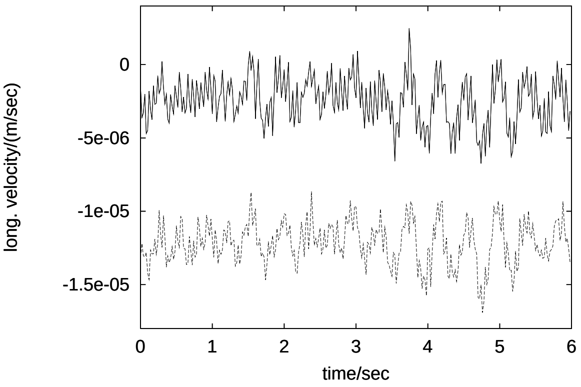

Figure 9: Longitudinal ground motion velocity measured by two seismometers at 34 m distance.

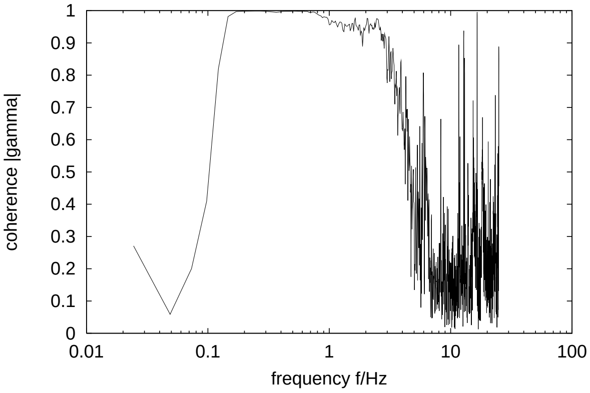

Figure 10: Coherence function of the longitudinal motion as measured by two seismometers at 34 m distance.

References

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[2] CMG-3T Operation Manual, Guralp Systems Ltd., Aldermaston, U. K., 1993

[3] C. Montag, Active Stabilization of Mechanical Quadrupole Vibrations for Linear Colliders, Nucl. Instr. Meth. A 378 (1996), 369-375