EFFECT OF VERY LOW FREQUENCY GROUND MOTION ON THE LHC

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Abstract

The power spectrum of ground motion noise is known to increase extremely fast with decreasing frequency. The wavelength of groundwaves will eventually become larger than the machine dimensions. Ideally the effect should disappear for these long waves since all the elements of the machine are supposed to move in the same way. In fact this is not the case since these long powerful waves loose coherence and therefore relatively slow orbit drifts are to be expected. A model is presented based on geophysical arguments and it is confronted with observations concerning slow orbit changes in large existing accelerators.

1 INTRODUCTION

The power of ground vibrations increases steeply with decreasing frequency. This can lead to non-negligible orbit deformations if the motion of accelerator quadrupoles is uncorrelated for very low frequencies. It turns out that this effect is much larger than the plane wave excitation where the ground motion wavelength matches the betatron wavelength[2,3] and which has a similar optical amplification factor. Indeed, only frequencies in the order of 1 *Hz* are involved in the latter case and the spectral power is extremely small such that the beam separation in the LHC due to this is less than 1/1000 of the *rms* beam size. The spectrum of ground motion (Fig.1), measured in several places around the world, looks very similar after elimination of local cultural noise.

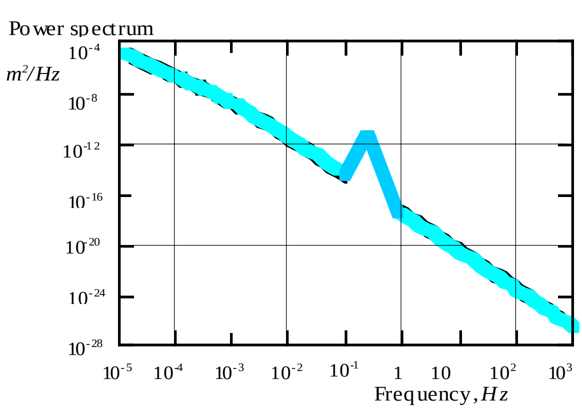

Figure 1 : Typical ground-motion power spectrum.

The aim of this paper is to examine the possible effects on the closed orbit of the LHC covering a frequency range of a few *Hz* down to very low frequencies where the power of the vibrations has increased considerably. Non-correlated, or partially correlated movements, are observed at short distances [4,9,10,16,17,18] in spite of wavelengths that are much longer. Orbit changes related to this can be measured in a large machine as LEP but the consequences are harmless since LEP is a two-beam single bore machine where the orbit effect cancels between the two beams. The same impunity does not exist in the LHC where the orbits of the two constituent rings may wander apart and hence partially separate the beams, causing loss of luminosity if no correcting action is taken. The observation of low frequency non-correlated motion has lead to the formulation of the *ATL* scaling law[4]. This law is not valid for frequencies above ~ 1 *mHz*. This is unfortunate for the LHC since it misses the 'fast' orbit changes that may be more difficult to handle. For that reason a model is proposed based on geo-physical arguments valid both for 'low' and 'high' frequencies.

2 BASIC GROUND MOTION MODEL

The *ocean well* spectrum that stands out in Fig.1 and extends from less than 0.1 to 1 *Hz* is known to be coherent[6,13,20]. That is not surprising. Indeed, the high-pass cut-off frequency of ~0.2 *Hz* together with the speed in water (1.5 kms^{-1}) suggest a limiting wavelength in the oceans of around ~7 *km*, not very different from the depth of the abyssal plain (between 3 and 5.5 *km*[5]). Clearly, these waves are surface waves and it is very difficult to imagine geological fault structures that would cause these waves to loose coherence over a fraction of a wavelength. Thus it is safe to remove the powerful ocean well spectral peak from the model since only the uncorrelated movements are a concern.

The remaining spectrum tends to fall with frequency as f^{-3} at frequencies above the *ocean hum*, while the frequency slope reduces to f^{-2} well below this [9]. Notice that the wavelengths involved in the latter case exceed 25 *km*. However, clear evidence exists on lack of correlation (randomness) of very low frequency noises at distances much less than the wavelength. The *ATL* scaling law matches the low frequency f^{-2} slope. It states that the random (integrated) relative motion between two points is proportional to their distance *L* while the proportionality factor *A* depends on the local properties related to the randomness of differential ground deformation. However, this scaling law yields non physical results above a certain frequency in the sense that it predicts differential movements that are larger than the absolute ones [15]. A different model is proposed. The first part is concerned with a general formulation of the motion of a single point, in principle valid everywhere, while the second part will describe the randomisation of the low frequency earth movements.

The maximum seismic length of the earth is ~1500 *s*[1]. The seismic 'depth' of the earth is about 1/3 of this [5] and hence defines a *cut-off* frequency of f_{co}~2 *mHz*. This is confirmed by the far away amplitude response of earthquakes. Fig.2 is taken from [15] and is a typical example. The response is compatible with a high-pass filter behaviour with an amplitude cut-off ω_{co}~1/400, hence a power f_{co}~0.8 *mHz*. This suggests an average high pass cut-off f_{co} ~1.5 *mHz*. It is worthwhile to note at this point that the seismic wave attenuation with distance is very small.

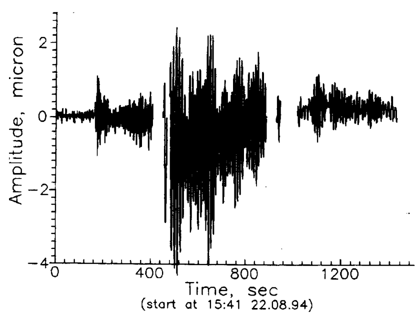

Figure 2 : Typical faraway response to earthquake. The fast oscillation is the response of the oceans pounding on the continents.

The model invokes a source with a f^{-3} frequency slope. That source actually exists: earthquakes. The examination of a substantial body of phenomenological material has lead to the Gütenberg- Richter law[1,5]:

$$\log(n) = -M, \qquad (1)$$

where *n* is the number of earth quakes in a given area with a magnitude *M* or larger. It is easy to see that this law formulated in that way corresponds exactly with a f^{-3} power density spectrum. The response of the earth to the seismic excitation in terms of a power density can then be expressed by the following function which combines the high-pass filter transfer function and the source spectrum:

$$\frac{dx^2}{df}(f) = \frac{k_{gm}}{f^2\sqrt{f_{co}^2 + f^2}}\left[m^2\ Hz\right]. \qquad (2)$$

The factor k_{gm} is a non-local quantity that varies from ~10^{-18} m^2/s^2 to ~10^{-16} m^2/s^2 depending on the state of global excitation. This power spectrum is shown in Fig.3 together with a number of observations taken from [7].

3 RANDOMNESS

The question now arises how two points, close together (much less than a wavelength), can move independently? From earthquake observations it is known that the depth of the sources is very often ~30 *km* (the Moho discontinuity[5,8]). This and the geographical spreading of the sources may explain the fact that the response can be incoherent while, as was pointed out before, shallow surface waves (ocean pounding on continental shelf) are always coherent. In fact it is known that the randomness of the differential movement at a given location depends strongly on the fractured state of the site. The surface behaves as a number of independent blocks that are excited from below. That is borne out clearly by the experimental observation on two points on either side of a construction joint[17].

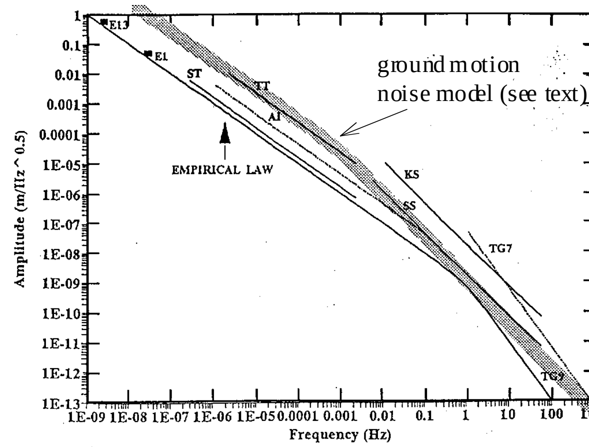

Figure 3 : Comparison with basic ground-motion model and observations. The line marked 'empirical law' is related to the model proposed in [7].

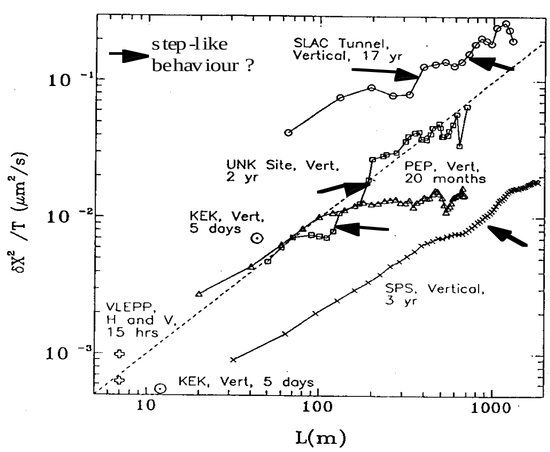

Figure 4 : Differential movement as a function of distance in a number of machines for several observation periods.

This then leads naturally to the notion of coherence length L_{ch}. That length has to be understood in a statistical sense: two points at a distance smaller than L_{ch} are likely to move coherently, while two points which are further away are likely to move incoherently. The notion of coherent length is well suited for accelerators where local differences will average out. Indications of coherence length can be found in Fig.4 taken from [12]. The power of the differential motion seems to jump to larger values above a given distance in each site. This distance can be taken as the manifestation of the coherence length. It varies from 100...200 *m* (UNK) to 600 *m* (SPS).

4 OBSERVATIONS WITH BEAM

The coherence length can be determined from orbit measurements. The only assumption to be made concerns k_{gm}. It was put at $k_{gm}= 10^{-18}\ m^2/s^2$. The integration of (2) yields the power of displacement of a single element:

$$dx^2(t) = \frac{k_{gm}}{f_{co}^2}\left(\sqrt{1+\left(f_{co}t\right)^2}-1\right). \qquad (3)$$

The orbit deformation can be found simply by multiplying (3) with the optical amplification factor $O_A=(\beta Kl/2sin(\pi q))^2N$, where β is the optical function at a quadrupole and Kl its integrated focalisation force. N is the number of uncorrelated blocks around the accelerator which is at the maximum the number of F or D quadrupoles. From [11] for HERA-proton and HERA-electron and from [19] for LEP (known effect of superconducting insertion quadrupoles removed) it was possible to estimate the local value of L_{ch} : 250 *m*, 280 *m* for the HERA machines and 130 *m* in LEP. Fig.5 shows the result of the measurement in LEP.

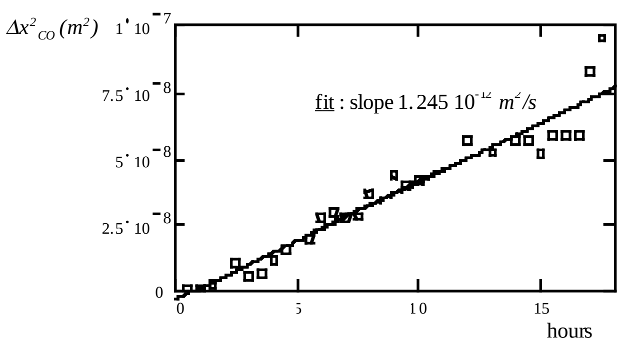

Figure 5 : Orbit deformation Δx_{co}^2 versus time in LEP, where fit is compatible with $L_{ch}=1.6\ L_{cell}=$ 130 *m*.

5 APPLICATION TO LHC

Equation (3) spans a large time/frequency scale. Long term misalignments can be calculated and are in good agreement with observations [14]. It also allows the computation of the *rms* half separation between the beams as a function of time. This can be expressed in terms of the *rms* beam size σ. It is to be expected that once in a while the global system is highly excited ($k_{gm}= 10^{-16}\ m^2/s^2$). In that case the half separation can reach nearly 0.5 σ in 500 *s* where the effect is linear in time. Clearly procedures must be ready in order to cope with such a rate of separation. In normal, quiet conditions the rate is a factor of 10 less and in that condition the same separation is reached after nearly 8 *hours*.

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