MEASUREMENT OF GROUND VIBRATIONS AND CALCULATION OF THEIR EFFECT ON THE DIAMOND LIGHT SOURCE

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Abstract

Due to the very small beam emittances with which they operate, all 3rd generation synchrotron radiation sources are particularly concerned with the effects of ground motion on accelerator components. Even small movements of magnetic elements of the accelerator, particularly the quadrupoles, will lead to problems with photon beam stability.

Using a state-of-the-art seismometer, measurements have been made over the Daresbury Laboratory site, during both normal site operations and when the levels of cultural and technical noise are particularly low.

These measurements can then be used to inform the preliminary design decisions being made for the 3 GeV synchrotron radiation source, DIAMOND.

The predicted effect of the measured ground vibrations on an example DIAMOND lattice is also presented. These results can then be used in the design of systems to mollify vibration effects, such as magnet girders and feedback damping.

1 INTRODUCTION

3rd generation synchrotron radiation sources are very sensitive to effects of ground motion. Small movements of magnetic elements of the accelerator, particularly the quadrupoles, will lead to problems with photon beam stability. For a synchrotron light source a typical specification can be given that the electron beam motion must not exceed 10% of the beam size in either plane. This paper presents measurements of ground motion at Daresbury Laboratory and calculates its effect on an example DIAMOND lattice.

2 MAGNET MOTION

2.1 The Effect Of Magnet Motion

Misalignments in the storage ring elements in synchrotron light sources cause closed-orbit errors in the position of the electron beam which must be corrected for. Vibration gives rise to deflections in the electron beam in the same way that misalignments do, albeit the deflection is transient. At higher frequencies the effect of vibration is to effectively degrade the brightness of the extracted photon beams, whilst at lower frequencies the motion can cause noise problems in experimental detector systems; the break-point between these two regimes depends upon the experiment.

2.2 Calculating the Beam Motion

The effect of a particular type of element motion can be quantified by an amplification factor

$$A_s = \frac{\left\langle \Delta s^{CO} \right\rangle_{rms}}{\left\langle \Delta j \right\rangle_{rms}} ,$$

where $\left\langle \Delta j \right\rangle_{rms}$ is the rms change in some set of co-ordinates (i.e. position, tilt angle, roll angle, pitch angle), $\left\langle \Delta s^{CO} \right\rangle_{rms}$ is the resulting rms closed-orbit deviation and the index s refers to the plane under consideration (horizontal or vertical). For static deviations the three main sources of closed-orbit error are:

1. Transverse misalignment of quadrupoles
2. Roll angle misalignment of dipoles
3. Fractional field imperfection in the dipoles

With ground vibration, the dominant effect will be to produce lateral movements of the elements rather than to induce rotations within them, so that only the first of the three sources above is relevant. Assuming that vibration is distributed randomly around the accelerator, the generated orbit distortion at a particular location i from a set of j quadrupoles with an rms vibration amplitude of $\left\langle \Delta a \right\rangle_{rms}$ is

$$\Delta x_i = \left\langle \Delta a \right\rangle_{rms} \frac{\sqrt{\beta_i}}{2\sqrt{2}\sin \pi Q} \sqrt{\sum_j \left(kl\right)_j^2 \beta_j} ,$$

where Q is the betatron tune and $\left(kl\right)_j$ the integrated strength of quadrupole j; the calculation can be performed in either the horizontal or vertical plane. This distortion is then scaled by the beam size at the observation point, given by

$$\sigma_i = \sqrt{\varepsilon \beta_i + \sigma_\varepsilon^2 \eta_i^2}$$

(ε is the emittance, σ_ε the dispersion and η_i the energy spread). It can be shown that for lattices that are broadly similar to each other, the sensitivity of the beam to vibrations scales roughly as

$$\frac{\Delta x_i}{\sigma_i} \propto \sqrt{\frac{N}{\varepsilon}} \qquad (1)$$

where N is the number of quadrupoles in the lattice.

3 GROUND MOTION MEASUREMENTS

3.1 Measurement Method

The measurements presented in this paper were made using a Guralp CMG-3T seismometer [1]. This is an hermetically sealed three-axis device that produces a digitised voltage proportional to the velocity measured in each axis. In each of the three axes (east-west, north-south and vertical) the position of an inverted pendulum is capacitively measured; coils are then used to drive the pendulum back to its centre position. The device output is digitised, buffered and read out via an RS-232 link to a PC for saving. The instrument was placed in a pit approximately 1 m deep and covered with a temporary shelter; the depth of excavation was sufficient to expose the Bunter sandstone upon which the laboratory is built. A layer of concrete was used to provide a uniform surface for the instrument.

3.2 Analysis of Measurements

In general, the ***power spectral density*** (PSD) of a noise signal is defined as

$$S_x(f) = 2\lim_{T\to\infty}\frac{1}{T}[X(f)]^2$$

where the Fourier transform of the noise signal is defined as

$$X(f) = \int_{-T/2}^{T/2} x(t)e^{-2\pi ift}\,dt \cdot$$

However, if as in our case the instrument used records velocity then the ***displacement power spectral density*** can be obtained from the velocity data by

$$S_x(f) = \frac{S_v(f)}{4\pi^2 f^2} \cdot$$

This is because although displacement and velocity are related by $v = dx/dt$, their Fourier harmonics are related by

$$V(f) = -2\pi if\,X(f) \cdot$$

MATLAB [2] was used to apply the calibration, calculate the power spectral density (applying suitable windowing and smoothing functions) and convert between velocity and displacement using the relationships above.

3.3 Results

Example results of three measurements are shown in Fig. 1. Samples were collected at a rate of 200 per second and subsequently 2^{17} samples were transformed to give the displacement power spectral density, shown here for the vertical axis only. The measurement locations were adjacent to the building that houses the existing Synchrotron Radiation Source (SRS); on the edge of the site adjacent to a busy road; and one measurement on a quiet part of the site taken during the night.

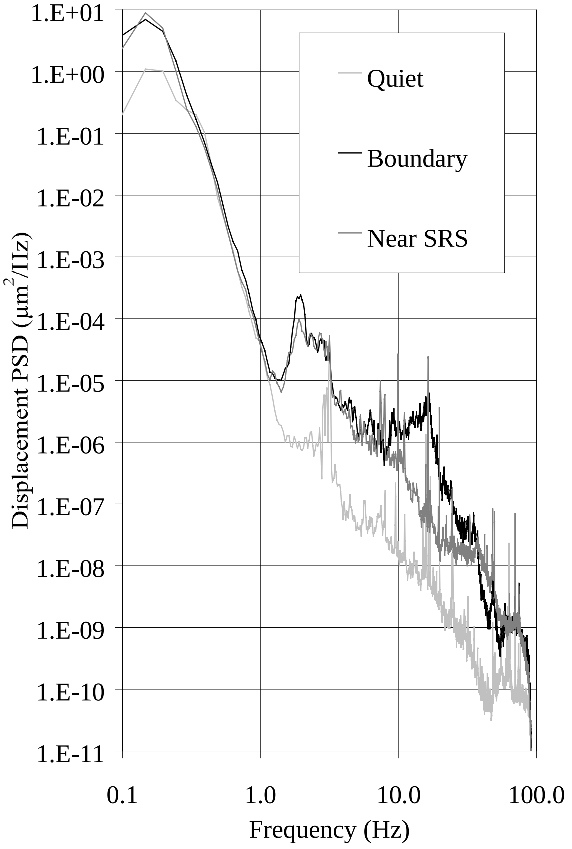

Figure 1: Displacement PSD measured at Daresbury Laboratory

It can be clearly seen that the level of ***cultural noise,*** which is significant at frequencies above a few hertz and much of which emanates from outside of the site, drops dramatically during the night time period. The proximity of the road adds a broad range of components above 10 Hz, while specific peaks, some of which are due to the operation of the SRS, are visible in all traces. An example of this ***technical noise*** would be the cryoplant compressor at around 18 Hz.

4 EFFECT ON DIAMOND

The magnitude of the vertical ground motion can be calculated from these measurements as

$$z_{rms}(f) = \sqrt{\int_f^{f_{\max}} S_x(f)\,df}$$

which gives the sum of the rms displacement observed for all frequencies above *f*.

For the purposes of this calculation, the DIAMOND specification is 24 cell, 3 GeV, with source points predominantly being within insertion devices (ID). The specification value for horizontal-vertical coupling in DIAMOND of 1 % is also assumed. However, several 3rd-generation light sources are now operating with coupling values as little as 0.3 %, and this would be a similar goal for DIAMOND after a period of operation.

DIAMOND has a combination of standard and long ID straight sections. The beam sizes and calculated amplification factors (for 1 % coupling) are shown in Table 1.

Table 1: Beam sizes and amplification factors

Straight Type	Beam size, σ (μm)		Amplification Factor	
	Horizontal	Vertical	Horizontal	Vertical
Standard	79.9	7.82	45	20
Long	166	15.6	102	41

The movement of the beam for a particular rms displacement, expressed as a percentage of beam size in that plane, is approximately independent of straight type. Figure 2 shows the calculated vertical beam movements, expressed as a percentage of beam size based on the real ground motion measurements presented earlier. For a DIAMOND storage ring of 150 m diameter on the Daresbury bedrock the quadrupoles will move incoherently for frequencies above about 1.5 Hz, increasing the beam movement by $\sqrt{N}$ compared to a single quadrupole. Fig. 1 shows the beam movement in the centre of the standard straights on DIAMOND that would be seen for each of the three sets of data, expressed as a percentage of the beam size.

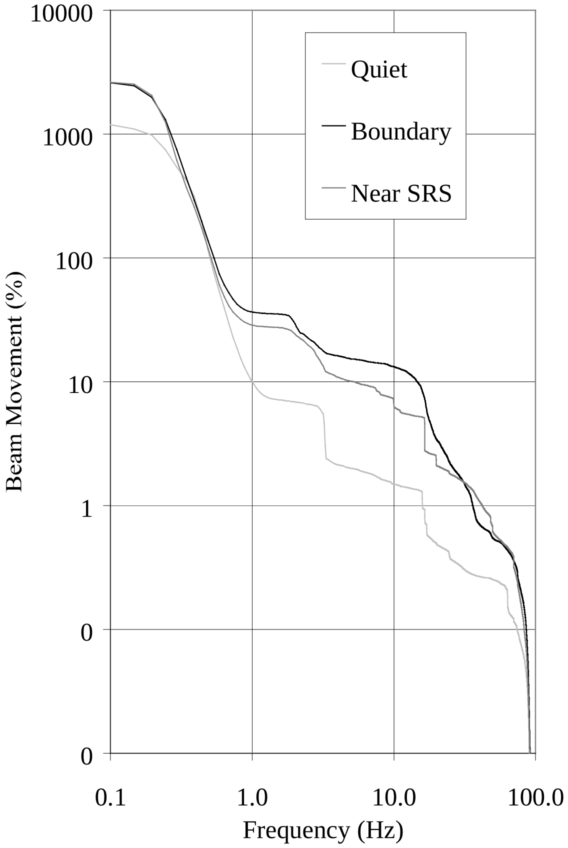

Figure 2: Vertical beam movements, for the ground motion data, assuming uncorrelated quadrupole motion.

5 DISCUSSION

The calculations show that 3rd-generation light sources are very sensitive to vibration, regardless of the exact lattice optics. Equation (1) shows that the sensitivity will be increased still further if the lattice contains additional cells; this is a fundamental consequence of the increased number of quadrupoles and the small emittance. Other 3rd-generation light sources have observed beam displacements from vibration, and have implemented feedback systems to counteract this. While such a system will help to counteract this level of vibration, it is important to avoid the larger levels of vibration arising from construction work or the movement of heavy equipment. This is because any feedback system by its nature only reduces the initial amplitude vibration in a particular frequency band by some factor (rather than eliminating it completely), so the greater the initial level of vibration the more residual vibration is still present when the feedback system is active.

The results in Figure 2 show that in order to obtain vertical electron beam motion of less than 10% of the beam size then a feedback system will be required above the low frequency coherence limit (estimated at about 1.5 Hz) to probably 15 Hz.

In all aspects of the design careful consideration needs to be given to the effect on all structures and systems of the predicted levels of vibration which will be experienced by the storage ring.

REFERENCES

[1] Guralp Systems Limited, 3 Midas House, Calleva Park, Aldermaston, Reading, Berks, U.K.

[2] The MathWorks Limited, Matrix House, Cowley Park, Cambridge, U.K.