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GROUND MOTION TOLERANCES FOR THE SSC*

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ABSTRACT

We attempt in this note to make plausibility arguments regarding the magnitude of tolerable ground motions for the SSC. A compleat, general and quantitative treatment of every conceivable effect awaits far more effort than could have been marshalled for this preliminary study. This note is in three parts: Section 1. A description of the types of motions likely to be encountered on any site and some generally obvious site recommendations. Section 2. Estimates of the consequences of such motions with calculations of only those few types which we consider dominant in the problem. A review of the type and strength of beam position feedback which may be required. Section 3. A summary of suggested tolerances resulting from the calculations and assumptions made.

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PREAMBLE

The issue of ground motion induced effects on particle accelerators has been raised in the past few years primarily with respect to the performances of large linear colliders and synchrotron radiation sources [Refs. 1-4]. It is well to emphasize that these machines belong to a class which we will call "open", in the sense that their beams or the useful products of their beams (synchrotron radiation) do not close on themselves.

It is possible in a linear collider, for example, for a displacement of some focussing element in one part of the machine relative to some other part to cause the two beams to miss each other at the collision point. With respect to light sources, the "local" direction of the closed equilibrium orbit determines the direction of the emerging photon beam which may miss target slits (far outside the machine) if the closed orbit is disturbed. Both of these effects manifest themselves in an increased "effective phase space" or in other words, reduced luminosity.

In contrast to the considerations above, in a circular e^+e^- or P^+P^- collider the closed equilibrium orbit may be adiabatically distorted (within certain limits) and the opposing beams will continue to collide with no resultant loss of luminosity since both beams will follow identical tracks. 'Adiabatically' is used in this context to denote that the time scale of any ground motion disturbance that we know about is long compared to the machine's revolution period – a condition that will be met even for a machine as large as the SSC – and where the problem of ground motion can be treated in first order.

However, the extent to which the SSC beams behave as if they were housed in common optical elements is a question that depends on the details of the adopted lattice. The analysis in Section 2 is based on Lattice Version $(2,4)_b$ (dated 12-18-85). We note, in particular, that at any given azimuthal location in the two rings, a lens that is focussing for one beam is defocussing for the other beam. This means that the beta functions are different and if the combined two lens package moves relative to the other lens packages a relative displacement between the beams will result. This places the SSC in a class different from the aforementioned and therefore deserves some study. Furthermore the two beams intersect at the Interaction Point (I.P.) with a finite crossing angle (50 microradians), which combined with the rather short bunch length (7 cm) can lead not only to loss of luminosity, but to several beam-beam diseases associated with the non-linear forces of off-axis beams on each other. This latter matter is beyond the scope of this report.

In the best of all situations, the end product of a tolerance study should, presumably, be a set of tolerable levels (amplitudes of ground motion in certain frequency bands) that ought not to be exceeded at the various sites under consideration. We emphasize here two points: First – ground motion results from both natural (for example weather) and cultural (man-made) causes. In either case only a certain sub-set of these sources can be controlled by choice of site. Second – in order to come to any conclusions at all, we have had to make certain, hopefully reasonable, assumptions about, for example, at what level we permit the beams to miss each other and how effective feedback countermeasures are likely to be. If, on subsequent examination, these assumptions are not borne out, clearly our tolerance recommendations need to be revised. As a final disclaimer we note that this study does not consider the potentially serious effects of motion amplification between the component and ground due to the magnet support structure. We remind the reader that even if the magnet containing cryostats are mounted directly to the tunnel floor, internal support resonances can occur. It would be prudent to apply an as yet unspecified engineering safety factor (10 ?) for this possibility.

1. TYPES OF GROUND MOTION

1.1 INTRODUCTION

In order to give some relevance to the calculations of the next section, we list in this section, and briefly describe the characteristics of, all the sources and their resulting motions that we know about. Fortunately only a small sub-set of this list will actually have to be considered for the problem at hand. Readers wishing more background information may wish to consult Reference 5 and the references contained therein.

Sources can be sorted into two broad categories, those due to the forces of nature and those due to man. With a few notable exceptions, the former give rise to site motions with long periods (years to fractions of seconds) and if distant, their waves can be treated in the plane wave approximation. The latter, having far less energy content, are caused locally and generally have frequency components from a few to 50 Hz and cannot be treated as plane waves.

1.2 NATURAL

1.2.1 Ground settlement

Experiences over that past 20 years at the SLAC laboratory, which is generally built on or in well cemented, grey, unweathered myocene sandstone, indicate the following:

(a) Over distances of several hundred meters, the horizontal and vertical positions of survey monuments and tunnel floors have a tendency to move relative to each other by amounts up to 3 mm in the first 6 months following construction. After this period, typical displacements are less systematic and in the range of 0.5 mm per year.

(b) Exceptions to the above are due to well identifiable causes.

- One portion of the 2 mile long accelerator housing has sagged up to 18 mm in 17 years relative to other portions because it is built on "well engineered" fill.
- Vertical rises can be identified with short term (1 year) "rebound" due to the removal of overburden.
- Comparable horizontal motions of subsurface structures appear related to asymmetric ground water loading.
- Dramatic changes of elevation (5 mm) of deep regions of the PEP tunnel have recently been observed due to the excavation of the adjacent SLC Collider Hall.

All this is well understood by civil engineers and can be summarized in a few general statements:

— It is well to work in areas of reasonably "competent soil" and to disturb the terrain as little as possible.

— Ground water levels, if not held constant (by drainage for seasonal or other variations) may be responsible for substantial motions.

If such precautions cannot be observed for whatever reason, increases result in the costs of the static (i.e. DC) orbit correcting system or more frequent resurveys and realignments.

1.2.2 Tectonic Motion

It is now well known that certain regions of the earth's crust deform or slip due to tectonic plate motion. Relative motions across active faults, their tributaries and other active regions may reach several inches per year. Since these regions are well known by now, we assume sites suffering from these effects will be avoided.

1.2.3 Earth Tides

The time varying forces exerted by the moon and sun distort the gravitational potential of the earth's surface causing diurnal and semidiurnal amplitudes of the landmasses ranging up to several centimeters. Atmospheric pressure changes can also cause distortions over large surface areas. These motions, having very long periods, may be dismissed from further consideration because over the dimensions of the SSC site they will not be responsible for relative motions of quadrupoles because the whole site moves up and down monolithically.

They are mentioned here to introduce the notion of coherence over the site. If, for the sake of discussion, we define monolithic motion as being flat over say a quarter wavelength (straddling the crest of a sinusoidal motion) and relate the frequency of the disturbance to its wavelength by its velocity in the ground, we can estimate at what frequency time dependent relative motions begin to occur on the site. Setting the diameter of the SSC to be 30 km and assuming a sound in the ground velocity of 2.5 km/sec, frequencies greater than .02 Hz become relevant.

Before we leave this item we note that progress in land surveying using satellites of the Global Positioning System (GPS) may have advanced, in the coming years, to a point at which not only relative horizontal coordinates can be determined to millimeter accuracy, but vertical ones as well. In that case it will be necessary to know the state of the earth tide over the periods of measurement.

1.2.4 Natural Seismic Disturbances

For classification purposes we separate these effects into two further categories: 1. Those due to earthquakes and 2. Continuous Microseismic Noise.

1.2.4.1 Earthquakes

Earthquakes do not affect the daily routine operation of a collider because they happen infrequently. The frequency of occurrence (or return period) in relation to the magnitude can be reasonably well evaluated for any given region of the country from historical data with sufficient statistical accuracy. One recalls that large events occur seldom, small events frequently. It is not our task to engage ourselves here in the details of seismic "risk" analysis of large inelastic events. The possible occurrence of such events affects principally the design of structures, supports and civil services to withstand the resultant accelerations.

We do, however, note that large events with epicenters thousands of kilometers away from the site, may nevertheless generate waves (typically surface waves of 20 second period and appreciable amplitudes hundreds of microns to millimeters), which due to multiple reflections may last for hours.

1.2.4.2 Ambient Microseismic Noise

Aside from such very local sources such as waterfalls, natural microseismic noise is related primarily to weather disturbances, both on and far off site. For example, we are informed by professional seismologists that wind in trees, or over the terrain in general is particularly bothersome to horizontal instruments near ground level but can be ameliorated by choosing station locations below ground. Noise power is predicted, and found, to be attenuated by a factor of 10 at a depth of 100 meters. We wonder about wind loading on large, or particularly tall, buildings! We have no quantitative measures of the wind-building interaction but suspect it could be readily measured for the landmark structure at Fermilab on some wintery Sunday when cultural activity is low and the wind is blowing. The vertical component of noise appears to be independent of depth.

Storms couple their energy to the ground in many ways. Perhaps the most interesting to our problem is due to storm generated ocean-wave coupling to the continent [Refs. 6,7]. Representative time averaged power spectral density plots are shown in Figure 1.1. They were taken from the Text "Quantitative Seismology" by Aki and Richards, (1980) [Ref. 8]. The small low frequency peak on the left has a period directly equal to that of the waves themselves, while the higher (double frequency) peak is said to be due to reflected standing wave

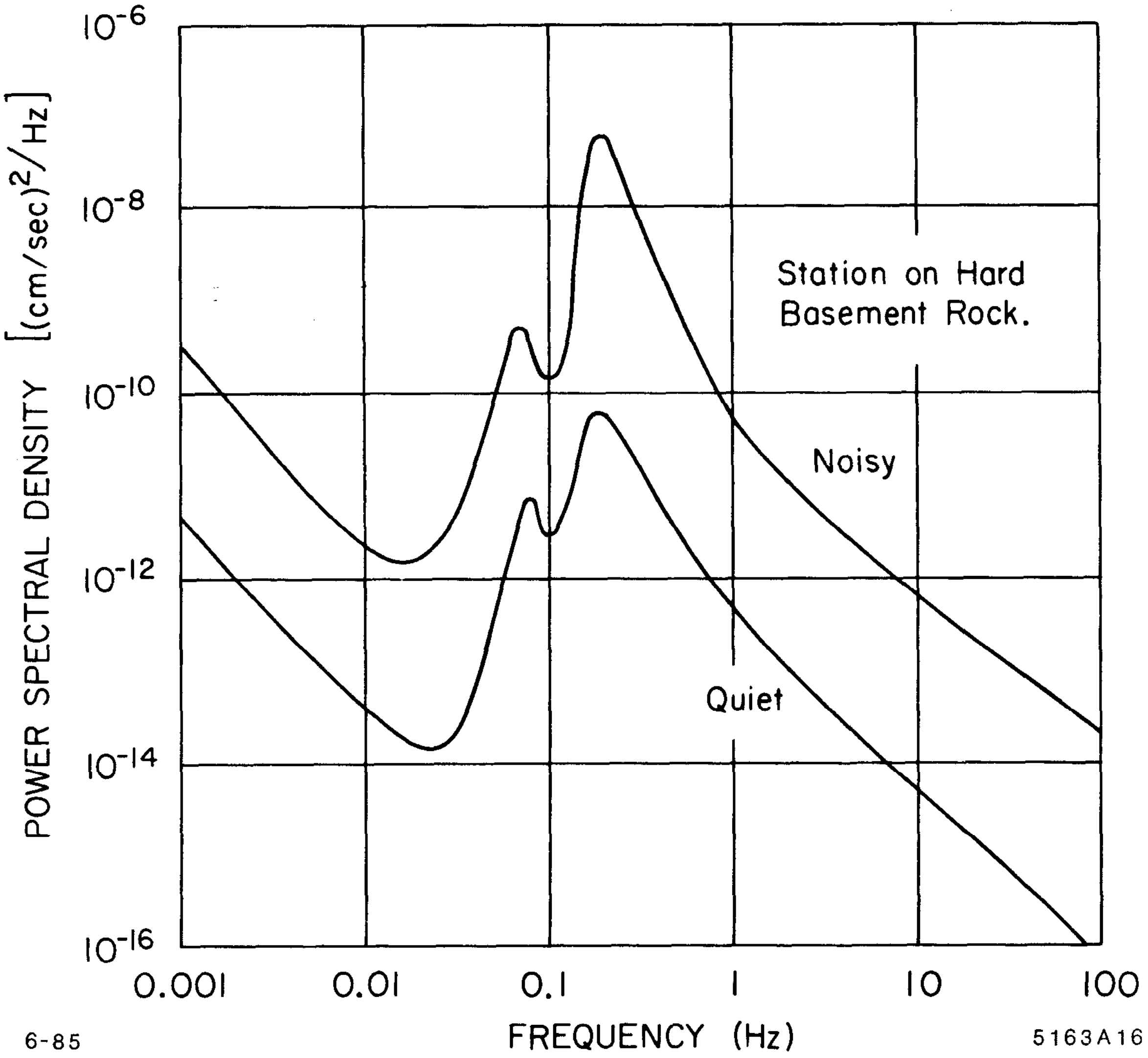

Fig. 1.1. Long Term Averaged "Maximum" and "Minimum" Noise Power Spectra (from Ref. 8).

action. In this time averaged representation the main peak occurs at 0.15 Hz (period 7 seconds) and has a full width at half maximum of about 0.15 Hz. Over short time scales, (hours) the peak may be much narrower and gradually shift in frequency. The width of such narrow peaks must be related to the degree of coherence of the wavetrains that go to make up the disturbance observed at any given point. This coherence must in turn be related to the angular size of the source and velocity dispersion in the inhomogenous intervening medium. Q = f/Δf values as high as 14 have been seen [Ref. 6]. Typical ground velocities of these waves, which sample depths comparable to their wavelengths, range between 2 to 4 km/sec [Ref. 9]. Attenuation inland from the coasts is small (one author mentions 10 db) so they should, and do, occur throughout the continent. It is worth noting however that: 'Just as there is no "standard" earthquake, there is no "standard" ocean wave spectrum.'

How do we translate the continuous fourier spectral power density data into approximate amplitudes for which we can get a feeling and use in subsequent calculations? Let us say that we are interested in the disturbance centered on the large peak and in a frequency band over its width at half maximum. Integrating the velocity density over the width of interest, we obtain for the rms ground particle velocity:

$$v_{\rm rms} = \sqrt{10^{-7}\ ({\rm cm/sec})^2/{\rm Hz} * 0.15\ {\rm Hz}} \approx 10^{-4}\ {\rm cm/sec}$$

which corresponds to a time averaged rms amplitude (at .15 Hz) of about

$$\frac{10^{-4}\ {\rm cm/sec}}{2\pi\ 0.15/{\rm sec}} = 10^{-4}\ {\rm cm} \approx 1\ \mu{\rm m}$$

If one wants to, one can fit the power density spectrum shown with an expression of the form:

$$P(f) = \frac{2A}{\nu}\ \left(\frac{\nu^2}{\nu^2 - (f - f_o)^2}\right)$$

in which $f_o = 0.17$ Hz , $2A/\nu = 7\ (\mu/{\rm sec})^2/{\rm Hz}$ and $\nu = 0.03$ Hz and select the frequency band of interest over which to integrate.

Figure 1.2 displays an (as yet unpublished) compilation of data recently made available to us [Ref. 10]. In this non-site specific plot one notices that the two ocean wave peaks are shifted to higher frequencies with respect to the Aki and Richards curves. It depends what part of the continent one happens to be. Some additional data is shown in the higher frequency bands.

Since we have stated that natural ground noise is related to weather activity, one would expect to see seasonal variations in observed levels. Table I [Ref. 11] from LASA in eastern Montana shows these variations. Unfortunately the Table does not contain data at the ocean wave frequencies but suggests that the low frequency disturbances dominate in the winter, while the higher frequencies peak in the summer when wind becomes more of a problem in the central part (Texas to North Dakota) of the continent. A detailed seismic site investigation for the Institute Laue-Langevin (located in Grenoble, France) can be found in Reference 12.

1.2.5 Cultural Disturbances

Man-made disturbances generally do not possess the energy content that nature can muster. Over a site as large as that for the SSC therefore, we must look at cultural effects as occurring locally and having little or no degree of coherence site wide, or over even a betatron wavelength:

$$\lambda \approx \frac{2\pi \mathrm{R}}{\nu} \approx 100 \text{ km}/100 \approx 1 \text{ km}$$

(The degree of signal coherence across the SLC Interaction region has been recently discussed in Reference 13.)

Their effects will attenuate mostly through geometric spreading. If the geometry of the problem can be adequately described on a two dimensional surface (planar geometry) then the observed amplitudes will scale as: $\mathrm{A} \propto \sqrt{1/\mathrm{r}}$, in which r is the distance between source and observer. If spherical geometry is called for, the dependence is: $\mathrm{A} \propto 1/\mathrm{r}$. We neglect here the effects of energy

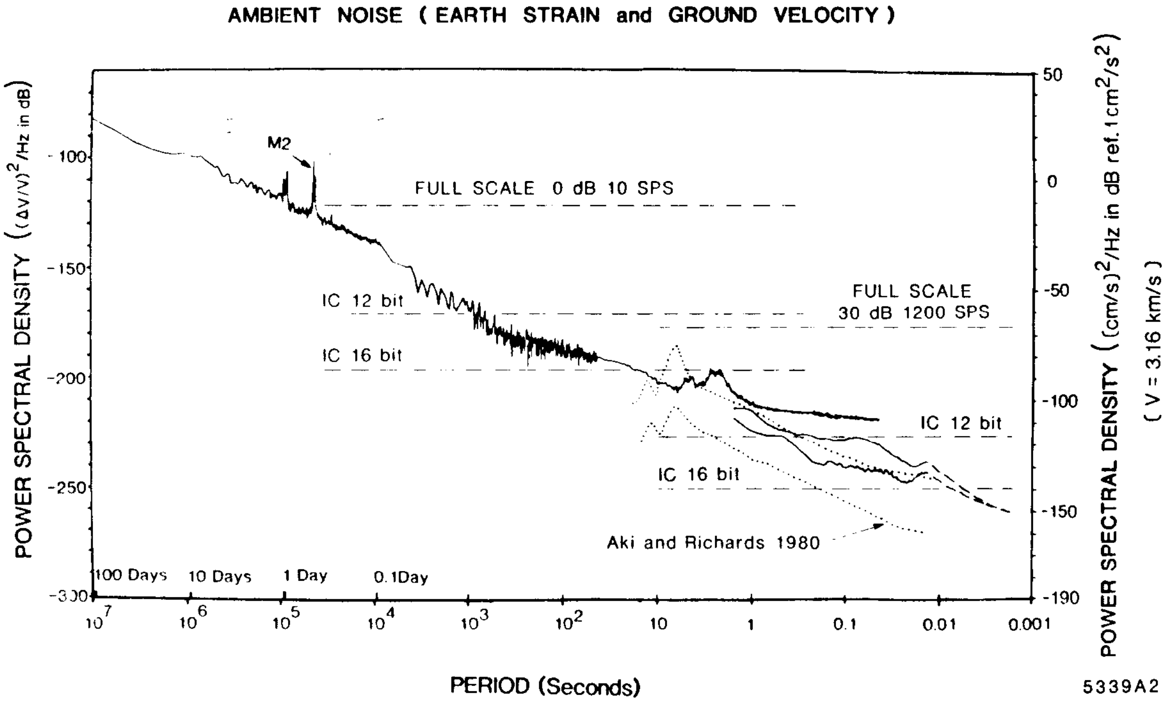

Fig. 1.2. Compilation of Ground Motion over a Wide Range of Periods (Ref. 10).

TABLE I

A variety of procedures for estimation of noise were followed, depending upon magnitude of event being investigated and data tapes being used. As the time-window used in spectral analysis was invariably 12.8 sec and as events of Appendix A generally had at most approximately 10 sec of noise preceding signal, there was a problem for a few earthquakes on this test. However, nearly all large earthquakes were on this list, and it can be demonstrated that values of the spectral discriminant D defined on page 487 for these events are not affected significantly if noise is not deleted. Small explosions yield signals sufficiently short that valid noise corrections could be made by use of data from the end of the segment of seismogram on the tape. Uncertainty in noise correction applies only to a few small earthquakes on this tape.

For the Kohler and SDAC tapes, noise corrections are based in most cases on an average of the data of 20 consecutive time-windows beginning 30 or so time-windows before arrival of the signal. Because of temporal instability of noise estimates, the noise estimates for the smallest events were based on the single time-window immediately preceding arrival of the signal. In all cases, the calculations for D based on noise elimination by use of the single window preceding signal was done only if the criterion for "signal" was met via use of the data for the 20 windows.

TABLE 1

AMPLITUDE OF NOISE VERSUS FREQUENCY VERSUS TIME OF YEAR (LASA)

Frequency Band	Julian Day											
	1-30	31-60	61-90	91-120	121-150	151-180	181-210	211-240	241-270	271-300	301-330	331-365
0.4-0.6	17.9	14.5	15.2	13.3	11.0	12.3	10.8	10.2	11.3	15.1	16.0	15.5
0.6-1.0	7.9	8.0		7.6	7.3	7.5	7.4	6.6	7.6	8.5	9.5	9.4
1.0-1.4	2.8	3.7	6.1	4.0	3.8	5.0	3.7	4.2	4.0	4.3	4.5	4.6
1.4-2.0	2.8	3.8	5.5	4.1	5.1	5.6	5.4	5.1	5.7	4.2	4.6	4.8
2.0-3.0	5.0	10.3	9.7	7.8	10.6	12.9	9.9	12.9	9.7	8.4	9.0	8.2
3.0-4.5	4.2	7.4	9.2	8.8	8.8	11.7	10.2	11.1	9.9	8.2	7.9	8.2

Noise in arbitrary amplitude units, the unit being the same for all windows. If one wishes to know relative noise per Hertz, divide values in table by width of each band in Hertz.

The noise values for each spectral band were the sum of Fourier components in each band, each band being specified by exact values of its bounding frequencies, these in turn being established by the Fourier component nearest 0.4, 0.6, 1.0, 1.4, 2.0, 3.0, and 4.5 Hz. Half of the amplitude value for Fourier components defining band limits was included in the sum of each adjacent band.

An investigation of characteristics of the noise at LASA was conducted based on the 20-window data of the 92 LASA events listed on the Kohler tape. Table 1 indicates the apparent seasonal dependence of spectral band noise at LASA, time intervals being indicated in Julian days. Relative noise values are as they appear on the seismogram uncorrected for instrument response.

It appears that noise from 0.4 to 0.6 Hz is about 1.5 times as great in winter as in summer, that noise from 0.6 to 1.4 Hz is nearly independent of time of year, and that noise at higher frequencies tends to be slightly higher in spring and summer than in fall and winter. Variability in noise level between subarrays at the same time is greater for higher frequencies than for lower, the inter-subarray variability at 3 to 4.5 Hz commonly being a factor of two to three and occasionally being nearly a factor of ten.

The values of Table 1 were calculated after deletion of the occasional very high noise level present in all bands. The presence of such values and the fact that variability of noise values in data for a single season is much greater than variation in seasonal means indicates that seasonal variation in noise level is not a very important aspect of LASA performance. This is particularly so if advantage is taken of inter-subarray variability by using data of subarrays having the most favorable noise conditions at any given time.

absorption in the medium, an assumption which is quite valid for the frequencies and local distances under consideration.

Sound is propagated through uniform, homogeneous and isotropic media both via compressional (P) waves and shear waves (S) whose velocities are determined by the bulk modulus (k), shear modulus (μ) and density (ρ) by the well known relations:

$$C_p = \sqrt{\frac{\mathrm{k} + (4/3)\mu}{\rho}}$$

$$C_s = \sqrt{\frac{\mu}{\rho}}$$

This means that the phase velocities of these two polarizations travel at substantially different velocities. Typically C_p/C_s ranges between 1.4 and 2. In the real world, the medium is anything but uniform, homogeneous or isotropic. At medium discontinuities waves will refract and reflect and change their polarization. Depending on boundary conditions waves may be confined to surfaces. Raleigh waves, for example, are combinations of S and P waves and travel at typically 0.9 C_s. The simple model calculations of Section 2 ignore these facts.

We dare at this point, however, to make some general comments regarding the "competence" of the soil on site. We have already alluded to the fact that the ground settlement issue is closely linked to the local properties of the ground at the depth of the tunnel which may be as little as 30 feet below grade. We want to emphasize that ground motion amplitudes can be substantially amplified when waves are propagated into soil regions of less competence. Seismologists and soils engineers are well aquainted with the hazards associated with low velocity materials such as clayey silts and the like. (In an extreme case: velocities in the material under Mexico City are said to be as low as 40 m/sec.)

1.2.5.1 Explosions

We list, but immediately dismiss from further discussion, the effects from blasting, nuclear and otherwise. The former, presumably, do not occur very often (several hundreds in the last 20 years), and local quarry or construction blasting ought to be controllable. Moreover, as will be seen in Section 2, unless the amplitudes become too large and/or inelastic, the beams should not be lost; only the luminosity will be briefly impaired.

1.2.5.2 Railroad Traffic

At this time we do not have any data on the amplitudes or frequencies of railroad generated noise. One can imagine that the motion of as massive an object as a freight train (1 to 10 Kilotons) moving at speeds up to 50 mph must couple some energy to the ground. As such effects are site specific, we recommend that this motion be measured, both near and far from tracks. The condition of roadbed, curves, and in particular the type of surrounding soil must play some part. Somewhat facetiously, if rail traffic turns out to be a problem and is unavoidable, one can, of course, always tell the experimenters to gate their detectors off when a train is coming by. At 50 mph it only takes about 20 minutes to traverse the dimensions of the site.

1.2.5.3 On and off-site Auto and Truck Traffic

Investigations at the SLAC Laboratory (population ≈ 1500) have shown that most transient events occur during working hours. To be more quantitative, Figures 1.3 and 1.4 show the total typical number of events having a peak amplitude greater than 0.5 microns in a 6 hour time interval as a function of time of day in the horizontal and vertical directions. The sensors were located on the surface in a not particularly well traveled area. Their location, we believe, is representative of a tunnel since measurements made tens of meters underground showed that signal rates and amplitudes were not much attenuated. Vertical disturbances dominate – not inconsistent with traffic. Number versus amplitude plots are

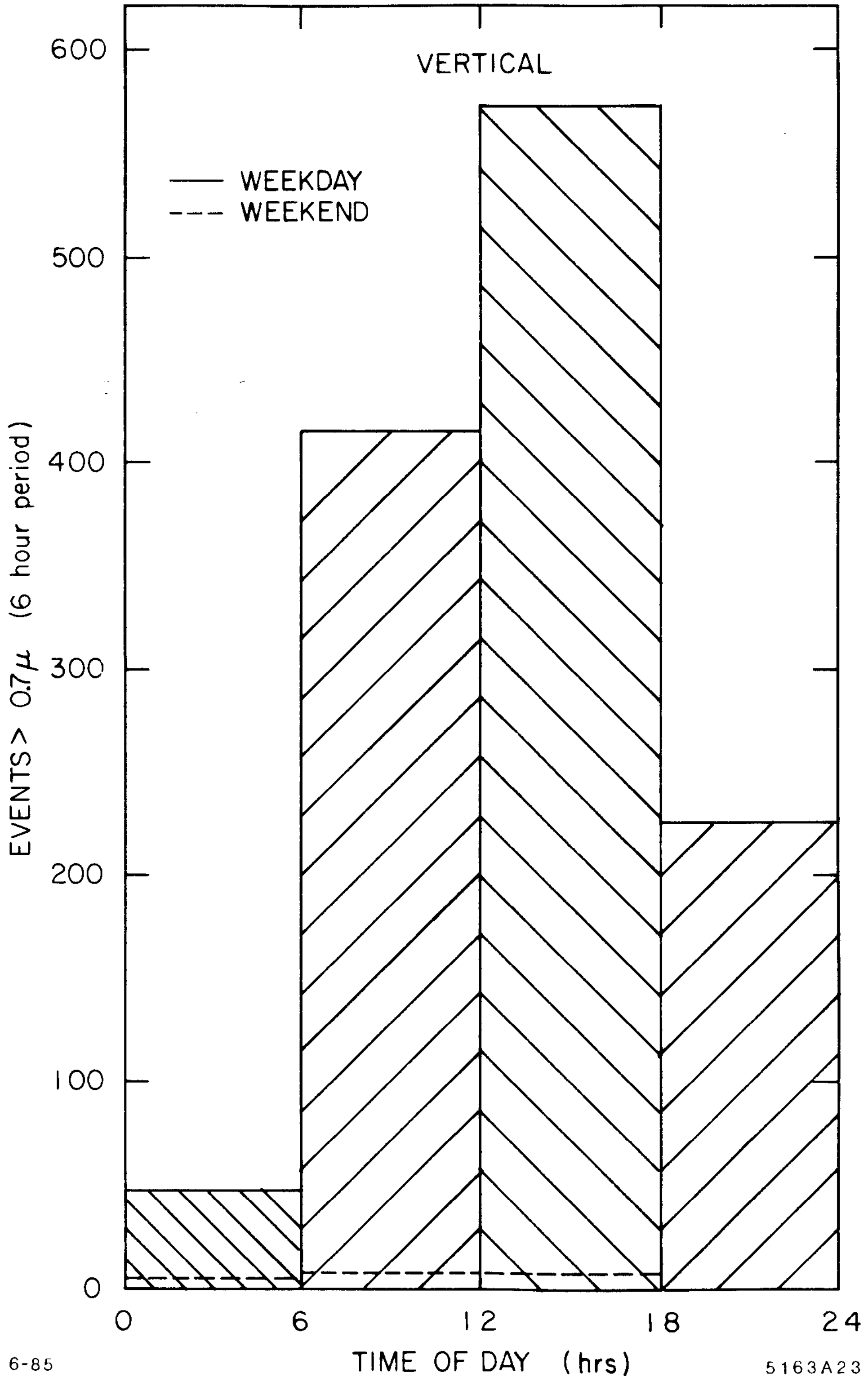

Fig. 1.3. Number of Vertical Transient Events/6 Hour Interval as a Function of Time of Day.

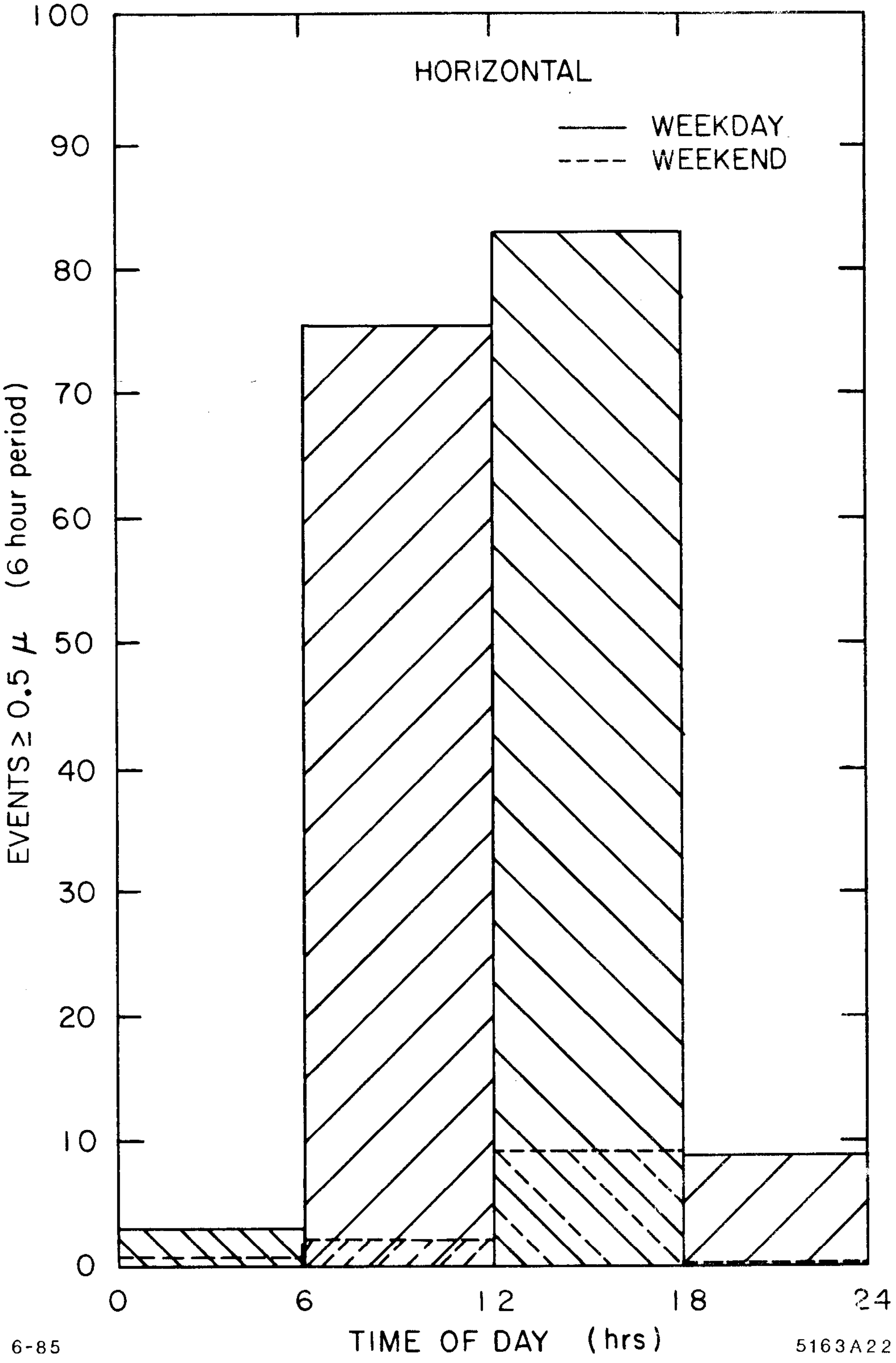

Fig. 1.4. Number of Horizontal Transient Events/6 Hour Interval as a Function of Time of Day.

shown in Figure 1.5. Further investigations showed the not unexpected result that the size of the vehicle, its velocity and condition of the road were parameters. The transient noise a vehicle traveling at 30-40 mph makes appears to be in the center of the frequency band 10 to 30 Hertz and lasts for 3 to 15 seconds as it goes by. Buses could be identified by their characteristic frequency signatures. The existence and use of near-by major highways should therefore be investigated for sites under consideration. On site traffic noise can be more readily controlled through location, road condition, speed limits, etc.. What has been said here also applies to noise created by on-site and offsite construction activity.

1.2.5.4 Continuously Operating Machinery

Large fans, water pumps, water hammer in cooling pipe headers, because they operate in the steady state, contribute to the general level of site noise. High velocity (up to 5 ft/sec) waterflow in the magnets themselves does not seem to be a severe problem. The severest offenders are heavy (say > 20 Hp) low frequency reciprocating devices such as air and helium compressors. Two 75 Hp vertical piston compressors operating at 6 Hz, for example, can produce a 1 micron peak to peak motion at a 100 ft distance and about 0.1 microns at a 1000 ft. This type of equipment can be replaced with modern centrifugal machinery that can be more easily isolated from the ground.

2. ESTIMATES OF THE CONSEQUENCES OF GROUND MOTIONS

2.1 BEAM SEPARATIONS AT THE I.P.

Because the quadrupoles contained in the asymmetric lattice packages are focusing for one beam and defocusing for the other beam, position errors of the quadrupole packages will produce a separation between the two beams in the closed orbits at the interaction regions.

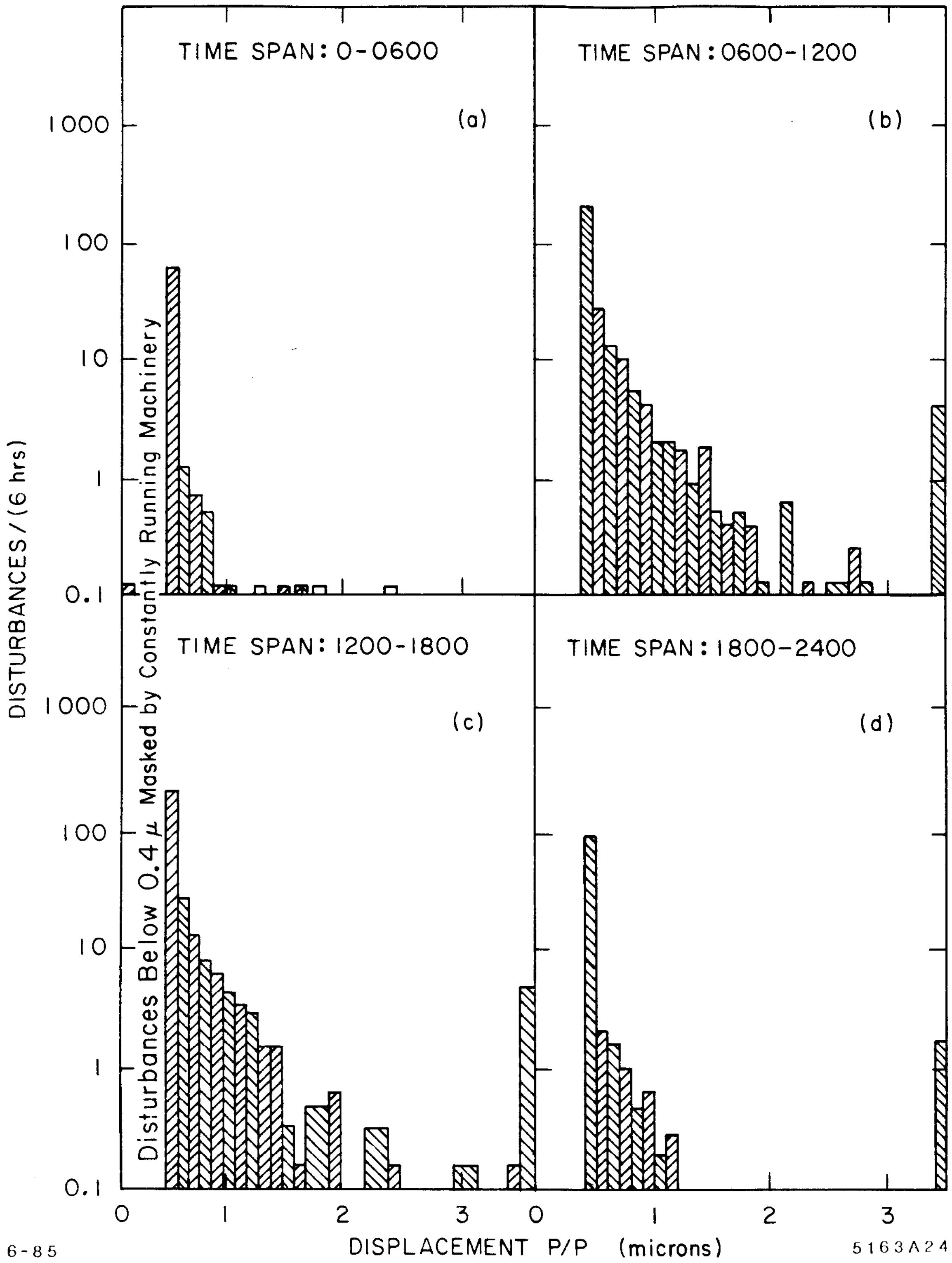

Fig. 1.5. "Amplitude Spectrum" of Transient Signals.

We define the following quantities: ν the betatron oscillation wave number, n the number of a quadrupole package counted from the interaction region, $\beta^\star$ the beta function at the interaction region, $gl(n)$ the integral of the quadrupole gradient in the n^{th} package, $\Delta y(n)$ the transverse position error of the n^{th} package, $\beta_F(n)$ and $\beta_D(n)$ the beta function of the two beams in package n, $\psi_F(n)$ and $\psi_D(n)$ the betatron phase shift from the interaction region for the two beams, and $B\rho$ the magnetic rigidity of the particle. The separation of the closed orbits at the interaction region is given by Courant and Snyder.

$$\Delta y^\star = \frac{\sqrt{\beta^\star}}{2\sin\pi\nu}$$

$$\times \sum_n \left(\frac{g(n)l}{B\rho}\right) \Delta y(n)\,[\beta_F^{1/2}(n)\cos[\pi\nu - \psi_F(n)] - \beta_D^{1/2}(n)\cos[\pi\nu - \psi_D(n)]]$$

We define ξ as the ratio of the relative closed orbit separation to the beam size at the interaction region.

$$\xi = \frac{\Delta y^\star}{\sigma^\star} = \frac{\Delta y^\star}{\sqrt{\beta^\star \epsilon}}$$

where $\sigma^\star$ is the rms beam size at the interaction region and ϵ is the beam emittance.

The maximum value of ξ for a position error of only one quadrupole package in a cell is given by:

$$\xi_1 = \frac{\Delta y}{2\sqrt{\epsilon}\,\sin\pi\nu}\left(\frac{gl}{B\rho}\right)\{\beta_F^{1/2} - \beta_D^{1/2}\}$$

Note: $\left(\frac{gl}{B\rho}\right)_F = \left(\frac{gl}{B\rho}\right)_D$ for all cells in the lattice.

The lattice $(2,4)_b$ has $\beta_F = 111\,\text{m}$, $\beta_D = 333\,\text{m}$, $gl/B\rho = .01/\text{m}$, $\epsilon = 50 \times 10^{-12}$ rad-m and $\sin\pi\nu = 1/2$ which gives:

$$\xi_1 = (10^{-2}/\mu\text{m})\Delta\text{y}$$

We have treated three separate types of errors.

- Case 1: The position errors of the quadrupole packages are completely uncorrelated. This is what one might expect from local noise.
- Case 2: The position errors are correlated by assuming that a plane wave moves across the ring at a constant velocity as in Reference 4.
- Case 3: The position errors are assumed to be perfectly correlated in such a way as to produce the maximum separation between the orbits of the two beams. This is a highly unlikely case and would require the action of an SSC demon, however, it does serve to define the limits of the worst case.

The calculation of Case 1 is straightforward and one obtains that the relative displacement from N_q quadrupole packages is equal to $\sqrt{\mathrm{N}_q}$ times the average effect from only one package.

For Case 2 the relative displacement is approximately given by $\mathrm{N}_q \mathrm{J}_m(\frac{2\pi \mathrm{R} f}{v})$ times the average effect from only one package where m is close to ν, and f and v are the frequency and velocity of the ground disturbance. For $m \approx 90$, the maximum value of J_m equals 0.15. For an assumed velocity of $v = 2.5$ km/sec and ring size $2\pi\mathrm{R} = 90\,\mathrm{km}$, this maximum occurs at a ground motion frequency near $f = 2.5\,\mathrm{Hz}$.

The last case, which is the worst case, yields a relative displacement equal to N_q times the average effect of one package. The total number of cell packages in SSC is 625 which yields the following values for ξ.

Case 1. $\xi = (0.25/\mu\mathrm{m})\,\Delta y$

Case 2. $\xi = (0.94/\mu\mathrm{m})\,\Delta y$

Case 3. $\xi = (6.25/\mu\mathrm{m})\,\Delta y$

In the vertical direction the separation of the orbits at the interaction region produces a longitudinal shift in the spatial crossing point. The relative shift of the longitudinal crossing point relative to the longitudinal beam size ($\sigma_z = 7$ cm) for a crossing of 50 μrad is given by

$$\frac{\Delta z}{\sigma_z} = 1.5 \frac{\Delta y}{\sigma_y^*}$$

Since the orbits must cross within the length of the bunch to about the same relative accuracy as the beam separation the crossing angle does not help to increase the tolerances.

ASSUMPTION: We will take as a maximum allowable value:

$$\xi < 0.1$$

which will result in a negligible luminosity degradation and hopefully will be sufficient to disallow any deleterious beam-beam effects. We have heard of an experiment conducted at the SPS P^+P^- colliders in which the beams were moved substantial fractions of beam size relative to each other without loss of lifetime. However, this experimental result was obtained for a the weak-strong beam case. For a strong-strong beam case, in which a higher value of the beam-beam tune shift may be approached, the behavior could be quite different. If, upon further investigation, a different value of ξ is chosen, the reader may scale the results appropriately.

In the absence of feedback , the following ground motion tolerances result:

- Case 1. $\Delta y < 0.4$ μm
- Case 2. $\Delta y < 0.1$ μm
- Case 3. $\Delta y < 0.02$ μm

2.2 FEEDBACK CONSIDERATIONS

The likelihood of any site being able to meet the tolerances discussed above is rather poor; therefore, it will probably be necessary to have a feedback system to force the two beams to collide at the interaction region. Of course, the actual requirements of such a feedback system will depend upon a study of the type of ground motion that is found to occur at the actual site, however, some general considerations and outline of such a feedback system can be presented.

First the feedback system can be rather slow with a total bandwidth of a few tens of hertz being sufficient.

Secondly some type of pickup will be required that can determine the beam separation down to a level where the colliding beam operation is not adversely effected. It should be noted that a feedback system will also be needed for the variation of the magnetic guide field, albeit possibly over a wider frequency range, due to effects such as power supply ripple and etc. The maximum separation of the beams, at the interaction point, that needs to be corrected is only a small multiple of the expected movement of the quadrupole package. If we assume that the maximum separation of the beams, at the IR, is 10 μm, we will require a magnetic bump with deflections of 0.016 μrad at the high β quadrupoles near the interaction region. An integrated magnetic field of 100 gauss meters is sufficient to produce this deflection. This amount appears to be straight forward.

The question of the error signal pickup requires discussion. If, as we surmise, beam-beam problems occur at the $\xi \simeq 0.1$ level, the luminosity will not have dropped much to provide an unambiguous signal. There is an up-down and right-left ambiguity for steering. The Jostlein technique [Ref. 14] addresses this question by "causing the beams to circle each other with <u>one micron</u> incremental separation by a properly phased, very small oscillation superimposed on the horizontal and vertical beam steering magnets". Since the counting rates are enormous, the frequency response of this system is said to be "up to many Hertz"

[Ref. 15]. We must now, years in advance of machine operation, made a guess regarding the efficacy of such a feedback proposal.

ASSUMPTION: Not totally arbitrarily, we guess that the system should be able to lock onto and correct incoherent ground motion amplitudes no greater than about 10 times those calculated in Section 2.1 because by that time the beams are beginning to miss each other pretty badly.

One might envisage the use of multiple feedback systems to increase the overall dynamic range in order to provide additional suppression factors. Again, the question of the error signal must be asked. At this time, we do not take the notion of using seismic signals, derived from sensors mounted on each quad in the ring, very seriously. More attractive is measuring beam displacements in quadrupoles adjacent to the interaction region in which β values are high.

2.3 BEAM SEPARATION EFFECTS FROM OTHER MAGNET MOTIONS

There are other types of magnet motion that can produce a separation in the closed orbits between the two beams, such as roll in the bending magnets, longitudinal motion of the bending magnets and transverse motion in the high beta quadrupoles in the insertion region. The motion of the bending magnets appears to have a much smaller effect on the separation between the two beams than what was calculated for the motion of the cell quadrupoles. Random motion of the few high beta insertion quadrupoles has a comparable effect on the beam separation as was calculated for random motion of all the cell quadrupoles (Case 1), while the worse case effect of highly correlated motion in the insertion quadrupoles is much less than the worst case effect of highly correlated motion in the cell quadrupoles.

2.4 EFFECT OF MOVEMENTS AND ORBIT DISTORTIONS IN THE SEXTUPOLES

It should be pointed out that movements and orbit distortions in the sextupoles can produce changes in the focussing properties of the ring. One measure of such effect is the change in the betatron oscillation frequency.

$$\Delta\nu = \frac{1}{4\pi}\sum_{n=1}^{\mathrm{N}_s}\frac{B''l(n)}{2B\rho}\;\beta_n\;\Delta x_n$$

where Δx_n is the beam position relative to the center of the nth sextupole. We assume that the highly correlated portion of the orbit distortion, which has a spatial period approximately equal to the betatron wavelength, produces a zero average tune shift; hence, the total tune shift is equal to the square root of the number of sextupoles times the tune shift due to one sextupole. For the lattice $(2,4)_b$, $B''l(n)/2B\rho \simeq 0.01\,\mathrm{rad/m^2}$, $\beta \simeq 200\,\mathrm{m}$, $\mathrm{N}_s = 625$, and

$$\Delta\nu \simeq [4\times10^{-7}/\mu\mathrm{m}]\,\Delta x$$

Clearly the variation of the beam position relative to the center of the sextupole magnets, due to ground motion, should have no deleterious effects.

2.5 LONGITUDINAL BUNCH OSCILLATIONS: RF NOISE

So far we have discussed the effect of the ground motion on parameters of the ring that adiabatically follow the ground motion. This has been possible because the natural time response of the beam is much faster (i.e. at a higher frequency) than the ground motion.

However, there is one important case where the response time is of the same order as that of the ground motion, namely synchrotron oscillations which will have a frequency of a few hertz.

For this case a change in the closed orbit results in a change in the path length a particle must travel between rf cavity stations. This results in a change in the rf phase of the voltage gain received by the particle; when this phase modulation is at the synchrotron oscillation frequency it is possible for the synchrotron motion of the particle to grow.

The size of this effect can be estimated by noting that the change in the path length of a closed orbit caused by the motion of various quadrupoles by $\Delta X(n)$ is given by

$$\Delta L_{\rm rms} = \sum_n \frac{gl(n)}{B\rho}\ \eta(n)\ \Delta X(n)_{\rm rms}$$

where $\eta(n)$ is the dispersion at quadrupole n . For the $(2,4)_b$ lattice, $\eta \sim 3\,\mathrm{m}$ $gl(n)/B\rho \sim .01/\mathrm{m}$ and $\mathrm{N}_q = 625$, which yields

$$\Delta L \sim \Delta X \rightarrow 20\ \Delta X$$

depending upon the spatial correlation between the errors. The rf wave length $\lambda \sim 1\,\mathrm{m}$ which yields, even in the worse case, a phase modulation amplitude of

$$\Delta\phi = 10^{-3}\ (\mathrm{deg}/\mu\mathrm{m})\ \Delta X\ .$$

For any realistic movement ΔX in the few hertz frequency range we see that the phase modulation amplitude will be much smaller than what one would expect from noise in the rf system. The phase lock system [Ref. 16] already designed to suppress longitudinal growth due to rf noise, should have no trouble suppressing growth due to the ground motion.

3. SUMMARY OF RECOMMENDED GROUND MOTION TOLERANCES

Throughout we assume that the beam centroids should not be displaced from each other by more than 10% of 1 sigma of their beam size at the interaction point.

Below, in Table II we list our recommendations for the three cases studied: totally random motion, coherent motion in the plane wave approximation with an assumed constant wave velocity of 2.5 km/sec, and the improbable but limiting situation with an SSC demon. The tolerances given in the first column are the tolerances calculated in Section 2.1 in absence of any feedback system and neglecting any resonances in the magnet support structures. The effect of the feedback on increasing the tolerances for frequencies below 20 Hz is shown in column two. We have assumed the feedback system to be capable of suppressing the effects of noise by a factor of 10 for the frequencies below 20 Hz. For the first case of random noise, which comes from local sources, we have divided the frequency range into two bands. The resonances of the magnet support structures are assumed to all be above 3 Hz so that only the local noise will be amplified by structure resonances. It can be shown that, if the bandwidth of the noise is much larger than the width of a structure resonance, the rms amplitude of the magnet motion, $\Delta y_{\rm m}$, is equal to $\sqrt{\rm Q}$ times the rms amplitude of the ground motion, $\Delta y_{\rm g}$, due to the noise from all the frequencies above the structure resonance, where Q is the quality factor. In the third column we take into account amplification of the ground motion of 10 due to resonances in the magnet support structure for the incoherent case only.

We have used the power spectrum (noisy station) given in Fig 1.1 and converted the curve into rms amplitudes in the appropriate frequency range and presented them in Table III. It should be noted that we have been reluctant to present Table III. It is feared that Table III will be misused because many of the readers may not fully appreciate that it refers to a hard rock site where **no cul-**

TABLE II

Recommended Ground Motion Tolerances

	no feedback rigid support	with feedback rigid support	with feedback with assumed support ampl. factor of 10
Case 1. Completely random local noise: $3 \text{ Hz} < f < 20 \text{ Hz}$	$< 0.4\ \mu$m	$< 4\ \mu$m	$< 0.4\ \mu$m
$f > 20$ Hz	$< 0.4\ \mu$m	$< 0.4\ \mu$m	$< 0.04\ \mu$m
Case 2. Correlated by plane waves: $0.02 \text{ Hz} < f < 3 \text{ Hz}$	$< 0.1\ \mu$m	$< 1\ \mu$m	$< 1\ \mu$m
Case 3. Improbable total correlation at the betatron wavelength:	$0.02\ \mu$m	$< 0.2\ \mu$m	$< 0.2\ \mu$m

TABLE III

Expectation of rms ground amplitudes in various frequency bands on a hard rock site as given in Fig. 1.1

(No cultural noise)

Freq. Band	$0.02 \text{ Hz} < f < 3 \text{ Hz}$	$3 \text{ Hz} < f < 20 \text{ Hz}$	$f > 20$ Hz
$< y >$ rms	$1\ \mu$m	$.003\ \mu$m	$3 \times 10^{-4}\ \mu$m

tural noise has been included. Nevertheless, it was felt that there might be some readers unfamiliar with the connection between the power spectrum curve and the expectation value of the amplitude, so it has been included **NOT AS A TYPICAL EXAMPLE** but as an illustrative example.

Discussion

The reader may now well ask: "What do these numbers really mean with respect to ground motions one might expect from typical sites?" We conclude that the situation is: (a) Definitely *not hopeless – an SSC can be built and operated.* (b) Unfortunately, it appears also that the problem *cannot be dismissed out of hand.* In other words one must now examine and evaluate in more detail the parameters that went into our assumptions in order to determine the most economic tradeoffs.

We believe:

- The effects of ground motion would become quite small if the lattice did not possess the focus – defocus properties of configuration $(2,4)_b$.
- Since the magnitude of ground motions are, among other things, a function of soil conditions, due care should be exercised in this matter.
- Weather and other uncontrollable natural sources and variable conditions introduce a range in the base levels of at least one order of magnitude. A feedback system ought to be able to counteract these effects.
- Care should be taken to avoid the introduction of controllable cultural noise, since this generally occurs at higher frequencies (> 3 Hz.) Motions at these frequencies are more likely to be amplified by the supports and are more difficult to suppress with a feedback system.
- The general design of components and civil structures should take into account the ground motion problem so that the recommended values of column 3 of Table II can be relaxed.

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