COMPENSATION FOR INCOHERENT GROUND MOTION

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1. Introduction

The power spectrum density and coherence function for ground motions are studied for the construction of the next generation electron-positron linear collider. It should provide a center of mass energy between 500 GeV-1 TeV with luminosity as high as 10^{33} to 10^{34} $cm^{-2}sec^{-1}$. Since the linear collider has a relatively slow repetition rate, large number of particles and small sizes of the beam should be generated and preserved in the machine to obtain the required high luminosity. One of the most critical parameters is the extremely small vertical beam size at the interaction point, thus a proper alignment system for the focusing and accelerating elements of the machine is necessary to achieve the luminosity. We describe recent observed incoherent ground motions and an alignment system to compensate the distortion by the ground motions.

2. System Description

The e^+e^- linear collider using C-band (5712 MHz) RF-system will use 7,120 accelerating structures, 3,560 klystrons and their pulsed-modulators power supplies to obtain 500 GeV C.M. [1]. Each unit in the main linac rf-system is composed of two 50 MW klystrons, their pulsed modulators, one rf-pulse compressor, four 1.8 meter long choke-mode accelerating structures and associated waveguide system. The main linac will be installed in two parallel tunnels with circular cross-section with diameters of 3 m and 4.2 m for the accelerator and klystron gallery, respectively. These tunnels will be constructed in a very stable granite region using TBM. Figure 1 shows a schematic description of the system as mentioned above.

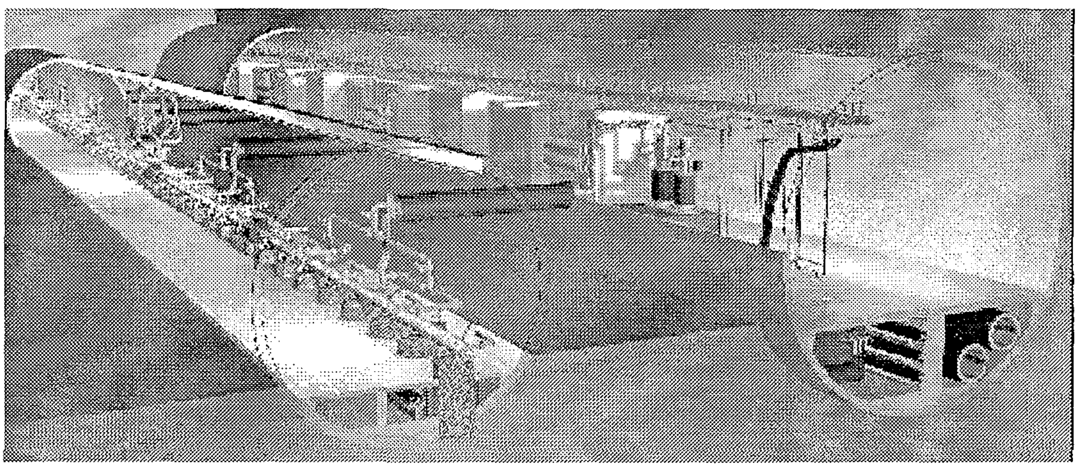

Figure 1: Schematic and overall description of the C-band linear collider.

Since the short-range transverse wakefield is a strong function of the iris aperture A (in inverse proportion to raising A to the 3.5^{th} power), it becomes very strong at higher frequency bands, resulting in very tight straightness tolerance. The straightness tolerance becomes ±50 μm (the maximum bow) for a 1.8 m long structure. The components of each beam line have to be aligned with a high accuracy. The standard deviation of any point over a range of the maximum betatron wave length in the vertical direction should be better than 30 μm. The linear collider should have extremely small emittance (invariant emittance=30 nm) to perform the required luminosity, thus precise alignment of machine components is essential to prevent emittance dilution. The ground motion spoils alignment of accelerator elements and results in emittance growth. We have estimated the duration time t for the emittance blow-up remaining within 10% [2]. The magnitude of t is 24 hours in case of C-band linear collider and 3 hours in case of X-band one using the same *ATL* coefficient, 1 nm^2/sec/m.

3. Ground Motions

3.1 General Remarks of the Ground Motion

The sensitivity of the beam orbit depends strongly on the correlation length of transverse motion of the quadrupole magnets. If this motion has good correlation over distance exceeding the betatron wavelength, the motion has only little influence on the beam jitter. For this reason we have to measure not only the spectrum of the ground motion but also correlation functions. The spectrum of the ground motion can characteristically be divided into two frequency ranges, the high frequency range above 1 Hz dominated by artificial noises and low frequency range related to natural ground motion which has strong dependence on the site.

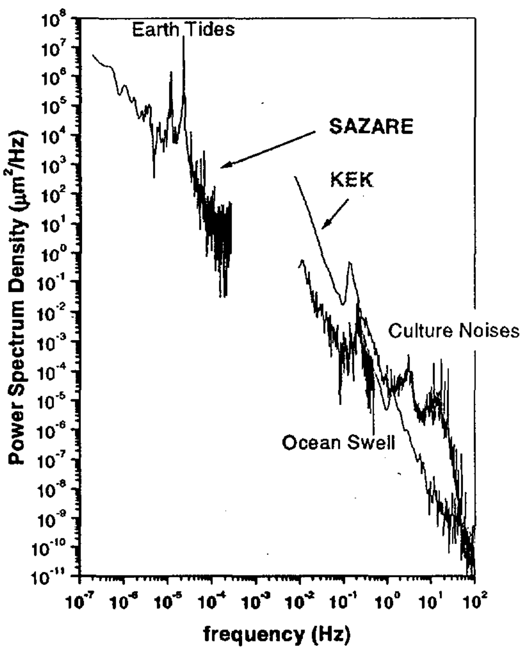

Figure 2: Typical ground motion spectrum. Black solid curves correspond to a quiet site and red one to a noisy site.

3.1.1 High Frequency Range

Typical power spectrum of the ground motion is shown in Fig. 2. The black curve shows no artificial culture noise but the red one very large culture noise contrastively. The former data is taken in the hard rock tunnel [2,3] and *ATL* coefficient is 0.05 nm^2/sec/m, the latter in the accelerator tunnel of KEK. *ATL* coefficient for KEK is 40 nm^2/sec/m. In the high frequency range, the observed amplitudes show crustal filter effect for the human activity (traffic noises, large electric equipment etc) in the vicinity of KEK [2,4]. The vibration level caused by the accelerator facility is not negligible [5,6]. These results propose to build the future linear collider in a site with low population and low culture noise level as paying the most closest attention to suppress the noises caused by the accelerator facility including its cooling water system, power transformer, compressor and air conditioner etc.. The wavelength of these vibration is as short as

1st page

Next page

200 m or less [9]. It is comparable to the betatron wavelength in the high energy part of the linear collider. We must investigate carefully on the orbit stability and emittance dilution.

3.1.2 Low Frequency Range

The low frequency range of the ground motion as shown in Fig. 2 is overlapping effect of earth tide and the slow ground motion. In case of the good hard rock place, the tidal motion has splendid coherence for the space distortion, thus its effect on beam behavior becomes negligible small though the tidal amplitude is larger than the beam size. Another broad peak appeared around 0.3 Hz is caused by ocean swell hitting coasts. This phenomenon results in well correlated ground motion [4, 7, 8]. The wave length of this motion is very large comparing to the betatron wavelength of the linear collider, thus its effect on the beam dynamics is negligible. Dominant part of the ground motion in the low frequency range is inelastic motion. This ground motion is diffusive and results in uncorrelated drift. One of the models describing this inelastic ground motion is *ATL* model (σ^2=*ATL*) [10, 11, 2, 5]. This model means that the variance of uncorrelated relative motion of two points is proportional to their distance *L* and the time interval *T* of observation. The value of *A* depends on the ground properties or fragmentation of the rocks [5]. Typical values of *A* in Japan are summarized in Table 1. Detailed description for our measurements is shown in the next section. In the frequency range f<0.1 Hz, measured continuous power spectra of the ground motion can be characterized by k/f^2. This coefficient k is site dependent correlated with geological and topographical properties taking part in the block movement of underground rocks. We have to investigate carefully on the orbit stability and emittance dilution caused by *A*, since the variance σ^2 is described by the integration value of power spectrum density. Table 1 and the stability estimation [2] give a clear instruction for the construction of linear collider.

Table 1 – ATL Coefficient in Japan

Data No	Site Name	A (nm^2/m/sec)
1	Tunnel of KEKB	4.0E+01
2	Rokkoh with Fault	3.6E+01
3	Rokkoh without Fault	3.3E+01
4	Kamaishi II-III	1.4E-01
5	Kamaishi I-II	5.7E-02
6	Sazare	5.0E-02
7	Esashi No. 1	5.7E-03
8	Esashi No. 2	2.0E-03

3.2 Incoherent Spectrum of the Ground Motion

We have to investigate definitely the time and space characteristics of the ground motion before construction of the linear collider, since the motion influences severely on the initial alignment of the machine, to say nothing of its operation. Especially, slow ground motion would destroy the straight trajectory of the carefully prealigned structure and lead to luminosity losses. Thus it is very important to study the characteristics of the slow drifts of the ground. In the low frequency range, the ground motion shows so called random like process. thus we can describe it as average behavior in a stationary condition. The variance σ^2 of the time series data $x(t)$ for the ground motion can be given,

$$\sigma^2 = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x^2(t)dt,$$

and the power spectrum density of $x(t)$ is,

$$P(f) = \lim_{T\to\infty} \frac{1}{T} \left| \int_{-T/2}^{T/2} x(t) \exp(-2i\pi f t)dt \right|^2 .$$

Then σ^2 becomes,

$$\sigma^2 = \int_{-\infty}^{+\infty} P(f)df.$$

Using the gorund motion data $x_1(t)$ and $x_2(t)$ taken simultaneously between two distant measuring points, we can get the cross-spectrum,

$$P_{12}(f) = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} x_1(t) \exp(-2i\pi f t)dt \int x_2(t) \exp(-2i\pi f t)dt,$$

and then the normalized cross-spectrum,

$$S_{12}(f) = \frac{P_{12}(f)}{\sqrt{P_1(f)P_2(f)}}.$$

The absolute value of this normalized cross-spectrum is the coherence function. It measures the linear dependence of one signal on another and ranges in value from zero to one. Values of 1 for the coherence function tend to indicate that both signals have strong correlation in that frequency band, while values of 0 indicate that there is no correlation in that frequency band. For the analysis of the experimental results, we can define an incoherent spectrum density,

$$P_{INC}(f) = \{1 - |S_{12}(f)|\} \cdot P(f),$$

and the variance of uncorrelated ground motion integrating $P_{INC}(f)$ over the frequency.

3.2.1 Actual Slow Ground Motion

A typical result obtained in the quiet granite tunnel is shown in Fig. 3. We took the data using the Leveling Sensor with Half Filled water (LSHF) [12, 13]. LSHF is insensitive to ambient temperature changing, but sensitive to the local ground motion. We set three LSHF's at intervals of 14 meters.

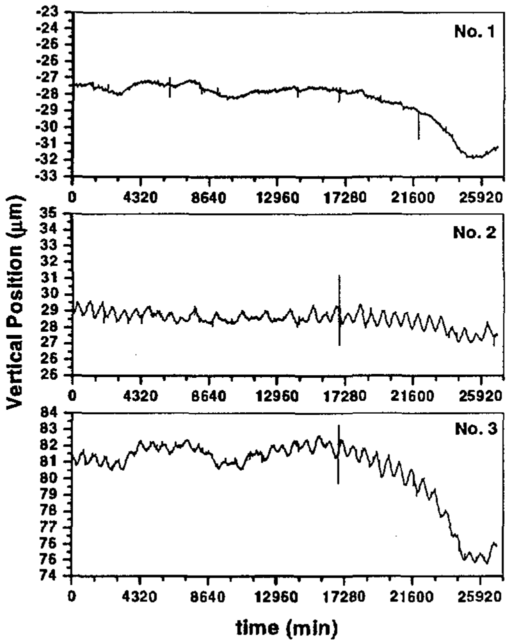

Figure 3: Ground motion in the quiet granite tunnel observed by three LSHFs.

Figure 3 shows the time series data on the vertical ground motions observed at three points in the tunnel, named No. 1, No. 2 and No. 3. We can see the earth tides on No. 2 and No. 3, but No. 1 does not clearly show the tides. This means that No. 2 and 3 sensors are set on the same large rock bed. On the other hand, we can speculate that No. 1 sensor is set on a floating lumped rock and this rock behaves insensitively to the earth tides. It is 14 m from No. 1 to No. 2, thus we can say that the size of the floating rock is less than 14 m. In the very slow drift region, however, these three points move about almost in phase, though their amplitudes are different.

The coherence between them are shown in Fig. 4. In the frequency range less than 30 μHz we can see that the coherence between No. 1 and No.2 is reduced to about 92% from the coherence between No. 2 and No. 3. The related incoherent power spectra are shown in Fig. 5. Integration over the frequency of these spectra gives *ATL* coefficients of Table 1 (Data No. 7 and 8). The No. 2 spectrum shows clearly two peaks corresponding to the earth tides. The peaks, however, are greatly reduced in the No. 1 spectrum and its average amplitude of f<10 μHz is nearly ten times as large as No. 2.

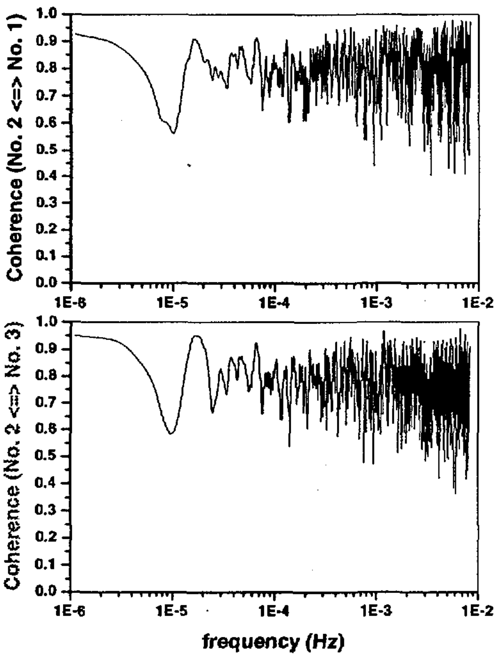

Figure 4: Coherence functions at Esashi.

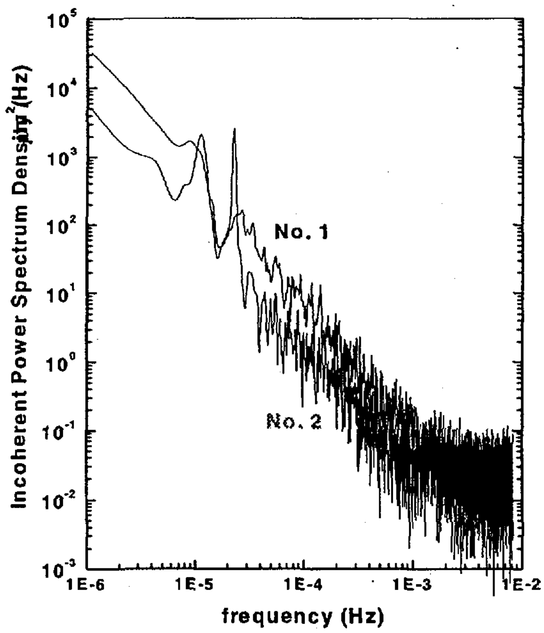

Figure 5: Incoherent spectra obtained in the tunnel of Esashi.

The same kind of incoherence in the short distance range are observed in the tunnel of Kamaishi mine, which is also quiet granite tunnel. Figure 6 shows the coherence observed on the same place but different days. The *ATL* coefficient should be influenced dominantly by the ground properties, in other words, it should depend on the degree of fragmentation of the rock. Thus the excavation method of the tunnel also affects significantly the coefficient [4, 2]. The excavation methods of Esashi and Kamaishi are very different from each other. In the former tunnel they cut the rock using a drilling machine, but the latter using dynamite (so called slow blasting method and very similar to NATM). Now we are executing several experiments to get more detailed information about the structures under the ground. Present our speculation in comparison with the results of Esashi is as followings:

- The tunnel is divided into finer blocks than Esashi's by its tunneling method and our obtaining result corresponds to the motion of each block.
- The size of the block depends on the method of excavation and the broken blocks are influenced by the underground water which should induce the motion of each block.

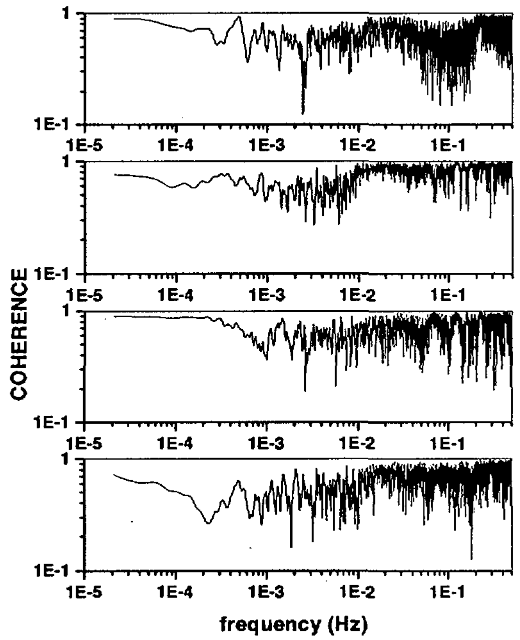

Figure 6: Coherence obtained in the quiet granite tunnel. Two sensors are set up 17 m apart from each other.

It is possible that day by day differences of the coherence include the time dependent data on the activity of underground water. In any case, this result means that we have to avoid any tunneling method to crush the basic rock into the fine blocks. Macroscopic effect of the excavation diminishes as a function of time, but the microscopic effect does not reduce and remains as large random motion described by the *ATL* coefficient. We can get the *ATL* coefficients in the tunnel of Kamaishi using the spectra and the coherence function observed there and the results are given in Table 1 as Data No. 4 and 5. These obtained coefficients are maximum and minimum values, respectively.

We have gotten another information of the noisy granite tunnel which includes a distinct fault. We set one of the two sensors at the fixed point, and the other was set at a distance of 60 m spanning over the fault or not spanning over the fault. The coherence related with the Data No. 2 rapidly decrease its amplitude in the frequency range higher than 0.1 Hz, in contrast to the amplitude for the Data No. 3 being almost flat up to 10 Hz. Although each spectrum is almost same, the *ATL* coefficients show a little difference reflecting the coherence as listed in Table 1. As a result of this section, we can say followings :

- We have to pay attention not only to the general *ATL* coefficient of a site, but also to local fluctuation of the coefficient in constructing a long scale linear collider.
- We should consider the available time interval for the first alignment of the machine. *ATL* coefficient of 1 nm^2/sec/m indicates that we must align the 30 km machine within 100 days, for example, corresponding to the accuracy better than 0.5 mm.

1st page

Next page

- We have to avoid any tunneling method to crush the basic rock into the fine blocks in order to exclude complex growth of the *ATL* coefficient.
- Independent active support system for each machine component is recommended.

4. Alignment System

We have a plan for the axis of the tunnel to follow the earth curvature. This tunneling method is effective in the initial alignment of the machine, since the height is referenced to the geoid. After the first rough measurement of the tunnel using the surveying instruments, the initial alignment for the acccelrator components will continue using the basic alignment sysytem. This basic system consists of LSHFs and wire positioning systems. We use these basic systems in order to align the length of 30 km machine within a tolerance of 30 μm. Two dimensional wire positioning sensor is developping now.

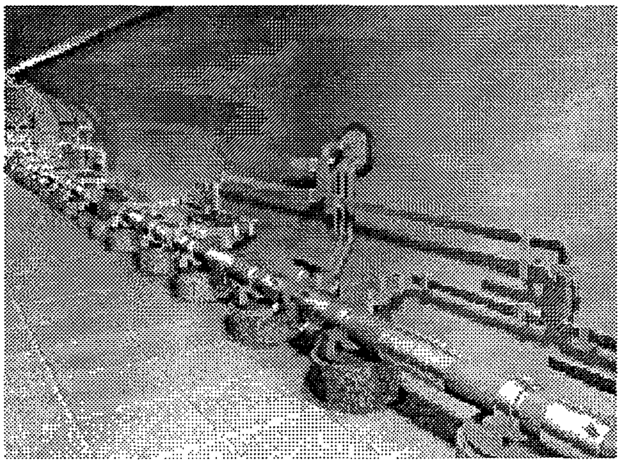

Figure 7: View of the accelerator tunnel. Accelerating structure, Q magnet, supporting system and component carrier.

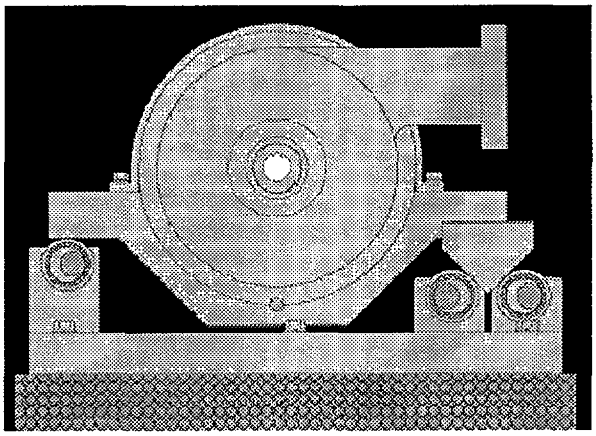

Figure 8: Structure positioning mount with roller cams. Rotation of the eccentric camshaft shifts the accelerator structure position [14].

In the first plan of the C-band linear collider, we would excavate a single tunnel of circular cross-section with diameter of 8 m using TBM, and set up the accelerating structure on the cylindrical concrete girder having active movers [13]. Now we have a new plan following our detailed study on the excavation including its expenditure and stability of *ATL* coefficient. It is possible to reduce 50% or more in the price by changing from the single tunnel (8 m diameter) to the dual tunnel (with diameters of 3 m and 4.2 m as mentioned above). From the view point of the *ATL*, the separated tunnel like this is preferable to suppress the the noises in the accelerator tunnel caused by the accelerator facility including its cooling water system, power transformer, compressor and air conditioner etc. We have got a new information about the *ATL* for the low frequency region as shown above, that is, we have to pay attention not only to the general *ATL* coefficient of a site, but also to local fluctuation of the coefficient in constructing a long scale linear collider. The maximum betatron wave length is about 30 m for the C-band linear collider, our present results, however, show that there would be a significant change on the *ATL* coefficient within the betatron wavelength. Thous we are now proceeding a new supporting system for the accelerator components. Figure 1 shows an outline drawing of it and

Fig. 7 zooms in on the accelerator components. They are set up on the low strain granite stands. These stands are fixed directly to the granite rock bed as shown in Fig. 1. The kinematic support being similar to the SLAC FFTB magnet positioner [14], as shown in Fig. 8, is attached to the top of each granite stand. We can position remotely using roller cams and the wire positioning system. With this goal an inexpensive active mechanical mover system to stabilize the alignment for the C-band linear collider should be developed.

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